

SMART TRANSPORT FOR CITIES & NATIONS Kockelman & Boyles

Smart Transport for Cities & Nations


THE RISE OF SELF-DRIVING
& CONNECTED VEHICLES



Kara Kockelman & Stephen Boyles

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The background is a light blue field filled with various transportation-related terms in different sizes and orientations, such as 'connectivity', 'design', 'policy', 'network', 'shared', 'connected', 'time-savings', 'efficient', 'freight', 'shared', 'connected', 'time-savings', 'efficient', 'freight', 'shared', 'connected', 'time-savings', 'efficient', 'freight'. At the top, there are icons of a car, a bus, and a traffic light. A dashed white line runs horizontally across the middle of the page.

Smart-driving technologies will transform our transportation systems, catalyzing significant mobility, safety, and environmental impacts. Technologies alone are not enough for an optimal transport future: innovative operational strategies, thoughtful policymaking, and strategic investments are needed.

This book investigates a variety of smart-transport technologies, policies, and practices for local streets and highways using driverless or autonomous vehicles (AVs), connected vehicles (CVs), roadside equipment, smartphones, and algorithms. Chapter authors explore ideas and equipment for more efficient intersection and network operations for connected and fully-automated vehicle (CAV) operations, alongside a suite of behavioral and traffic-flow forecasts for regions and nations under a variety of vehicle mixes (smart plus conventional, semi-autonomous versus fully autonomous, connected but not automated). The authors also suggest proactive policymaking for vehicle- and occupant-licensing, liability, privacy standards, and micro-tolling as technologies become publicly available and travel behaviors change.

Dr. Kara Kockelman is a registered professional engineer and holds a Ph.D., M.S., and B.S., in civil engineering, a master's of city planning, and a minor in economics from the University of California at Berkeley. She has been a professor of transportation engineering at the University of Texas at Austin for the past 19 years. She is primary and co-author of over 140 journal articles and one book across a variety of subjects, nearly all of which involve transportation-related data analysis. Her primary research interests include planning for shared and autonomous vehicle systems, the statistical modeling of urban systems (including models of travel behavior, trade and location choice), energy and climate issues (*vis-à-vis* transport and land use decisions), the economic impacts of transport policy, and crash occurrences and consequences.

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**SMART TRANSPORT FOR CITIES &
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CONNECTED VEHICLES**

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First Edition

Smart Transport for Cities & Nations: The Rise of Self-Driving & Connected Vehicles

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COMMONLY USED ACRONYMS

AIM	autonomous (fully automated) intersection management
AV	fully automated or “autonomous” vehicle (AV)
BPR	Bureau of Public Roads
BSM	basic safety message or blind spot monitoring
CAV	connected autonomous vehicle (a communicating and self-driving vehicle)
C/AV	connected and/or automated vehicle (not necessarily fully automated)
CR	conflict region
CRF	crash reduction factor
CTM	cell transmission model
CV	connected vehicle
DOT	department of transportation
DSRC	dedicated short-range communication
DTA	dynamic traffic assignment
DUE	dynamic user equilibrium
FCC	Federal Communications Commission
FCFS	first-come, first-served
FHWA	Federal Highway Administration
FTC	Federal Trade Commission
H-AIM	hybrid autonomous intersection management
HAV	highly automated vehicle
HV	human-driven vehicle
IMU	inertial measurement unit
LWR	Lighthill–Whitham–Richards model
MCT	marginal cost toll
MP	market penetration
NHTSA	National Highway Traffic Safety Administration
OBU	onboard unit

OD	origin-destination
PDE	partial differential equation
POD	portable onboard device
SAV	shared AV
SO	system optimum
SwRI	Southwest Research Institute
TAZ	traffic analysis zone
TBR	tile-based reservation
TMC	traffic management center
TNC	transportation network company
TSTT	total system travel time
TxDOT	Texas Department of Transportation
UE	user equilibrium
VMT	vehicle-miles traveled
VOT	value of time
VOTT	value of travel time
WTP	willingness to pay
WWD	wrong-way driver

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Preface

The world is changing, connected and automated vehicle (CAV) technology promises dramatic disruptions to transportation. Mobility for the elderly and the young may increase. A significant fraction of the 30,000 annual road deaths in the United States may vanish. By driving more efficiently, automated vehicles may reduce congestion, emissions, and fuel consumption. Land use and travel behavior patterns will shift as people can use driving time for other productive ends. By entering supply chains and logistics services, CAVs promise major impacts on the economics of freight, and employment in this sector.

As transportation professionals struggle to predict the impacts of this disruptive technology --- both positive and negative --- it is refreshing to see great interest in proactively planning for these technologies before they become mainstream. The authors of this book have spoken with many representatives from public agencies, engineering firms, and academia, and there is a common interest in trying to understand what impacts CAVs will likely have, how to maximize the potential benefits, and how to minimize unintended consequences. Even if there is still uncertainty in exactly what CAVs can do technologically, legally, or socially, planning in advance is much easier and more cost-effective than trying to resolve issues that arise after CAVs are widespread.

This book is the result of several research projects sponsored by the Texas Department of Transportation (TxDOT) which began in 2015. It covers a wide range of issues which are relevant to transportation professionals wanting to know what CAVs mean for them. Its chapters include discussion of legal and policy issues, current public opinions and forecasts of CAV willingness-to-pay and market share, models for estimating safety and traffic operations benefits, discussions of current technology options, and case studies evaluating ridesharing and other technology/policy scenarios.

This book is intended to be useful to transportation professionals and students who are interested in learning how CAVs may impact the transportation sector, and in learning the methods used to generate these forecasts and predictions. Some familiarity with transportation planning and traffic engineering terminology and concepts is presumed, but any terms and ideas specific to CAVs are explained in the chapters. While some readers may find the results from surveys and case studies enough for their purposes, others may wish to apply the methods and modeling principles used to original scenarios of their own. It is intended to be usable as a reference, and most chapters can be read independently of the others.

Many individuals played key roles in making this book a reality. The authors are grateful to Scott Schauer-West, who spent hundreds of hours on formatting details, copyright information, and other massive contributions to make this work possible. We are also thankful for Lexi Cepak, an undergraduate research assistant who assisted in compiling and editing much of the work found in this book, and Devin Wilkins, who led the design of the book cover. TxDOT's financial support across multiple AV-related research projects was critical for thousands of hours of work that resulted in this current manuscript. In particular, we would like to thank TxDOT's Darrin Jensen, Jianming Ma, Becky Blewett, Janie Temple, Danny Magee, Melissa Montemayor, Travis Scruggs and Darcie Schipull for their proactive feedback through every stop of the original manuscript's development. We also wish to thank Maureen Kelly of U.T.'s Center for Transportation Research for their editing support.

We hope that this book serves you well in describing some of the changes CAVs may bring. The future in transportation is at once bright with the possibility dramatic gains in mobility, safety, and efficiency, as well as cloudy, with significant uncertainty around policy and technology trends, and unintended behavioral consequences. The future is also now, and policy decisions made in the coming years will shape the trajectory of CAV technology for decades to come. We look forward to working alongside you and other professionals to realize the incredible potential of these technologies.

In dedication to our families & collaborators,

Kara Kockelman and Stephen Boyles

CHAPTER 1 INTRODUCTION AND REPORT SUMMARY

1.1 Chapter Summaries

Chapter 2: Identifying CAV Technologies

To understand the potential impacts of smart driving technologies, this chapter synthesizes existing and emerging smart driving technologies to (i) gain an initial understanding of their impacts on safety, operations, and design, and (ii) align these with the strategic goals of local transportation agencies to develop recommendations. An initial qualitative analysis was conducted to pinpoint noteworthy impacts of these technologies. The scope was limited specifically to smart driving technologies that are likely to have significant public-sector involvement. The research team completed these tasks:

- Conducted an initial scan of media to define an extensive list of smart driving technologies and their categorization, in alignment with the National Highway Traffic Safety Administration (NHTSA)'s taxonomy.
- Scanned media reports, technical reports and presentations, manufacturers' websites, and academic papers to determine the current state-of-practice of each technology.
- Developed initial analysis to describe each technology's likely impacts on safety, operations, and design.

Chapter 3: Concept of Operations

The United States Department of Transportation (USDOT) has committed to the development of a fully connected transportation system that will enable advanced vehicle safety applications. The program began in 2006 as the Vehicle Infrastructure Integration (VII) program and is currently known as the Connected Vehicle (CV) program. This program has focused on a number of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) applications, such as forward collision warning (FCW), emergency electronic brake lights (EEBL), intersection violation warning, signal phase and timing (SPAT), signal prioritization and pre-emption, blind spot detection/warning, and others.

Increasing connectivity among vehicles, roadside devices, and traffic management systems creates the potential for both novel benefits to society as well as novel risks, particularly from the emerging cyber security risk to vehicles that are increasingly computerized and connected. The vulnerability of individual vehicles for targeted disruption has increased as their control systems, and even their entertainment systems, have shifted towards computer control, and greater connectivity. The evolution of Advanced Driver Assistance Systems (ADAS) towards semi- or fully automated vehicles also exacerbates this risk as the software may naively react to an Over-the-Air (OTA) message that is incorrect, whether benign or malicious.

Chapter 4: Estimating the Safety Benefits of CAV Technologies

In order to assess potential benefits to the transportation system and its users stemming from CAVs, it is first critical to assess the existing scope of problems faced by the traveling public. To these ends, this chapter attempts to quantify these problems across two major domains: congestion and crashes. During the course of the research, initial estimates, which were then refined using the results of the other analyses performed. Section 4.1 describes the preliminary estimates generated at the beginning of the research, and Section 4.2 the updated estimates generated near the end.

Chapter 5: Demonstration of CV Applications Pertaining to Traffic Management Operations

Smart-driving technologies are changing the landscape of transportation. Significant mobility, safety and environmental benefits are anticipated from these technologies, which enable safer and more comfortable driving in general. However, in order to realize the maximum potential benefits for the overall transportation system, these

technologies alone are not enough. Rather, policymaking and innovation in infrastructure and operations strategies, among other measures, are crucial.

The objectives of this chapter were to develop and demonstrate a variety of smart-transport technologies, policies, and practices for highways and freeways using AVs and CVs, smartphones, roadside units, and related technologies.

Chapter 6: Technology Implementation: Generating and Integrating Inertial Measurement Data with Flow Models for Traffic Monitoring

In this chapter, we identify two possible improvements to the problem of traffic state estimation (that is, creating traffic maps and forecasts from traffic measurement data), that directly result from the presence of Connected and Automated Vehicles (CAVs). These improvements can be summarized as follows:

- Using vehicle connectivity to generate traffic measurement data automatically, relying in the currently available traffic monitoring infrastructure. In the present case, our objective is to investigate the use of Inertial Measurement Units (IMUs), which can act as position sensors, while preserving user privacy. These IMUs can send traffic measurement data over Bluetooth, to currently available Bluetooth traffic readers.
- Since these IMU sensors generate trajectory estimates, which typically differ from the measurement data generated by both GPS sensors and fixed traffic sensors, our objective is to design a computational scheme that can integrate the trajectory estimates generated by the IMU sensors into traffic flow model, to generate traffic maps.

Chapter 7: Legal Environment of Self-Driving Vehicles with CAVs

The law is often cited as one of the primary obstacles to the effective and efficient integration of connected and/or autonomous vehicles (C/AV) onto public roadways (Davidson and Spinoulas 2015). Without well-defined liability, privacy, and licensing structures, some observers worry that automobile manufacturers may be reluctant to conduct research or install new technologies in vehicles (GAO 2013, p.28).

For states where testing of C/AVs is underway and there is enthusiasm about further integration of the benefits and capabilities of automated transportation onto state highways, policymakers are eager to learn more about the intersection of this new wave of technology with the existing legal infrastructure. Specifically, policymakers are interested in whether the existing law prohibits or impedes testing or deployment of the technology or, conversely, whether greater legal oversight may be desirable. Moreover, in light of the limited federal regulation of C/AV transportation, there are questions about the most useful role of states and local governments in overseeing this new technology.

Chapter 8: Texas Legal Environment for Self-Driving Vehicles

This chapter explores the effect of a state's legislature on the implementation of innovative and connected vehicle technologies. Texas is used here as a case study example for other states passing similar legislation. Specifically, the legality of licensing C/AVs for Texas roadways and deciding legal responsibility in the event of an accident involving on AV are examined. Crash litigation is especially important to ensure that AV manufacturers are not dissuaded from producing them simply because the risk of being liable for an accident is too high. While part of this burden falls at the feet of the automotive manufacturer, it is also up to state legislatures to clearly outline expectations regarding these technologies before they are implemented.

Chapter 9: Traffic Models for Automated Vehicles

A chapter of this book defines the notion of user equilibrium (UE) and system optimum (SO). Applying tolls is then introduced as a mechanism that allows UE and SO to coincide. The marginal cost toll (MCT) policy is then presented, followed by some macroscopic traffic models that approximate it. Discussion on some of the drawbacks of such macro-models are presented, which provide the motivation for the current study.

Connected and automated vehicle (CAV) technologies have a promising future in improving traffic safety, including mitigating crash severity and decreasing the possibility of crashes by offering warnings to drivers and/or assuming vehicle control in dangerous situations. Given the complexities of technology interactions and crash details, the overall safety impacts of multiple CAV technologies have not yet been estimated. This research seeks to fill that gap by using the most current U.S. General Estimates System crash records to estimate the economic and functional-years crash-related savings from each CAV application. Safety benefits of Forward Collision Warning, Cooperative Adaptive Cruise Control, Do Not Pass Warning, Control Lost Warning, Cooperative Intersection Collision Avoidance Systems, Electronic Stability Control, and other safety-related CAV-type technologies are estimated here. Results suggest that eleven CAV technologies, such as Forward Collision Warning, when combined with Cooperative Adaptive Cruise Control, and Cooperative Intersection Collision Avoidance Systems, can save Americans \$76 billion each year (along with almost 740,000 functional-life-years saved per year). These estimates are based on pre-crash scenarios that depict the critical event occurring immediately prior to a crash (e.g., rear-end and intersection-related situations) and under conservative effectiveness scenario assumptions; the savings are due to crash avoidance and/or moderation of crash severities. Among the various combinations of driving situations and technology applications, Forward Collision Warning coupled with Cooperative Adaptive Cruise Control is anticipated to offer the biggest safety benefits, by saving more than \$53 billion (in economic costs) and 497,100 functional person-years in 2013.

Chapter 10: Anticipating the Emissions Impacts of Autonomous Vehicles Using the MOVES Model

Connected and autonomous vehicles (CAVs) are expected to have significant impacts on the environmental sustainability of transportation systems. This study examines the emission impacts of CAVs, presuming that CAVs are programmed to drive more smoothly than humans. This work uses the US Environmental Protection Agency's (EPA's) Motor Vehicle Emission Simulator (MOVES) to estimate CAVs' emissions based on driving schedules or profiles. CAV engine load profiles are anticipated to be smoother than those of human-controlled vehicles (HVs), because CAVs are designed to be more situationally aware (thanks to cameras and radar communication) and enjoy faster reaction times and more sophisticated throttle and break control than HVs. Human drivers tend to demonstrate significant and frequent speed fluctuations and have relatively long reaction times.

This study uses EPA driving cycles and Austin-specific driving schedules to reflect national, trip-based and local, link-based driving behaviors. Those driving cycles are smoothed using spline functions, to estimate how CAVs may handle; and emissions results suggest that the smoothed CAV cycles deliver lower average emission rates (in grams per mile) for all five species of interest. For example, with gasoline vehicles, smoothing of the Federal Test Procedure (FTP) cycle delivers 5% fewer volatile organic compounds (VOC), 11.4% less fine particulate matter (PM_{2.5}), 6.4% less carbon monoxide (CO), 13.5% less oxides of nitrogen (NO_x), and 3% less sulfur and carbon dioxide (SO₂ and CO₂). Using Austin link-based cycles, average reductions were 10.9% for VOC, 19.1% for PM_{2.5}, 13.2% for CO, 15.5% for NO_x, and 6.6% and SO₂ and CO₂. While added travel distances by CAVs may negate many of these benefits, it is valuable to start discussing a shift to gentle driving, to obtain these reductions via emerging technologies.

Chapter 11: Application of Traffic Models

This book describes analyses of the traffic impacts of connected and automated vehicles under multiple scenarios. It describes how automated vehicles can be integrated into the traditional four-step planning process, including mode and route choice, using static traffic assignment. It shows how dynamic traffic flow models can represent capacity increases. It describes two traffic simulation models that were developed: The Autonomous Intersection Management microsimulator and a simulation-based dynamic traffic assignment application, as well as results from simulating arterial, freeway, and city networks. Finally, it discusses the traffic impacts of shared automated vehicles.

Chapter 12: Improvement and Implementation of Dynamic Micro-tolling

Currently, AV, connected vehicle (CV), and CAV technologies are still in the development stage, meaning CAVs are not widespread and are currently too expensive for the average household to afford. However, companies are investing more money into CAV technologies. As these technologies develop further, perceptions and availability of CAVs are poised to change for the better. CAVs have a spate of benefits to offer to the user, other vehicle users, and the environment. These benefits include improved safety, reduced travel times, and reduced roadway

emissions. While 100% CAV penetration is unlikely in the near future, the increase in number of CAVs on the roadways is almost certain. Therefore, understanding how different levels of CAV penetration on roadways can affect other commuters and the environment is important. Since HVs will still be present on the roadway, existing infrastructure will have to remain in place so these users can continue to travel comfortably. Therefore, the interplay between CAVs and HVs using current infrastructure, such as traffic lights and traditional stop signs, becomes an area of interest.

This majority of this chapter is concerned with the interplay between human and autonomous drivers. The following sections outline the test networks and results used to see how travel time, safety, and emissions are affected by the inclusion of CAVs at different roadway penetrations. In order to adequately explore the effects on travel time with HVs and CAVs, multiple types of roadway networks are tested. These networks are also tested under different scenarios such as rush-hour traffic demands or more relaxed demand levels. Once the decision of which networks to use and what scenarios to model were decided upon, simulations were performed to demonstrate the effects of CAVs at different penetration levels.

Modern simulation tools and computational power allow for much more fine-grained simulation of traffic networks, referred to as *microsimulation models*. Using such a realistic traffic simulator, demonstrations could be created to assess the potential of using tolls for reducing average travel time and increasing average utility. In response to the suboptimal performance of existing macro-models, a novel tolling scheme, denoted “ Δ -tolling” (*delta-tolling*), is introduced. Δ -tolling approximates the marginal cost of each link using only two variables (current travel time and free-flow travel time) and one parameter. Due to its simplicity, Δ -tolling is fast to compute, adaptive to current traffic, and accurate.

Chapter 13: Design and Implementation of a Shared Autonomous Vehicle System in Austin, Texas

Autonomous vehicles (AVs) and shared autonomous vehicles (SAVs) have the potential to significantly change society’s transportation systems and land-use patterns, thereby impacting the quality of life for urban dwellers. A shift to self-driven cars affects what people do in their vehicles, their values of travel time, road safety, traffic congestion, and the natural environment. Cities and other government agencies will have the opportunity to integrate SAV technologies systemically within roadway networks to further promote these concepts, as well as to provide low-cost transit options, further propagating the benefits. The assumptions enabling this forward thinking will provide initial insight into AV technology and their application within the Austin network. The station and queuing geometry utilizes context sensitive design, promoting multi-modal access. This insight into SAV dynamic ridesharing (DRS) systems enables potential initial integration of this technology, given the benefits logistically of fleet systems. Different station locations are examined, (and can serve as a template for other special trip generators in cities across the globe) serving different areas of the metropolitan region, and providing a differing level of service to the users of the Austin transit system. This culminated in the decision of electric cars providing service to four regionally distributed station systems, generating a benefit-to-cost (B/C) ratio of 4.42.

Chapter 14: Making the Most of Curb Spaces in a World of Shared Autonomous Vehicles

With the recent developments of connected and autonomous vehicles (CAVs) as well as technologies in traffic and transportation systems, CAV applications will have the ability to radically change the urban grid system and challenge urban planners to repurpose existing public infrastructure. As CAV technology matures and accounts for higher proportions of the operating traffic, parking demands will be greatly reduced in central business district centers. Curbside parking spaces may be given back to pedestrians, repurposed for active transit users, or removed entirely to create additional roadway capacity.

This chapter examines Austin’s parking supply and offers case study examples for curb-parking repurposing. It emphasizes how the potential implications of SAVs enable more utilitarian uses of curb-parking and offer an empirical study into repurposing this public area, providing municipalities the ability to develop the means to eventually liberate this public land from parked vehicles and repurpose it for a larger community benefit. The supply and demand for these alternative spaces is provided here for developing the decision support system, as well as their physical location, attributes, and pricing regimes. This analysis offers recommendations for future

usage of existing curb spaces and ways to ensure curb-parking is ready for SAV-using settings. The suggestions offered here may serve as a model for other cities and may be valuable in long-term city development and planning

Chapter 15: Preparing Data for Modeling Disaggregated Travel Modes: A Tool for Taking Advantage of Existing Travel Modes and Open Source Data

Car-sharing and ride-sharing offer travelers another mode of transport in and between cities. Such modes have the potential to take off with the transformative implementation of connected and autonomous vehicles (CAVs). To provide decision-makers reasonable information about mode splits, congestion, fleet operations, parking shifts, and other impacts of these new modes, transportation planners and researchers need microsimulation for vehicle tracking and advanced travel modeling approaches. Activity-based models (ABMs) typically anticipate travel choices at the level of individuals, and normally offer greater temporal and spatial details than traditional, behaviorally and spatially aggregate models. Four-step travel demand modeling is trip-based and at the level of aggregate traffic analysis zones (TAZs). As a result, ABMs are better able to anticipate the impacts of self-driving vehicles, ride-sharing, and car-sharing for the 20-year horizon that is typical of transportation planning practice. ABM takes the individual's daily activities chained by a series of travel trips, also called "tour" if the last trip ends where the first trip starts, e.g., home, as the travel demand input. The input can be simply summarized as "4Ws": Who this person is, where he/she lives and works, what daily activities he/she undertakes, and when he/she plans to perform activities. This study delivers a methodological framework to prepare the "4W" inputs, taking advantage of existing travel model data (including standard travel survey data) and open-source data (like Open Street Maps). It provides a series of coded algorithms that output a complete synthetic population, with locations for all non-home activities, trip chains or tours, and travel schedules. The tool is particularly useful for state, regional and local transportation-planning divisions and agencies - and their consultants, who already have the network and travel data and seek to convert their existing trip-based models to microscopic (person-based) travel chains and ABMs that better support simulation of future years, with self-driving vehicles and other technologies implying much more complex transportation scenarios.

Chapter 16: Emerging Transportation Applications

The United States Department of Transportation (USDOT) has committed to the development of a fully-connected transportation system that will enable advanced vehicle safety applications. The program began in 2006 as the Vehicle Infrastructure Integration (VII) program and is currently known as the Connected Vehicle (CV) program. This program has focused on a number of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) applications, such as forward collision warning (FCW), emergency electronic brake lights (EEBL), intersection violation warning, signal phase and timing (SPAT), signal prioritization and pre-emption, blind spot detection/warning, and others.

Increasing connectivity among vehicles, roadside devices, and traffic management systems creates the potential for both novel benefits to society as well as novel risks, particularly from the emerging cyber security risk to vehicles that are increasingly computerized and connected. The vulnerability of individual vehicles for targeted disruption has increased as their control systems, and even their entertainment systems, have shifted towards computer control, and greater connectivity. The evolution of Advanced Driver Assistance Systems (ADAS) towards semi- or fully-automated vehicles also exacerbates this risk as the software may naively react to an Over-the-Air (OTA) message that is incorrect, whether benign or malicious. Transportation research is currently at a tipping point; the emergence of new transformative technologies and systems, such as vehicle connectivity, automation, shared-mobility, and advanced sensing is rapidly changing the individual mobility and accessibility. This will fundamentally transform how transportation planning and operations should be conducted to enable smart and connected communities. The transportation systems can be substantially improved, and become safer, more efficient and reliable, thanks to the emergence of connected and autonomous vehicle technology. Dynamic routing and traffic-dependent navigation services are already available for users. Such applications need to estimate the present traffic situation and that of the near future at a forecasting horizon based on measurement data available in real-time, possibly supplemented with past data on traffic patterns. Using this measurement data and prior information, one can estimate the state of traffic on a road network, which consists in estimating all the traffic variables (e.g. cars density, speed), everywhere in the network, at the current time. This estimation requires the fusion of traffic data and traffic models, which are typically formulated as partial differential equations (PDEs).

Chapter 17: Benefit-Cost Analysis

Connected and automated vehicles (CAVs) have the potential to significantly change surface transportation. CAVs will likely influence and hopefully diminish externalities associated with driving such as crashes, congestion and emissions, with further impacts on connecting communities, land use and economy. However, the ultimate impacts of CAVs remain quite uncertain, and much depends on how they are ultimately deployed and used.

The objective of this chapter is to evaluate the potential costs and benefits of using smart transport technologies to harness CAV capabilities, where local transportation agencies would have a role in deploying such strategies. This is accomplished by conducting a cost-benefit analysis for a variety of strategies and assessing benefits that may be achieved seeking to harness connected and automated vehicle technologies, while at the same time considering associated costs.

In Section 17.2 of the chapter, transportation objectives are defined, along with measures to evaluate impacts to system performance. The potential strategies that are evaluated in this chapter are outlined in Section 17.3, along with anticipated impacts to the overall transport system objectives and performance measures. Each of these evaluated strategies bring extra costs for vehicle users and infrastructure. Infrastructure costs such as construction, operation, and maintenance are assessed for each strategy, while costs related to installing in-vehicle communication units, and vehicle automation capabilities (and their associated maintenance) are the responsibility of vehicle owners and are not considered here.

Chapter 18: Other Findings and Related Work

In this chapter, brief summaries of other work relative to the materials explored in this book are examined. Specifically, how this content ties in to this C/AV work and its' relevancy moving forward. These publications can be read in detail in their long-form published versions, available in their respective journals.

Chapter 19: Recommendations and Best Practices

In this chapter, an overview of current research discussed in this book is provided, followed by a summary of recommendations for transportation stakeholders. Sections within this chapter are broken into short-term, mid-term and long-term efforts and are legally-focused, stressing what actions transportation agencies should take in coordination with their local governments to prepare for the advent of autonomous vehicles.

CHAPTER 2 IDENTIFYING CAV TECHNOLOGIES

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2.1 Introduction

To understand the potential impacts of smart driving technologies, this chapter synthesizes existing and emerging smart driving technologies to (i) gain an initial understanding of their impacts on safety, operations, and design, and (ii) align these with the strategic goals of a transportation agency, for developing recommendations. An initial qualitative analysis was conducted to pinpoint noteworthy impacts of these technologies. The scope was limited specifically to smart driving technologies that are likely to have significant public-sector involvement. The research team completed these tasks:

- Conducted an initial scan of media to define an extensive list of smart driving technologies and their categorization, in alignment with the National Highway Traffic Safety Administration (NHTSA)'s taxonomy.
- Reviewed media reports, technical reports and presentations, manufacturers' websites, and academic papers to determine the current state-of-practice of each technology.
- Developed initial analysis to describe each technology's likely impacts on safety, operations, and design.

2.2 Identifying Smart Driving Technologies

To clarify the scope of smart driving technologies and understand their impacts, an extensive literature review was conducted. This review is focused on the definition, functions, working mechanisms, maturity, limitations, and cost of each technology. NHTSA's four-level taxonomy of autonomous vehicles (AVs) was adopted to facilitate the discussion (the research team also compared this with the Society of Automotive Engineers five-level taxonomy of AVs).

NHTSA's Taxonomy

NHTSA has defined five vehicle automation technology levels in (including Level 0 which indicates no automation). Levels 1 through 2 encompass technology that is commercially available today; Levels 3 to 5 are being tested.

- **Level 0**, or no automation, means that the driver is completely responsible for the primary vehicle controls: braking, steering, throttle, and motive power.

- **Level 1**, or driver assistance automation, indicates that one or more specific control functions are automated. Examples include electronic stability control (ESC) and pre-charged brakes (where the vehicle automatically assists with braking to enable the driver to regain control after skidding or to stop faster than possible by acting alone). Other examples include adaptive cruise control (ACC) and lane-keeping assistance (LKA). Though there are multiple functions that may be a part of Level 1, assistance with lateral and longitudinal control is never occurring concurrently. This is the major difference between Levels 1 and 2.
- **Level 2**, or partial automation, implies automation of at least two primary control functions designed to work together to relieve the driver's control of those functions. Examples include a combination of ACC and LKA.
- **Level 3**, or conditional automation, indicates that vehicles at this level enable the driver to cede full control of all safety-critical functions under certain traffic and environmental conditions. Based on these conditions, the vehicle may require the driver to interfere from time to time. The driver is still expected to be available for occasional control, but only after a warning and some comfortable transition time (3 to 5 seconds).
- **Level 4**, or high automation, indicates that the vehicle is designed to perform all driving functions for the entire trip, but is limited to travel only in certain scenarios. For example, vehicles may be limited to travel only on certain roads or under limited weather conditions. This design anticipates that the driver will provide the destination or navigation input, but the driver is not expected to be available for vehicle control at any time during the trip.
- **Level 5**, or full automation, is nearly identical to Level 4, except that vehicles are not restricted to certain scenarios. They are free to travel on any road and under any condition. Similar to Level 4, fully automated vehicles do not require a driver to be capable of performing operational functions at all times, but there may be an option for them to take control.

Recognizing the prominent safety, environmental and mobility potential of emerging automotive technologies, NHTSA released a document entitled "Preliminary Statement of Policy Concerning Automated Vehicles" (NHTSA, 2013). In this document, NHTSA provides definitions of different levels of automation, current automated research programs at NHTSA, and principles recommended to states for driverless vehicle operations (including but not limited to testing and licensing). According to NHTSA definitions, the term automated vehicles refers specifically to "those in which at least some aspects of a safety-critical control function (e.g., steering, throttle, or braking) occur without direct driver input." Vehicles that can provide safety warnings, but cannot control functions, are not fully automated.

According to these definitions, with increasing levels of automation, drivers have decreasing engagement in traffic and roadway monitoring and vehicle control. From level 0 to level 4, the allocation of vehicle control function between the driver and the vehicle falls along a spectrum from full driver control (Level 0), driver control assisted/augmented by systems (Level 1), shared authority with a short transition time (Level 2), shared authority with a sufficient transition time (Level 3), to full automated control (Level 4). Table 2.1 provides an outline of the five automation levels based on the NHTSA definitions.

Several mainstream companies, such as Waymo (Google car) Toyota, Nissan, and Audi, are currently developing and testing their own prototypes (Smiechowski 2014). With rapid advances in vehicle automation and connectivity, NHTSA (NHTSA 2013 & 2014) recognizes key policy needs for connected and autonomous vehicles (CAVs). Navigant Research (2014) estimated that 75% of all light-duty vehicles around the globe (almost 100 million annually) will be autonomous-capable by 2035. In accordance with this timeline, Litman (2014) expects that AVs' beneficial impacts on safety and congestion are likely to appear between 2040 and 2060. If AVs prove to be very beneficial, Litman (2014) suggests that human driving may be restricted after 2060. Section 2.2 provides further detail on the driving technologies.

Table 2.1 Five automation levels based on NHTSA (2013) definitions

	Vehicle Controls	Traffic and Environment (Roadway) Monitoring	Examples
L0	Drivers are solely responsible for all vehicle controls (braking, steering, throttle, and motive power).	Drivers are solely responsible; system may provide driver support/convenience features through <i>warnings</i> .	Forward collision warning; lane departure warning; blind spot monitoring; automated wipers, headlights, etc.
L1	Drivers are still <i>solely responsible</i> , but vehicle systems can <i>assist or augment</i> the driver in operating one or more of the primary vehicle controls. Only one of the primary vehicle controls systems may provide assistance during any one time.	Drivers are solely responsible for monitoring the roadway and safe operation although <i>warnings</i> may be provided as with L0.	Adaptive Cruise Control (ACC), automatic braking (dynamic brake support and crash imminent braking), lane-keeping, Electronic Stability Control (ESC).
L2	Drivers have <i>shared authority</i> with system. Drivers can cede active primary control in certain situations and may be physically disengaged from operating the vehicles. Drivers are expected to be available to take control <i>on short notice</i> .	Drivers are responsible for monitoring the roadway and safe operations and are expected to be <i>available</i> for control <i>at all times</i> . <i>Warnings</i> may still be provided.	ACC combined with lane centering.
L3	Drivers are able to <i>cede full control</i> of all safety-critical functions <i>under certain conditions</i> . Drivers are expected to be available for occasional control, but with <i>sufficient transition time</i> .	When ceding control, drivers can <i>rely heavily on the system</i> to monitor traffic and environmental conditions require transition back to driver control.	Automated or self-driving car approaching a construction zone and alerting the driver sufficiently in advance for a smooth transition to manual control.
L4	Vehicles perform <i>all safety-critical driving functions</i> and monitor roadway conditions for an entire trip. Drivers will provide destination or navigation input but are <i>not expected to be available for control</i> at any time during the trip.	System will perform all the monitoring.	Driverless car.
L5	Vehicles perform <i>all safety-critical driving functions</i> and monitor roadway conditions for an entire trip. Vehicles are <i>not</i> restricted in where and under which conditions they can travel. Drivers will provide destination or navigation input, but	System will perform all the monitoring.	Driverless car.

	are <i>not expected to be available for control</i> at any time during the trip.		
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2.3 Driving Technology Synthesis

Level 0 Technologies

Forward Collision Warning: NHTSA defines a forward collision warning (FCW) system as “one intended to passively assist the driver in avoiding or mitigating a rear-end collision via presentation of audible, visual, and/or haptic alerts, or any combination thereof.” An FCW system has forward-looking vehicle detection capability, using sensing technologies such as cameras, radar, and Lidar. Sensor data are processed and analyzed, and alerts are provided if a collision with another vehicle is imminent.

Blind Spot Monitoring: There are two different types of blind spot monitors (BSM, not to be confused with Basic Safety Message): active and passive. An active BSM generally uses radar or a camera to detect when another vehicle gets close to the BSM-equipped vehicle. If any such vehicles are detected, the BSM-equipped vehicle will notify its driver. The type of notification can depend on how likely it is that two vehicles will collide; as the likelihood of collision increases, so does the magnitude of the warning that the driver receives. The other type of BSM is the passive, which involves only additional mirrors. Car manufacturers offer the choice to have a special small convex mirror added in the corner of the regular rearview mirror, which can provide additional visual access to the blind spot.

Volvo was the first to introduce blind spot technology in 2005 under the trade mark of Blind Spot Information System (BLIS). Originally BLIS used cameras but the newest BLIS technologies use radar. Many other manufacturers currently have very similar blind spot technologies as well (e.g., Audi’s Side Assist). A more advanced system is available on Infiniti’s models, as well as other luxury brands like BMW and Acura. Infiniti’s blind spot system consists of two sub-systems: in addition to the blind spot warning, there is a blind spot intervention sub-system. The former notifies the driver of vehicles in the blind spot while the latter will work to keep the vehicle in its lane if it is not safe to change lanes.

Active blind spot detection usually comes as an optional feature in most mid- to high-end cars. Purchasing this add-on will increase the vehicle price by around \$250–500. There are plenty of models where a consumer can buy the entire safety package (which might also include lane departure warning, FCW, and cross traffic alert) for around \$1000 (Howard, 2013).

Lane Departure Warning: Lane departure warning is similar to blind spot monitoring. The system detects the approaching vehicles’ speed and distance from neighboring lanes and warns the driver of potential danger if the driver wants to change lanes. A lane departure warning system can also warn the driver if it detects that the car is leaving its current lane.

It is anticipated that in the future, the system will incorporate features such as monitoring the driver’s eye activities to determine drowsiness (Carmax, 2015). Lane departure warning is available on Infiniti models as an option; the package runs from \$3,600 to \$10,500.

Traffic Sign Recognition: Traffic sign recognition (TSR) is a technology capable of identifying and displaying upcoming traffic signs that may be missed by drivers. A typical system functions using a camera to detect oncoming traffic signs, a recognition system that identifies the meaning of the signs recorded by the camera through image processing, and a display pane. The road sign information can be displayed on either the vehicle’s instrument panel cluster or on the driver’s navigation system screen. TSR systems’ reliability, especially at high speeds, depends on the camera’s image resolution. In a natural environment, TSR may encounter three main challenges, namely poor lighting and visibility, the presence of other objects, and variation of traffic and road signs.

The first TSR systems were developed by Mobileye (a technology company that develops vision-based advanced driver assistance systems) in 2007 and have been available since 2008 on the BMW 7 Series as a dual vision and satellite navigation system. Honda also released its advanced driver assistive system called “Honda SENSING” in late 2014 (Honda Motors Co., 2014). According to Mobileye, TSR systems have been developed with high detection accuracy and may have additional information from digital maps and navigation systems (Mobileye, 2015). TSR systems can also function in conjunction with other Mobileye technologies, including lane-centering technology, intelligent headlight control, and other systems that use visual sensors.

Left-Turn Assist: Left-turn assist (LTA) systems use a camera and GPS to warn drivers against attempting a left turn into an intersection where the conditions are unsafe. When LTA is activated, laser scanners installed on the car’s front begin sensing for approaching cars, trucks, and even motorcycles up to 100 meters (330 ft.) away. If the sensors detect an approaching vehicle from the opposite direction and the driver’s vehicle continues to move into the intersection, the LTA system will generate a warning and may even activate the vehicle’s automatic braking (in the case of Level 1 automation). The LTA is designed to work at very low speeds, less than 10 km/hour (roughly 6 mph).

LTA was first mass publicized by BMW in 2011 and further research is currently being conducted on utilizing V2V communication (NHTSA, 2014). V2V communication increases safety by using a wireless local area network to detect other vehicles with similar concealed devices. Caltrans and the University of California at Berkeley’s Partners for Advanced Transportation Technology (PATH) program have performed research on intersection collision avoidance systems within the past few years (Caltrans Division of Research, Innovation and System Technology, 2013). The research tested driver attitudes and behaviors when making left turns at signalized intersections, and found that 78% of the time, drivers conformed to the LTA system’s guidance.

Adaptive Headlights: Adaptive headlights can adjust the direction as well as the brightness to best fit current traffic and surrounding environment. This ensures that the driver has sufficient lighting while at the same time ensuring that the light only minimally interferes with other drivers on the road. Thus, adaptive headlight can greatly improve safety. A study released in 2012 by the Highway Loss Data Institute found that Acura, Mercedes, Mazda, and Volvo vehicles with swiveling headlights were involved in 5% to 10% fewer insurance claims than vehicles without them.

Adaptive headlights have already been widely used in Europe and Japan, and many manufacturers (e.g., BMW) currently have adaptive headlights technology. As of 2013, Toyota had sold 16,600 cars in Europe and Japan with this adaptive headlight technology that is currently unavailable in the United States. As the advancement of headlight technology has been steadily increasing, there has been increasing pressure on federal policymakers to change regulations (Gitlin, 2014). NHTSA stated that it would look into the issue and plans to start a research study to assess the adaptive headlights (Nelson, 2013).

The additional price of having this technology added on to one of these cars was approximately \$600, a number that is expected to decrease with economies of scale (Nelson, 2013).

Level 1 Technologies

Adaptive Cruise Control: Adaptive Cruise Control (ACC) systems allow vehicles to maintain a constant speed under operation, just as a conventional cruise control system would. However, when approaching a slower moving vehicle, drivers with a conventional cruise control system must respond by braking and slowing down to adjust their speed to the vehicle ahead. In contrast, an ACC system is able to address this concern by detecting the speed of the leading vehicle and adjusting its own speed accordingly. In ACC, the system maintains a comfortable and safe distance between itself and the leading vehicle. This “safe distance” is usually chosen by the driver as one of three possible choice: near, medium, and far. Once the space ahead is clear again, the ACC will accelerate the vehicle back to the desired cruising speed. Currently, most ACC systems use radar or laser (less popular) headway sensors and a digital signal processor to determine the distance and speed of the vehicle ahead (Honda Motors Co. Inc., 2015). Sensor information is transmitted to a central controller, which reads the desired settings of the driver. The central controller also controls the engine and/or braking system to respond appropriately.

ACC systems were first introduced into the consumer market in the early 2000s (TRW, 2011). Early systems deployed both lasers and radars on vehicles, but radars are more popular because they function better in inclement weather. Nevertheless, an ACC system is still limited by heavy rain and snow and will shut off under severe weather conditions. In addition, it is common that an ACC system must be reengaged if the vehicle slows down below some threshold. While many automobile manufacturers still do not include ACC systems as a standard feature, the technology is offered in many luxury models. ACC systems currently range in price from \$500 to \$2,500 (Howard, 2013). ACC systems are expected to further integrate with crash detection systems and other V2V communication technology.

Cooperative Adaptive Cruise Control: Cooperative adaptive cruise control (CACC) works by having vehicles form a “tightly packed platoon” with one another and then having each vehicle send messages via V2V communication in order to optimize driver comfort and highway throughput. Drivers will usually not need to take any longitudinal action (i.e. brake or throttle) because the vehicle will respond appropriately on its own. With CACC, drivers still need to supervise the vehicles closely due to the possibility of unforeseen disturbance such as vehicle cut-in into the middle of the platoon (Bujanovic et al., 2018). As such, CACC is a driver assistance function, and drivers are still fully responsible for the driving.

There are two main objectives of CACC technology. The first objective is improving driver comfort. By allowing a CACC vehicle to adjust speeds without the need for driver interference, a driver will feel more comfortable. However, this objective can already be achieved with ACC, without the need for V2V communication. Another objective of CACC is to greatly increase highway throughput by allowing closer headway between vehicles that are both CACC-equipped. This is possible because the brake reaction time (BRT) of a CACC vehicle following another CACC vehicle is only 0.1 seconds. This is almost five times less than the fastest human BRT, which is 0.47 seconds. In addition, throughput will increase, given that any change ahead due to braking, hazards, etc., can be immediately relayed to following vehicles, preventing abrupt slowdowns or stops (van Arem, van Driel, & Visser, 2006).

There are some limitations with CACC. Reduced time gaps between two vehicles can only occur when both vehicles have CACC technology. Therefore, the impact of CACC relies heavily on market penetration. One study found that CACC technology needs to have at least 40% market penetration to have any considerable impact (van Arem, van Driel, & Visser, 2006). However, strategies such as managed lanes may be used in order to see the benefit of CACC even before there is a high market penetration.

Automatic Emergency Braking: Also known as forward collision avoidance, automatic emergency braking (AEB) has the potential to significantly decrease collisions by automatically braking a vehicle when an imminent collision is foreseen. AEB systems are made up of sensors that observe and categorize objects within range, control systems to process the data produced by the sensors, and an automatic braking actuation system to physically stop or slow the vehicle.

To assess the impacts of AEB, (Doecke, Anderson, Mackenzie, & Ponte, 2012) analyzed and recorded data that included vehicle trajectories, speeds, braking location, and impact locations from 103 real-world crashes. This study showed that AEB technologies are capable of reducing the impact speed of unavoidable crashes, as well as preventing some crashes altogether. They also estimated that the baseline system was able to prevent 54% of all unobscured pedestrian crashes, 63% of all rear end crashes, and 22% of all straight crashes into fixed object crashes. These results strongly indicate that by application of a baseline AEB system, the number of crashes involving visible pedestrians, rear end collisions, and objects struck head on would decrease significantly.

A complication with the current AEB systems is their inability to differentiate between an actual impending collision and a false alarm. However, this issue may possibly be resolved as more advanced AEB technologies continue to emerge.

Lane Keeping: Lane-centering and lane-keeping technologies are used to keep automobiles from drifting out of a lane on high-speed roads. The system is designed to function as a safety tool rather than a fully hands-free driving mechanism. With lane-centering, the adapted system uses electronically controlled steering to

maintain a center position in the lane. The technology uses a camera mounted on a vehicle's windshield to watch the lane markers on the road; the camera is able to recognize both yellow and white lines. If the camera detects that the driver is beginning to drift out of a lane without the use of a turn signal, the device will alert the driver with a warning sound, and then activate the electronic steering control to direct the vehicle back into the center of the lane (Toyota Motor Corp., 2015). Alternatively, this may also be done by having the vehicle apply slight brakes on one side of the vehicle but not the other, which will allow it to come back to the center of the lane. Electronic steering is a safety device that may be overridden by the driver.

There are several limitations to current lane-centering technology. First, the cameras use visible light and require clear lane markings in order to function. Thus, inclement weather and reduced visibility in low-light conditions are primary concerns. Likewise, the technology cannot function on roads without clear lane markings, such as neighborhood streets. In fact, many systems have a minimum speed requirement (Brandon, 2013). As of 2018, many vehicles come standard with the Lane Keeping technology. Many other vehicles can have it added on for around \$1000, as part of a larger package that includes multiple other Level 1 functions.

Electronic Stability Control: ESC is potentially the most beneficial safety technology introduced to date. It is an extension of antilock brake technology and traction control system technology (Sivinski, 2011). ESC is one of the main active safety systems (meaning it works to prevent accidents rather than working to prevent injuries once an accident occurs). It is designed to ensure that a driver can always be in full control of the vehicle. It works to prevent skidding and rollovers, which can often happen during high-speed maneuvers or on slippery roads on rainy days (MEA Forensic Engineers & Scientists, 2013).

ESC works by measuring the steering input and comparing this to the yaw angle (i.e., how much the car has actually turned). If there is any difference in these values, then the ESC will automatically apply brakes on any wheel(s) as needed so that the car steers in the desired direction. Also, if needed, the engine throttle can be lowered to avoid power skids (Cars.com, 2012).

ESC imparts significant safety benefits. In 2011, a report funded by the USDOT found that the amount of all fatal car crashes was reduced by 23% for those that have ESC. Furthermore, the amount of single-vehicle fatalities in a car was reduced by 55% (Sivinski, 2011). The study also noted that, though ESC is beneficial everywhere, it is particularly effective in locations that are prone to ice, hail, and/or slush during the winter season. However, it is important to not overlook the fact that there is always the small possibility that when an accident does occur, the presence of the ESC may have contributed to the control loss (MEA Forensic Engineers & Scientists, 2013).

Since 2012, all new passenger vehicles, trucks, or busses weighing less than 10,000 pounds are required to have ESC systems, as per Federal Motor Vehicle Safety Standards. Given that the life span of some vehicles is more than 20 years, not all vehicles on our roads will have ESC until after 2030; however, most vehicles will probably possess this technology soon after 2020.

Parental Control: Parental control aims at increasing the safety of teenage drivers. This feature is designed to reduce the risk and severity of crashes by using a series of different technologies that control teenage driving behavior.

The first parental control system introduced by Ford, MyKey (Ford, 2015), includes features such as speed control, which allows the owner to set a limit of 80 mph; volume control that allows the owner to adjust the volume of the radio remotely; a belt reminder system that can mute vehicle's radio and chime for few seconds; a fuel reminder that is issued earlier than usual; and a speed reminder set at 45, 55, or 65 mph. Chevrolet's newest model Malibu, on sale toward the end of 2015, will provide the "Teen Driver" system. This tool can "help encourage safe driving habits" (General Motors, 2015) by providing a series of features such as stability control, front and rear park assist, side blind zone assist, rear cross traffic alert, forward collision alert, daytime running lamps, forward collision braking, traffic control, and front pedestrian braking. Given the early life of this tool, at the moment there are no available data or analyses to quantify the benefits of this measure. However, presuming that this feature will be widely developed by other competitors, parental control could become an affordable standard option.

Level 2 Technologies

Compared to the L0 and L1 systems, L2 and L3 systems place greater control and decision-making on the vehicle's automated components. This section describes major Level 2 technologies.

Traffic Jam Assist: Traffic jam assist (TJA) functions on limited access highways at slow speeds (Marinik et al., 2014). This system provides full control of driving in congested conditions. Under these two conditions, primary lateral and longitudinal controls are ceded by the driver. The driver will have direct supervision of the vehicle during this process, will receive continuous system feedback, and is still responsible for the overall operation of the vehicle. The Mercedes S-Class features a representative TJA system. The driver is expected to be engaged in driving with TJA, with hands on the steering wheel. If the system detects that the driver is not touching the steering wheel, a warning will be issued and the TJA function will be disabled after a few seconds. The European HAVEit project (Highly Automated Vehicles for Intelligent Transport)—designed to “develop technical systems and solutions that improve automotive safety and efficiency” (Strauss, 2010) — demonstrated this concept on heavy trucks.

High Speed Automation: General Motors has described a “super cruise” system, one providing full-speed range ACC in conjunction with lane-keeping. Cameras and radars are used for sensing, and the system can automatically steer, accelerate, and brake in highway driving. Drivers may leave hands off the steering wheel until either the driver wants to change lanes, the system can no longer handle deteriorating road conditions, or an unexpected issue occurs. Other car manufacturers are developing similar products include Honda (Europe), Infiniti, Audi, and BMW. Infiniti's system automatically reduces the discrepancies between the intended and actual path, and claims to reduce driver fatigue by reducing fine-grained steering adjustments. BMW's system not only provides lateral and longitudinal control, but also responds to merging traffic and can perform a lane change when safe. Google developed AVs (i.e., Google driverless cars) that can operate up to 75 mph on highways. It can combine ACC and lane-keeping, does not change lanes automatically.

Automated Assistance in Roadwork and Congestion: One system demonstrated in Europe's HAVEit project was automated assistance in roadwork and congestion. This system aims to enable automated driving through a work zone, so as to support the driver in overload situations like driving in narrow lanes (Strauss, 2010). It considers the possibility that lane lines are not accurate, and it uses other objects for guidance, such as trucks, beacons, and guide walls.

Level 3 Technologies

In Level 3, direct supervision by drivers is not needed in conventional situations. When the driver is required to resume control, these technologies allow sufficient transition time. This section outlines some specific Level 3 technologies.

Automated Operation for Military Applications: The U.S. Army sponsored development of the Autonomous Mobility Applique System, a program designed to retrofit existing military trucks with a range of systems, from active safety to full Level 3 automation. The purpose of this project is to allow military vehicles to operate on any road types and off-road, with or without a driver in full control.

Level 4 and 5 Technologies

Kill Switch: A dead man's switch, or kill switch, is a safety-oriented feature that is installed to give the driver the ability to cease operation of the vehicle in the case of an emergency or driver incapacitation. The dead man's switch has been most commonly used in the railway industry in the form of a lever or pedal that must be manually engaged for the machine to remain active. If disengaged, the machine then would alarm the driver, slow to a stop, and shut down. Conceptually, this type of switch is ideal for a train on tracks, but the use of such switch in a vehicle on a roadway with other vehicles is far more complicated.

Automated Valet Parking: Auto-valet refers to technology designed to assist with or fully perform the act of parking. Luxury vehicles have added parking assistance options that allow the user to find a parking space

and simply control the gas and brake pedals while the vehicle independently maneuvers the steering wheel until it is parked.

In 2013, Ford unveiled its “Fully Assisted Parking Aid” feature. This feature allows the driver to find a parking spot and get out of the vehicle, leaving it to park itself. The advantage of getting out of the vehicle prior to parking is that the vehicle will now be able to fit in much tighter spaces, allowing parking lots to make more efficient use of space. It also allows for safer parking (McGlaun, 2013). There was speculation that this feature would be released on some 2015 Ford models but this has not yet happened.

A more sophisticated version of the valet feature is the “Remote Valet Parking Assistant” by BMW, which should be available within the next few years. This feature only requires the driver to drive into the parking lot/structure and get out. The driver will then tell the vehicle to go park itself through an application on a smart device. The driver will receive notification on the device when the vehicle has parked itself. When the driver is ready to leave, he or she will tell the car to come to parking lot exit via the smart device. An added benefit of this technology, over Ford’s technology, is that it will save drivers’ time. BMW has stated that its technology “does not require expensive changes to the infrastructure of existing parking garages” (Kable, 2014).

An initial screening of existing technologies was refined based on their significance through internal team discussions. A total of 20 smart driving technologies were identified. In Table 2.2, these 20 technologies are presented along with their technological maturity, safety potential, and potential need for regional transportation stakeholder involvement.

Table 2.2 List of CAV technologies: Benefits and Maturity

Level 0 Automation				
Technology	Maturity Time Frame	Major Safety Benefits	Safety Benefit Significance	Maturity
Forward collision warning	Short	Prevent rear-end collision	High	High
Blind spot monitoring	Short	Reduce crash risk at merging and weaving areas	High	High
Lane departure warning	Short	Prevent lane departure crashes	High	Medium
Traffic sign recognition	Short	Assist driving	Intermediate	Medium
Left-turn assist	Short	Prevent potential conflict	High	Medium
Pedestrian collision warning	Short	Prevent pedestrian collision	High	Medium
Rear cross traffic alert	Short	Prevent backing collision	High	Medium
Adaptive headlights	Short	Improve light condition and visibility of environment	Intermediate	High
Level 1 Automation				
Adaptive cruise control	Short	Prevent rear-end collision	High	High
Cooperative adaptive cruise control	Short	Prevent rear-end collision	Low	Medium
Automatic emergency braking	Short	Prevent rear-end collision	High	Medium
Lane keeping	Short	Prevent lane departure crashes	High	Medium
Electronic stability control	Short	Prevent rollover	High	High
Parental control	Short	Prevent speeding	Intermediate	Medium
Level 2 Automation				

Traffic jam assist	Medium	Driving assist	Low	Medium
High speed automation	Medium	Driving assist	High	Medium
Automated assistance in roadwork and congestion	Medium	Driving assist	High	Medium
Level 3 Automation				
On-highway platooning	Long	Driving assist, prevent rear-end crashes	Intermediate	Medium
Automated operation for military applications	Long	Prevent human fatalities	Unknown	Low
Level 4/5 Automation				
Self-driving vehicle	Long	Replace human drivers	High	Low
Emergency stopping assistant	Long	Response when human drivers lose control	High	Low

2.4 Potential Impacts

Benefits and Risks to Drivers

Smart driving technologies can change the driving paradigm in the long run. With the L3 and L4 technologies, the vehicles themselves will play the major role in fulfilling all tasks for driving, and human drivers will cede authority of control over the vehicles. Compared to human drivers, L1 – L4 driving technologies can address human errors caused by limited vision, fatigue, and over- under-reaction. The benefits from these technologies fall into three major categories:

- 1) **Situational awareness:** Smart driving vehicles are able to see all around simultaneously and may have the ability to communicate quickly with other smart vehicles and devices on the road or roadside.
- 2) **Shorter reaction times:** Smart driving vehicles have much shorter reaction times compared to human drivers and can correspondingly relax headway requirements. In general, smart driving vehicles' reaction times and computer precision may also permit reduced safety margins, in the forms of narrowed lanes and higher speed limits in work and school zones.
- 3) **Fatigue and distraction-free driving:** Smart driving vehicles eliminate fatigue, distraction, and drinking as possible crash causes.

While smart driving technologies offer the above benefits to drivers and may in turn bring fundamental changes to the safety, mobility, and environment of transportation systems. Some risks are also envisioned with the new system:

- **Cyber-security:** Smart driving vehicles are subject to cyber-physical threats, due to the heavy usage of wireless communication, navigation, and computing components.
- **Reliability:** In extreme conditions, such as bad weather, the sensing capability of L1 to L4 cars can become worse, the same as a human driver. Also, automotive software systems may have bugs and cannot respond to certain special situations. These factors altogether can undermine the system reliability.
- **Complications of human-machine interactions:** In Level 2 and 3 automations, the shared authority between human drivers and automation components can pose challenges in complicated driving scenarios, when the ability to switch between the two is a necessity. Seamlessly transitioning the authority between automated components and human drivers in response to developing situations will require a comprehensive and intuitive interface.
- **Liability:** When human drivers and automation components have shared authority over driving, the liability issue requires more careful legislative considerations.

Impacts on Safety

Ninety percent of crashes are due to human factors (according to who?). Smart driving technologies can offset many human errors that lead to crashes (as shown in Table 2.2). It is worth mentioning that risk compensation is often an issue to consider when systems are improved (e.g., soon after cruise control was introduced, the crash rate increased as that convenience allows drivers to pay less attention to the road). Safety from vehicle automation and V2V communications may affect a number of behaviors, including the mode and route decisions for vehicle occupants and more vulnerable users. For example, greater safety may encourage bicyclists and pedestrians to take riskier (but faster) routes through or along major arterials and intersections. Trust in automation may similarly encourage drivers to pay less attention to the road. Increased risk may offset the benefits of automation on the safety of the traffic network. To better appreciate such impacts, trip, mode, and route choice models should be modified to include the effects on safety behaviors, including risk compensation.

Impacts on Infrastructure

The transportation system consists of road infrastructure (pavement, traffic signs, marking) and cyber infrastructure (detectors, signal controllers, communication systems). Smart driving technologies will influence both aspects.

Road Infrastructure: Smart driving technologies will influence transportation infrastructure in terms of design and operations. The current infrastructure is designed primarily for human drivers. Due to the safety benefits, dramatic crash reductions may precipitate a significant reduction in, or elimination of, infrastructure and activity that currently supports, or is a result of, vehicle collision events. This includes a wide range of current economic domains, such as emergency responders (police, EMTs, firefighters, medical helicopters), hospital and emergency room capacity, overall healthcare costs, insurance costs, a lower demand for new cars, and fewer collision repair services. On the other hand, since smart driving vehicles rely on sensors (e.g., cameras) to recognize the surrounding environment, the requirements for lane markings, traffic signs, and roadside devices will have to increase to ensure safety for road users.

Cyber Infrastructure: Smart driving technologies allow collection of more real-time data through vehicular onboard sensors, and from these data, traffic and road conditions can be inferred. This can change current schemes of detector-based data collection and management.

Impacts on Operations

With the increasing prevalence of smart driving technologies, a series of operational strategies can be improved or developed, which includes the following:

- **Intersection Signal Control:** With full automation and V2V communication, it is possible to change the paradigm of current signal control, which is queue-based. Instead, the intersection's signal equipment can respond to upcoming flow on a vehicle basis. Simulation studies show that up to a 90% improvement in throughput can be attained.
- **Freeway Metering:** The primary purpose of freeway metering is to prevent traffic congestion on freeways by maintaining smoother and safer merging patterns. With V2V communication and blind spot monitoring features, the merging is anticipated to be accomplished via cooperation between the individual vehicles' systems.
- **Managed Lanes:** Managed lanes can be used to incentivize the use of smart driving technologies, and create the environment for platooning vehicles, which are equipped with the CACC. This will improve travel time and travel time reliability for corresponding travelers.
- **Traveler Information:** Smart driving vehicles with connectivity (Dedicated Short Range Communications or cellular) will be able to receive navigation, signal, and traffic information more effectively, which will reduce the needs of roadside message signs. Also, through disseminating information strategically, it is possible to use the road resources more effectively, respond faster to demand variations, and thus mitigate congestion.

- **Road Weather Management:** Smart driving vehicles can sense weather changes and send such information to traffic management centers (TMC) via roadside devices. This allows more accurate and reliable sensing of weather information and identification of weather-sensitive hotspots.
- **Tolling:** With the DSRC module, tolling will become easier to implement, reducing dependency on RFID (radio-frequency identification) devices, camera/image processing, or manual operations at tolling stations.
- **Work Zone Management:** Smart driving vehicles will allow construction zone information to be more effectively disseminated upstream of the work zone and allow vehicles to pass through obstructions safely and efficiently.
- **CV-enabled Traffic Management:** CV-enabled traffic management is the result of the evolution of regular TMCs that have undergone changes allowed by the availability of “big data”. In the future, TMCs will increase their ability to be proactive, responsive, and adaptable. This will be necessary as they aim to support increasingly dynamic transportation networks.
- **Shared Vehicle Mobility:** Level 4 AVs can enable shared mobility, which will alter the vehicle ownership model and change the fleet composition in the long run. This can save parking space in urban areas and reduce the cost of traveling.
- **Auto-valet Parking:** This feature allows a driver to tell the vehicle to go park itself through an application on a smart device. The driver will receive notification when the vehicle has parked itself. This feature will save drivers time as the vehicle finds parking on its own. With reduced cruise time searching for a parking space, since the vehicle and park a bit further away from the major congestion, emissions will be reduced.

2.5 Conclusion

This chapter provided an overview of smart driving technologies, along with a brief qualitative discussion regarding their potential impacts on drivers, safety, infrastructure, and operations. The NHTSA’s taxonomy provides a clear framework to categorize the existing and emerging smart driving technologies. At the time of writing, Level 0 through Level 2 technologies are prevalent, which attracted the most attentions from car manufactures, policymakers, and researchers. Some of these technologies, e.g. adaptive cruise control, have already been deployed on many passenger cars in the real world. Meanwhile, Level 4 and 5 technologies have also showed great potential in different application scenarios. In terms of impacts, we have envisioned both positive and negative ones. While common wisdom has perceived the great benefits of smart driving, we would like to caution the potential risks in cyber-security, technology reliability, human-machine interactions, and liability. With respect to system management, smart driving can bring fundamental changes to a number of operations strategies and stimulate share mobility services.

CHAPTER 3 CONCEPT OF OPERATIONS (CONOPS)

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3.1 Background

The United States Department of Transportation (USDOT) has committed to the development of a fully connected transportation system that will enable advanced vehicle safety applications. The program began in 2006 as the Vehicle Infrastructure Integration (VII) program and is currently known as the Connected Vehicle (CV) program. This program has focused on a number of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) applications, such as forward collision warning (FCW), emergency electronic brake lights (EEBL), intersection violation warning, signal phase and timing (SPAT), signal prioritization and pre-emption, blind spot detection/warning, and others.

Increasing connectivity among vehicles, roadside devices, and traffic management systems creates the potential for both novel benefits to society as well as novel risks, particularly from the emerging cyber security risk to vehicles that are increasingly computerized and connected. The vulnerability of individual vehicles for targeted disruption has increased as their control systems, and even their entertainment systems, have shifted towards computer control, and greater connectivity. The evolution of Advanced Driver Assistance Systems (ADAS) towards semi- or fully automated vehicles also exacerbates this risk as the software may naively react to an Over-the-Air (OTA) message that is incorrect, whether benign or malicious.

Purpose of the Concept of Operations

A Concept of Operations (ConOps) describes the goals and objectives of a system and identifies user needs and high-level design criteria. Goals and objectives of the ConOps outlined in the document are intended to be high-level and may not necessarily be quantifiable or testable. Specifically, the ConOps document:

- Lays a foundation for the design, test, deployment, and implementation of smart transport technologies, such as CAVs.
- Provides a resource for the development of engineering requirements and supports decision makers in their assessments, deployment, and evaluations of the smart transport systems under a variety of scenarios and settings.

Intended Audience

A ConOps helps stakeholders focus on the proposed system's capabilities and understand the effects on other internal and external systems and practices. Stakeholders of this ConOps document include regional transportation agencies, researchers, local and state governments, law enforcement, private-sector agencies, system engineers and architects, system implementers, equipment manufacturers, and application developers. The ConOps also helps system engineers and architects to understand the constraints, assumptions, requirements, and priorities set forth to design and deploy smart transport systems.

Content and Organization of this Document

The ConOps is an early and critical step in the systems engineering process, and the purpose is to provide a description of why a system is needed and how it would be used considering the viewpoints of the various stakeholders. The ConOps:

- Describes the environment and use of the system in a non-technical and easy-to-understand manner.
- Presents the information from multiple viewpoints.
- Bridges the gap between the problem and stakeholders' needs.

Overall, the ConOps describes the basic who, what, why, where, when, and how a smart transport is designed and deployed.

- Who – the stakeholders are, what their responsibilities are, how they will use the system.
- What – the existing components or systems to be examine and /or integrated together.
- Why – the problems or issues the system will solve.
- Where – the geographic limits of the system.
- How – the resources needed to plan, design, deploy, and operate the system.

3.2 User-Oriented Operational Description

This section describes who-does-what once smart transport technologies are in practical use, steps best taken by various stakeholders, and their responsibilities. Activities within individual steps may differ between cities and states, as well as type of facility (e.g., tollway versus interstate).

CV Applications

Over the last five years, application prototyping and assessment has been a focus of federal connected vehicle research and development activity. As a result of these efforts, more than three dozen connected vehicle application concepts have been developed, many through prototyping and demonstration. As a part of this process, the USDOT CV program has categorized the applications into three main categories: safety, mobility, and environment. Although this is not meant to be an extensive list of CV applications, they form a target set of applications that may be available on deployed DSRC devices. Figure 3.1 shows these applications as they have been defined by the USDOT.

<p>V2I Safety</p> <ul style="list-style-type: none"> Red Light Violation Warning Curve Speed Warning Stop Sign Gap Assist Spot Weather Impact Warning Reduced Speed/Work Zone Warning Pedestrian in Signalized Crosswalk Warning (Transit) 	<p>Environment</p> <ul style="list-style-type: none"> Eco-Approach and Departure at Signalized Intersections Eco-Traffic Signal Timing Eco-Traffic Signal Priority Connected Eco-Driving Wireless Inductive/Resonance Charging Eco-Lanes Management Eco-Speed Harmonization Eco-Cooperative Adaptive Cruise Control Eco-Traveler Information Eco-Ramp Metering Low Emissions Zone Management AFV Charging / Fueling Information Eco-Smart Parking Dynamic Eco-Routing (light vehicle, transit, freight) Eco-ICM Decision Support System 	<p>Mobility</p> <ul style="list-style-type: none"> Advanced Traveler Information System Intelligent Traffic Signal System (I-SIG) Signal Priority (transit, freight) Mobile Accessible Pedestrian Signal System (PED-SIG) Emergency Vehicle Preemption (PREEMPT) Dynamic Speed Harmonization (SPD-HARM) Queue Warning (Q-WARN) Cooperative Adaptive Cruise Control (CACC) Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG) Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE) Emergency Communications and Evacuation (EVAC) Connection Protection (T-CONNECT) Dynamic Transit Operations (T-DISP) Dynamic Ridesharing (D-RIDE) Freight-Specific Dynamic Travel Planning and Performance Drayage Optimization
<p>V2V Safety</p> <ul style="list-style-type: none"> Emergency Electronic Brake Lights (EEBL) Forward Collision Warning (FCW) Intersection Movement Assist (IMA) Left Turn Assist (LTA) Blind Spot/Lane Change Warning (BSW/LCW) Do Not Pass Warning (DNPW) Vehicle Turning Right in Front of Bus Warning (Transit) 	<p>Road Weather</p> <ul style="list-style-type: none"> Motorist Advisories and Warnings (MAW) Enhanced MDSS Vehicle Data Translator (VDT) Weather Response Traffic Information (WxTINFO) 	<p>Smart Roadside</p> <ul style="list-style-type: none"> Wireless Inspection Smart Truck Parking
<p>Agency Data</p> <ul style="list-style-type: none"> Probe-based Pavement Maintenance Probe-enabled Traffic Monitoring Vehicle Classification-based Traffic Studies CV-enabled Turning Movement & Intersection Analysis CV-enabled Origin-Destination Studies Work Zone Traveler Information 		

Figure 3.1 Applications Defined by the USDOT

Source: http://www.its.dot.gov/pilots/cv_pilot_apps.htm

Current CAV Technology

The USDOT CV program consists of both hardware and software applications and tools. The hardware is focused on the DSRC technology, although other communication technologies are under study, and these devices are installed either as statically mounted infrastructure devices, or as mobile devices installed in vehicles. CV application development has primarily been focused in one of three domains: safety, mobility, and environment. Development tools include the Systems Engineering Tool for Intelligent Transportation (SET-IT) tool for application development within the CVRIA , and the Cost Overview for Planning Ideas and Logical Organization Tool (CO-PILOT) for estimating CV pilot deployment costs . These technologies and software applications are shown in Figure 3.2.

The vehicle OBE provides the vehicle-based processing, storage, and communications functions necessary to support CV operations. The radio(s) supporting V2V and V2I communications are a key component of the vehicle OBE. This communication platform is augmented with processing and data storage capability that supports the CV applications. See Figure 3.3.



Figure 3.2 RSU DSRC Roadside Devices Manufactured by Savari and Cohda Wireless

Sources: <http://www.savari.net/technology/>; <http://cohdawireless.com/Products/Hardware.aspx>



Figure 3.3 OBE DSRC Vehicle Devices Manufactured by Savari and Cohda Wireless

Sources: <http://www.savari.net/technology/>; <http://cohdawireless.com/Products/Hardware.aspx>

3.3 System Overview

Scope and Applicable Physical Environment

The scope of a smart transport system encompasses the hardware, software, applications, and use-case scenarios for utilizing CAV technologies in combination with an integrated traffic management system. The physical environment for which this is applicable is any vehicle or roadway that will be outfitted with smart transport hardware and will be executing or benefitting from smart transport software and applications.

System Goals and Objectives

The goals of implementing a smart transport system on roadways are to enhance the safety and mobility of all users and promote environmental benefits from a more efficient system. These goals are supported by a number of specific objectives:

- Utilize reliable CAV hardware and software in both vehicle and roadside installations
- Integrate data from CAVs into local transportation agency's traffic management system
- Ensure secure communication and data storage

System Capabilities

The system should fulfill the needs of the stakeholders to provide secure and timely data regarding the state of a traffic system, including its vehicles, roadside devices, and traffic management systems. The system should also be highly reliable and secure.

System Architecture: Physical Components and Interfaces

The CVRIA would likely be used to construct a set of system architecture viewpoints that describe the functions, physical and logical interfaces, enterprise relationships, and communication protocol dependencies necessary to deploy applications within a CV environment. The CVRIA supports policy considerations for certification, standards, core system implementation, and other elements of the CV environment. Across the CVRIA, language and components have been standardized so that disparate implementations across the nation can take place and ensure communication and data consistency.

The USDOT in partnership with Iteris has developed a software tool to represent the relationships among the CVRIA components, called the Systems Engineering Tool for Intelligent Transportation (SET-IT). .6 shows an example diagrammatic output of the SET-IT tool and shows a Physical Layer 0 architecture. It illustrates high-level communication links between various physical objects within an EVA application. In the diagram, communication links are shown as Peer-to-Peer. These links are shown in black and red colors. Red lines indicate trusted and confidential communication, while black lines indicate trusted, non-confidential communication. In a test environment such a distinction is not critical. However, it has been left in place to allow testing applications that require trusted or confidential communication. Local traveler information includes messages from nearby ITS equipment (e.g., DMS) or from a traffic management center to the RSU so that it can transmit messages to vehicle OBEs, such messages may include small area-wide alerts. Driver information may include travel advisories, vehicle signage data, fixed sign information, detour information, etc.

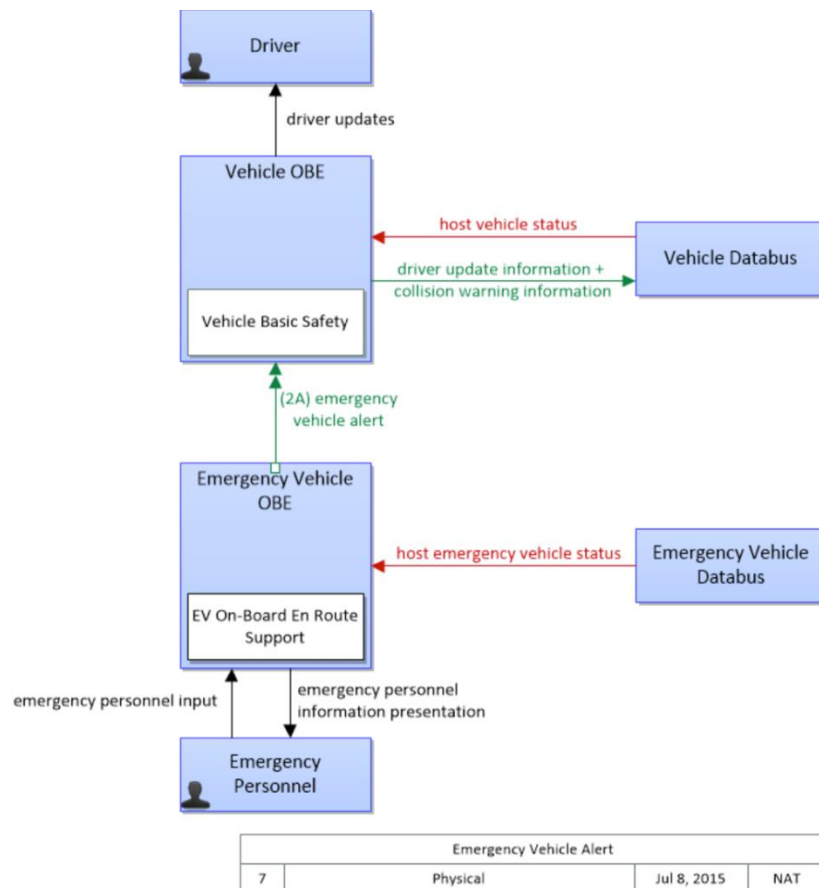


Figure 3.4 SET-IT Physical Diagram for EVA

Source: <http://www.iteris.com/cvria/html/applications/app29.html#tab-3>

3.4 Operational and Support Environment

Operation and support of a smart transport system contains a number of critical components:

- Smart Vehicles: Partially/fully automated &/or connected
- Smart Infrastructure: Wide geographic distribution, reliable up-time, & data “portals” for traffic managers
- Smart Management: Highly integrated regional transportation agency traffic management center, tollway authorities, and law enforcement

These components cross previously separate stakeholder boundaries and involve both public and private organizations and interests. The operational and support environments for an OBE will be vastly different for those of an RSU, etc.

3.5 Operational Scenarios

The operational scenarios described below show how various users of a smart transport system might experience CAV technologies, such as emergency vehicle alerts, wrong-way driver notifications, and road maintenance data over wide geographic areas. The concept of a smart transport system is a very broad topic and covers many use cases, applications, and entities. The scenarios below are just a sampling of use cases that were included in the scope of this phase of work.

Emergency Vehicle Alert (EVA)

Emergency vehicles, within the context of the current Connected Vehicle environment, include police vehicles, ambulances, fire trucks, first responders, as well as maintenance and utility vehicles in certain situations, such as snow plows, road striping vehicles, and tow trucks. A loose definition of ‘emergency vehicles’ in this context is any vehicle that is expected to, and legally, conducts unusual behavior on a typical roadway. Unusual behavior may be any non-standard traffic maneuver, such as traveling at higher or lower speed than expected for the roadway, traveling in a different direction than defined traffic flow—either by crossing a roadway or driving upstream against traffic, or any other action that would benefit the safety and efficiency of themselves and nearby vehicles by providing information on the nature of their movement or intentions.

Emergency vehicles, like ambulances, police cars, fire trucks, and construction vehicles, broadcast out an EVA when they are activated, which can be received by nearby CVs. A driver, or an automated vehicle, that receives this alert could then make informed decisions about how to react, such as slowing down or pulling over. An implementation might look like what is shown in Figure 3.5, where a CV receives an EVA from an ambulance that is approaching from behind and is currently a certain distance away. As the vehicle gets closer, the decision could be made to pull over to allow the ambulance to pass.



Figure 3.5 EVA Scenario

Electronic Emergency Brake Lights (EEBL)

The EEBL application is intended to warn a driver of a significant deceleration event that is occurring in the forward path of the vehicle (Figure 3.6). The remote vehicle monitors its speed and acceleration, and upon reaching a defined threshold deceleration, it sets an event flag in the BSM. This flag is broadcasted, alerting nearby vehicles of the sudden deceleration. As nearby vehicles receive the message(s) with the event flag, they evaluate the relevance of the event relative to their trajectory or planned path. If determined relevant, an alert can be provided to the driver, or in automated vehicles, the throttle can be automatically reduced and the brakes applied as necessary. In extreme situations, steering maneuvers could also be automated if braking would not be sufficient to prevent a collision. Relevance is calculated based on the relative speed of the vehicles and subsequent time-to-collision.

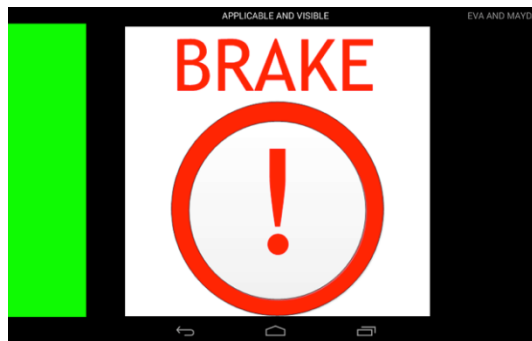


Figure 3.6 Potential In-vehicle Display of EEBL Message

Static Wrong-way Driving Detection

A static wrong-way driver detection application is a process that runs on an infrastructure system, presumably on an RSU at the roadside. The process utilizes an operator-defined map of an area that is to be monitored. The map may be in various forms, but two common examples include a geo-bounded region with a defined direction and a list of points that define one or more lane segments with an implied direction. The process receives BSMs from passing vehicles and each are checked against the available map to determine if they are traveling in the allowed/defined direction within an allowable heading tolerance. When a vehicle is detected driving the wrong way, the process can provide an alert out to the vehicle driving the wrong way, to other nearby vehicles to alert them, and to traffic management center operators and law enforcement personnel. An example illustration of potential in-vehicle alerts is shown in Figure 3.7.



Figure 3.7 CV WWD Messages Sent by RSU

Intelligent Message Propagation (IMP)

This CV application would enable vehicles or infrastructure devices (RSUs) to pass along (propagate) messages they have received, which would be very useful, for example, in a scenario where RSU coverage is sparse or otherwise unavailable and would enable CVs to continue to be informed of important events without RSU coverage. V2V message propagation is also viable for this application. This application would be applicable over large geographic areas with many vehicles, enabling a message to rapidly move from vehicle-to-vehicle. The final use of the message would depend on the message content, and could be consumed by individual vehicles, for example in the case of a weather-related warning, or could be consumed by an RSU, for example in the case of a stranded motorist. In Figure 3.8, a simulated CV traffic system is shown with the effective DSRC range of vehicles shown in red and that of RSUs shown in green. This illustrates how a smart transport system could be enabled without a 100% coverage of RSUs, as long as there is sufficient market penetration of CVs.



Figure 3.8 Simulated CVs along I-410 in San Antonio Showing Potential for Message Propagation Between RSUs

Road Condition Monitoring (RCM)

According to current estimates, potholes cause approximately \$6.4 billion in damage annually, making timely detection and repair of degraded roadways a significant concern for citizens and governments alike. Current methods for detection of poor road conditions consist of manual surveying, which is limited by the available resources of a traffic management entity. While the prevalence of smartphones has increased the ability for individuals to report road condition issues, the use of CV communication protocols presents a unique

opportunity to enable vehicles to identify regions of pavement that require immediate maintenance, and to observe trends in pavement conditions over time. The necessary technologies to accomplish this, such as accelerometers, GPS-based localization systems, and CV DSRC, are becoming more widely available, enabling new applications to be developed to enhance the collective situational awareness of the vehicles themselves, and of the traffic system as a whole.

One method for determining the condition of a roadway is by utilizing the incoming accelerometer and GPS data to quantify road condition based on its roughness, which can be scaled across various spatial windows that reflect different aspects of road health. For example, a smaller spatial window will detect shorter term anomalies in road condition, such as might be caused by a pothole or piece of debris in the road, while a larger window will detect more general roughness on a segment of road, which may indicate road surface deterioration. Data that has been received by another vehicle or an RSU can be utilized to illustrate the road conditions across a broad geographic area, which can then be displayed graphically as shown in Figure 3.9.

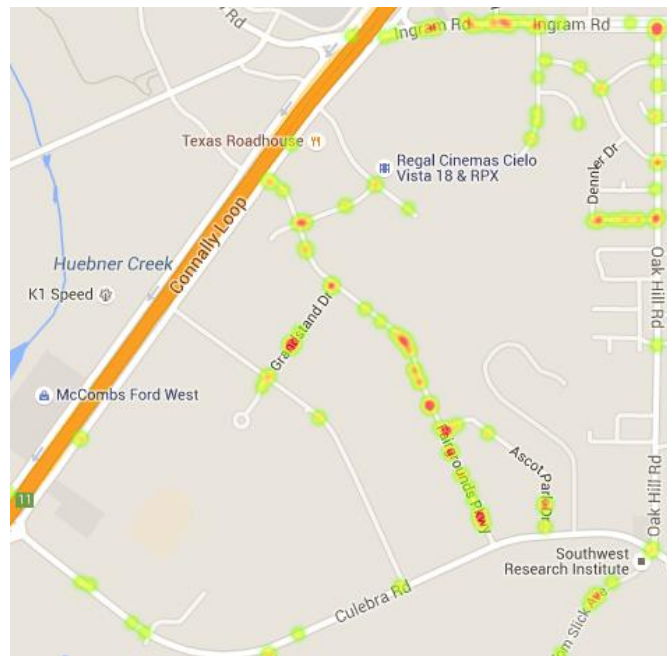


Figure 3.9 Incident Data Sent to TxDOT

This data could be used by nearby vehicles to avoid routes with heavy damage and could be used by local transportation stakeholders to gain a clear picture of immediate maintenance needs, as well as help to inform longer-term maintenance planning.

Dynamic Wrong-way Driving and Road Hazard Detection

In contrast to the static wrong way driving detection process, a dynamic detection process does not require a predefined map to be input by an operator. Instead, the process is configured to listen to BSMs from vehicles within range and aggregate them into an understood map of the nominal driving patterns in the area. As more and more BSMs are received, it enforces the learned map and establishes a baseline that is used similar to an operator-defined static map or region of interest. BSMs are monitored against the map the same way as in a static wrong way driving detection process and wrong way driver alerts are generated in the same way. Because of the nature of the map generation, the process can quickly be applied to new areas and is only restricted by the RF coverage area of the RSU.

Additionally, subtler deviations from the nominal patterns can be detected and used to identify localized road hazards, such as debris on the road and potholes. Multiple sequences of BSMs that similarly deviate laterally from the learned lanes can provide useful information to roadway operators, with much less delay than waiting for users to report issues or for traditional sensors or detection methods. See Figure 3.10.

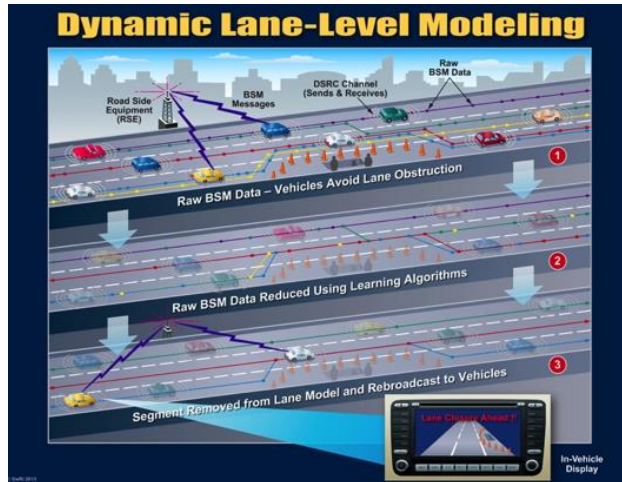


Figure 3.10 Smart Transport System Lane Learning

3.6 Summary

This chapter has explored a concept of operations (ConOps) that describes the goals and objectives of a system. These directly feed into design practices to meet user needs. ConOps are foundational for the design, test, deployment, and implementation of smart transport technologies, like CAVs, and serve as a resource for the development of engineering requirements and decision-making processes that facilitate deployment and evaluation of smart transport systems.

CHAPTER 4 ESTIMATING THE SAFETY BENEFITS OF CAV TECHNOLOGIES

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4.1 Introduction

In this section, Najm's (2007) latest pre-crash typology is presented first to help map the vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and AV safety applications to specific crash types. In this way, safety benefits for each application can be estimated, using economic costs and functional-years lost per typical crash of each variety. The final part of this section introduces three technology-effectiveness scenarios to reflect uncertainty in how many crashes will benefit from such technologies and hopefully cover the range of the total economic benefits and quality-life-years to be saved by the various CV and AV applications.

Typology of Pre-Crash Situations

To appreciate the safety effects of having CAVs in the US, each crash's pre-crash scenario typology was used here to estimate the economic cost savings and quality-life-years saved (Najm 2010 and Jermakian 2011). The pre-crash scenarios (or crash types, effectively) are based on the National Highway Traffic Safety Administration's extensive General Estimates System (GES) year-2004 crash database (Najm 2010). Here, the same pre-crash typology is used, but results are based on the nation's 2013 GES crash database. More details on the differences in these data sets can be found in Li and Kockelman (2016).

In this study, only light-duty vehicle crashes (i.e., those involving passenger cars, sports utility vehicles, vans, minivans, and pickup trucks) are investigated. The GES variables of Body Type and Special Use were queried to identify all light-duty vehicles. Body Type was set to include types 01–22, 28–41, and 45–49. Special Use was set equal to 0. Furthermore, in order to eliminate double counting of crashes in each scenario, pre-crash scenarios were updated by removing all scenarios in the number order via a process of elimination; in this way, the resulting frequency distribution sums to 100%. For example, one crash record can be assigned to pre-crash scenarios 1, 5, and 10, but this crash record will only belong to pre-crash scenario 1 because of its number order.

The 37 scenario identification codes can be used to select records from the GES database, and all pre-crash scenarios can be categorized into crash types, a more general term to segment or distinguish crashes. Table 4.1 illustrates each pre-crash scenario and the crash types to which they belong.

Table 4.1 Mapping of Crash Types to New Pre-Crash Scenario Typology (Naim et al 2007)

No.	Pre-Crash Scenario	Crash Type
1	Vehicle failure	Run-off-road
2	Control loss with prior vehicle action	
3	Control loss without prior vehicle action	
4	Running red light	Crossing paths
5	Running stop sign	
6	Road edge departure with prior vehicle maneuver	Run-off-road
7	Road edge departure without prior vehicle maneuver	
8	Road edge departure while backing up	
9	Animal crash with prior vehicle maneuver	Animal
10	Animal crash without prior vehicle maneuver	
11	Pedestrian crash with prior vehicle maneuver	Pedestrian
12	Pedestrian crash without prior vehicle maneuver	
13	Pedalcyclist crash with prior vehicle maneuver	Pedalcyclist
14	Pedalcyclist crash without prior vehicle maneuver	
15	Backing up into another vehicle	Backing
16	Vehicle(s) turning – same direction	Lane change
17	Vehicle(s) changing lanes – same direction	
18	Vehicle(s) drifting – same direction	
19	Vehicle(s) parking – same direction	Parking
20	Vehicle(s) making a maneuver – opposite direction	Opposite direction
21	Vehicle(s) not making a maneuver – opposite direction	
22	Following vehicle making a maneuver	Rear-end
23	Lead vehicle accelerating	
24	Lead vehicle moving at lower constant speed	
25	Lead vehicle decelerating	
26	Lead vehicle stopped	
27	LTAP/OD at signalized junctions	Crossing paths
28	Vehicle turning right at signalized junctions	
29	LTAP/OD at non-signalized junctions	
30	Straight crossing paths at non-signalized junctions	
31	Vehicle(s) turning at non-signalized junctions	
32	Evasive action with prior vehicle maneuver	Run-off-road
33	Evasive action without prior vehicle maneuver	
34	Non-collision incident	Non-collision
35	Object crash with prior vehicle maneuver	Object
36	Object crash without prior vehicle maneuver	
37	Other	Other

4.2 Monetary and Non-Monetary Measure of the Pre-Crash Scenario Loss

Crashes incur both economic and non-economic costs. Economic costs reflect goods and services that must be purchased or lost productivity as a result of motor vehicle collisions (Blincoe 2015). This includes medical, legal and court, emergency services, insurance administration, travel delay, property damage and repairs, workplace losses, and lost productivity (at paid work and at home) costs. Comprehensive costs reflect

additional social losses, including pain and suffering by crash victims and their family members. In 2010, quality-of-life losses from U.S. crashes were estimated to be 71% of all (\$835 billion, comprehensive) U.S. crash costs (Blincoe 2015). Such non-economic losses are substantial and very important to the appropriate evaluation of CAV technologies’ safety benefits and cost-effectiveness calculations.

With Najm’s (2007) identification codes of pre-crash scenarios used in the 2004 GES database, the frequency of each pre-crash scenario and the injury severity rating to a person is derived by using the National Safety Council’s KABCO scale in the 2013 GES crash records. The KABCO scale records injury severity as resulting in a death (K, for killed), an incapacitating injury (A), a non-incapacitating injury (B), a possible injury (C), or no apparent injury/property-damage only (O).

The KABCO ratings were translated into the Maximum Abbreviated Injury Scale (MAIS) to estimate economic costs and functional-years lost. MAIS levels of injury severity (for the crash victim who suffered the greatest injury) have seven categories, ranging from uninjured (MAIS0) to fatal (MAIS6), thus differing somewhat from the KABCO scale, which has six categories from fatal (K) to injury severity unknown (ISU). Here, Blincoe’s (2015) KABCO/MAIS translator, designed on data from the 2000-2008 NASS CDS, was employed, to convert all GES injury severities from KABCO to MAIS. Table 4.2 shows the KABCO/MAIS translator used in this paper.

Table 4.2 KABCO to MAIS Translator (NHTSA 2010)

	MAIS0	MAIS1	MAIS2	MAIS3	MAIS4	MAIS5	MAIS6	
K	0.0032	0.011	0.0019	0.0041	0.0027	0.0007	0.9765	1.00
A	0.0376	0.5782	0.1924	0.1259	0.0444	0.0171	0.0043	1.00
B	0.0906		0.1113	0.0348	0.0085	0.0014	0.0015	1.00
C	0.2188	0.7014	0.0674	0.0101	0.0021	0.0001	0.0001	1.00
O	0.8191	0.1759	0.0047	0.0002	0	0.0001	0	1.00
U	0.2429	0.5961	0.1039	0.0406	0.0047	0.0117	0	1.00

The economic and comprehensive unit costs of police-reported crashes were calculated in U.S. Dollars for the year 2010 for each level of MAIS injury severity. Since this study’s estimates are based on the 2013 GES crash database, a cumulative rate of inflation between 2010 and 2013 was used (6.8% over 3 years). 4.3 shows the unit costs of economic and comprehensive costs of police-reported crashes in 2013, after adjusting for inflation.

Table 4.3 Unit Costs of Policed-Reported Crashes, 2013 Dollars (NHTSA 2015)

Crash Severity	Economic costs: Cost per Crash (2013\$)	Comprehensive Costs per Crash (2013\$)
MAIS0	\$3,043	\$3,043
MAIS1	\$19,057	\$43,925
MAIS2	\$59,643	\$424,376
MAIS3	\$194,662	\$1,056,758
MAIS4	\$422,231	\$2,602,338
MAIS5	\$1,071,166	\$5,970,187
MAIS6	\$1,496,841	\$9,786,218

4.3 Mapping the Advanced Safety Applications to the Specific Pre-Crash Scenarios

The first step of this estimation process involves mapping each advanced safety application to specific, applicable pre-crash scenarios. Najm et al. (2013) recently mapped many safety applications using V2V technology, including Forward Collision Warning (FCW), Intersection Movement Assist (IMA), Blind Spot Warning and Lane Changing Warning (BSW and LCW), Do Not Pass Warning (DNPW) and Control Loss Warning (CLW), to 17 pre-crash scenarios that can be addressed by V2V technology. For example, FCW can reduce the frequency of rear-end crash types, including the pre-crash scenarios of “Following Vehicle Making a Maneuver”, “Lead Vehicle Moving at Lower Constant Speed”, and “Lead Vehicle Decelerating and Lead Vehicle Stopped”, but not “Lead Vehicle Accelerating”.

Intersection Movement Assist (IMA) can be mapped to certain crossing-paths crash types, including the pre-crash scenarios of “Left Turn Across Path of Opposite Direction (LTAP/OD) at Non-Signalized Junctions”, “Straight Crossing Paths at Non-Signalized Junctions”, and “Vehicle(s) Turning at Non-Signalized Junctions”. Cooperative Intersection Collision Avoidance Systems’ (CICAS’) objective is a cooperative intersection collision avoidance system to warn drivers of impending violations at traffic signals and stop signs (Maile and Delgrossi 2009). Compared with IMA, CICAS has a more powerful function, which warns drivers of running a red light or stop sign, or of other red-right or stop-sign runners; CICAS can also coordinate intersection movements, and thus take the place of the IMA, Red Light Violation Warning (RLVW), and Stop Sign Violation Warning (SSVW) systems. Therefore, CICAS addresses the following pre-crash scenarios: “Running Red Light”, “Running Stop Sign”, “LTAP/OD at Signalized Junctions”, “Vehicle Turning Right at Signalized Junctions”, “LTAP/OD at Non-Signalized Junctions”, “Straight Crossing Paths at Non-Signalized Junctions”, and “Vehicle(s) Turning at Non-Signalized Junctions”.

BSW and LCW technologies will benefit the “Vehicle(s) Turning - Same Direction”, “Vehicle(s) Changing Lanes - Same Direction”, and “Vehicle(s) Drifting - Same Direction” pre-crash scenarios. DNPW is expected to improve safety in “Vehicle(s) Making a Maneuver - Opposite Direction” and “Vehicle(s) Not Making a Maneuver - Opposite Direction” pre-crash situations. CLW can help avoid or mitigate the severity of “Vehicle Failure,” “Control Loss with Prior Vehicle Action”, and “Control Loss Without Prior Vehicle Action” pre-crash situations.

Road Departure Crash Warning (RDCW) is a combined application of Lateral Drift Warning (LDW) and Curve Speed Warning (CSW), which can warn drivers of impending road departure (Wilson et al. 2007). The major function of the LDW is to monitor the vehicle’s lane position, lateral speed, and available maneuvering room by using a video camera to estimate the distances between the vehicle and the left and right lane boundaries and is able to alert the driver when it appears the vehicle is likely to depart the lane of the road. The main contribution of CSW is to monitor vehicle speed and upcoming road curvature and be able to alert the driver when the vehicle is approaching the upcoming curve at an unsafe speed. The RDCW application has the potential to improve the traffic safety of the pre-crash scenarios of “Road Edge Departure with Prior Vehicle Maneuver”, “Road Edge Departure Without Prior Vehicle Maneuver”, and “Road Edge Departure While Backing Up”, according to their definitions.

The Vehicle-to-Pedestrian (V2P) communication has the potential to detect pedestrians and pedal cyclists in a possible crash situation with a vehicle and warn the driver (Harding et al. 2014). To be more specific, the

pedestrians can carry a device (such as a mobile phone) that can send out a safety signal using dedicated short-range communications (DSRC) and communicate with in-vehicle DSRC devices, so both the detected object (pedestrian or pedal cyclist) and the driver could be warned if a possible conflict arises. Four pre-crash scenarios, “Pedestrian Crash With Prior Vehicle Maneuver”, “Pedestrian Crash Without Prior Vehicle Maneuver”, “Pedal Cyclist Crash With Prior Vehicle Maneuver”, and “Pedal Cyclist Crash Without Prior Vehicle Maneuver” can be addressed by this safety application.

The safety applications described above emphasize CV technologies, such as V2V, V2I, and V2P. AV technology is rapidly advancing and will also play a key safety role by reducing or even eliminating many human-related factors leading to crashes, and greatly improve warning response times and decisions.

Lane-Keeping Assist (LKA) technology alerts the driver when lane deviations are detected in the vehicle. The system can also work in conjunction with the Radar Cruise Control system to help the driver steer and keep the vehicle on course (Bishop 2005). The LKA technology maps to pre-crash scenarios of “Road Edge Departure with Prior Vehicle Maneuver”, “Road Edge Departure Without Prior Vehicle Maneuver”, and “Road Edge Departure While Backing Up”, which are also addressed by the RDCW. Therefore, a combination of V2I and AV technologies (RDCW and LKA) has been mapped to these pre-crash scenarios.

Automatic Emergency Braking (AEB) can use radar, laser, or video to detect when obstructions or pedestrians are present and be automatically applied to avoid the collision or at least to mitigate the effects in the case that a collision is imminent. According to AEB’s function, almost all pre-crash scenarios can gain benefits from it, except for the Non-Collision Incident.

Not all of Table 4.1’s pre-crash scenarios have been mapped to specific safety applications on the basis of CV and AV technologies. Due to the uncertain characteristics of the pre-crash scenarios of “Non-Collision Incident and Other”, there is no corresponding safety application to address. According to this situation, none of the safety applications mentioned above can avoid the accident or mitigate the accident severity. On the other hand, the “Other” pre-crash scenario may obtain benefit from those safety applications, so the combination impacts of CV and AV based safety applications will be exerted on this scenario.

Table 4.4 lists all the pre-crash scenarios and corresponding safety applications on the basis of CV and AV technologies, with the exception of Non-Collision Incident.

Table 4.4 Mapping Pre-crash Scenarios to CAV Technologies

No.	Pre-Crash Scenario	CV Safety Apps	AV Safety Apps	Fully Automated Vehicle
1	Road Edge Departure with Prior Vehicle Maneuver	Road Departure Warning System	Automatic Emergency Braking + Lane-Keeping Assist	Fully Automated Vehicle
2	Road Edge Departure Without Prior Vehicle Maneuver			
3	Road Edge Departure While Backing Up			
4	Control Loss with Prior Vehicle Action	Control Loss Warning		
5	Control Loss Without Prior Vehicle Action			
6	Pedestrian Crash with Prior Vehicle Maneuver	Vehicle to Pedestrian	Automatic Emergency Braking	Fully Automated Vehicle
7	Pedestrian Crash Without Prior Vehicle Maneuver			
8	Pedalcyclist Crash with Prior Vehicle Maneuver			
9	Pedalcyclist Crash Without Prior Vehicle Maneuver			
10	Vehicle(s) Turning - Same Direction	Blind Spot/Lane Change Warning	Automatic Emergency Braking	Fully Automated Vehicle
11	Vehicle(s) Changing Lanes - Same Direction			
12	Vehicle(s) Drifting - Same Direction			

No.	Pre-Crash Scenario	CV Safety Apps	AV Safety Apps	Fully Automated Vehicle
13	Vehicle(s) Making a Maneuver - Opposite Direction	Do Not Pass Warning	Automatic Emergency Braking	Fully Automated Vehicle
14	Vehicle(s) Not Making a Maneuver - Opposite Direction			
15	Following Vehicle Making a Maneuver	Forward Collision Warning	Automatic Emergency Braking	
16	Lead Vehicle Accelerating			
17	Lead Vehicle Moving at Lower Constant Speed			
18	Lead Vehicle Decelerating			
19	Lead Vehicle Stopped			
20	Running Red Light	Cooperative Intersection Collision Avoidance Systems	Automatic Emergency Braking	
21	Running Stop Sign			
22	LTAP/OD at Signalized Junctions			
23	Vehicle Turning Right at Signalized Junctions			
24	LTAP/OD at Non-Signalized Junctions			
25	Straight Crossing Paths at Non-Signalized Junctions			
26	Vehicle(s) Turning at Non-Signalized Junctions	None	Automatic Emergency Braking	
27	Evasive Action with Prior Vehicle Maneuver			
28	Evasive Action Without Prior Vehicle Maneuver			
29	Animal Crash with Prior Vehicle Maneuver			
30	Animal Crash Without Prior Vehicle Maneuver			
31	Object Crash with Prior Vehicle Maneuver			
32	Object Crash Without Prior Vehicle Maneuver			
33	Vehicle Failure			
34	Backing Up into Another Vehicle			
35	Vehicle(s) Parking - Same Direction			
36	Non-Collision Incident	None		
37	Other	Combined Impacts of Safety Applications	Automatic Emergency Braking	

4.4 Effectiveness Assumptions of Safety Applications

Simply mapping the technology to the target pre-crash scenarios is not enough to estimate the safety benefits. A technology must successfully correspond to pre-crash scenario(s) in order to complete the safety benefits analysis. The best way to understand the actual effectiveness of these technologies is to utilize field tests and collect data from real-life operation.

However, use of technologies mentioned above is still rare at present, and there is a lack of available field test data to conduct related research. Recent Insurance Institute for Highway Safety (IIHS) (2015) findings suggest a 23% crash reduction factor (CRF) for rear-end crashes in cars that have an FCW system enabled. When combined with active AEB, crash counts (of all types) appear to fall by 42% (IIHS 2015). However, few vehicles currently have AEB or FCW at all speed levels; for example, a Volvo S60 passenger car has this apply only at speeds less than 30 mi/hr. In fact, IIHS’ estimates are biased low, because they only apply at about half the speeds, so about half the crash benefits that true AEB (at all speeds) would yield. The CRF for rear-end crashes can be reduced by 84% with the combination of FCW and AEB in the moderate scenario.

The CRFs used in Table 4.5 reflect the Moderate-impact Scenario, assuming 100-percent market penetration of each CV and AV technology listed. CRFs for Conservative and Aggressive scenarios are set to be 75% and 125%, respectively, of the Moderate-impact scenario, but the CRF of every application would be maxed out 1.0. Table 4.5 through 4.7 present the CRF assumptions across the nine settings (three scenarios and three application combinations). The CRFs of safety applications for other severity types are assumed to be 95%, 90%, 85%, and 80% of the reduction rate of fatal crashes, in the order of Incapacitating Injury (A) to Property Damage Only (O). Instead of assuming the same crash reduction rate for each safety application across all severity types, these assumed CRF values are expected to decrease as crash severity decreases, since some of the more severe crashes will be avoided, but not completely averted, and thus shift into the less severe categories. This means that the combined effect of *all* these safety technologies and applications is then applied to all “Other” crash types, with CRFs of 0.1, 0.2, and 0.3 for fatal crash reductions across the three impact scenarios.

Table 4.5 CRF (Cumulative) Assumptions of the Fatal Crashes in Conservative Scenario

No.	Pre-Crash Scenario	CV-Only Safety Applications(CFR)	CV + AV Safety Applications Combined (CFR)	CV + Full Automation Combined (CFR)
1	Road Edge Departure with Prior Vehicle Maneuver	Road Departure Warning System (0.18)	Automatic Emergency Braking + Lane-Keeping Assist (0.36)	Fully Automated Vehicle (0.54)
2	Road Edge Departure Without Prior Vehicle Maneuver			
3	Road Edge Departure While Backing Up			
4	Control Loss with Prior Vehicle Action	Control Loss Warning (0.18)	Automatic Emergency Braking (0.27)	Fully Automated Vehicle (0.45)
5	Control Loss Without Prior Vehicle Action			
6	Pedestrian Crash with Prior Vehicle Maneuver	Vehicle to Pedestrian (Pedestrian) (0.27)	Automatic Emergency Braking (0.45)	Fully Automated Vehicle (0.63)
7	Pedestrian Crash Without Prior Vehicle Maneuver			
8	Pedalcyclist Crash with Prior Vehicle Maneuver	Vehicle to Pedestrian (Pedalcyclist) (0.18)	Automatic Emergency Braking (0.36)	Fully Automated Vehicle (0.54)
9	Pedalcyclist Crash Without Prior Vehicle Maneuver			
10	Vehicle(s) Turning - Same Direction	Blind Spot/Lane Change Warning (0.27)	Automatic Emergency Braking (0.36)	Fully Automated Vehicle (0.63)
11	Vehicle(s) Changing Lanes - Same Direction			
12	Vehicle(s) Drifting - Same Direction			
13	Vehicle(s) Making a Maneuver - Opposite Direction	Do Not Pass Warning	Automatic Emergency Braking	

No.	Pre-Crash Scenario	CV-Only Safety Applications(CFR)	CV + AV Safety Applications Combined (CFR)	CV + Full Automation Combined (CFR)		
14	Vehicle(s) Not Making a Maneuver - Opposite Direction	(0.18)	(0.27)	Fully Automated Vehicle (0.45)		
15	Following Vehicle Making a Maneuver	Forward Collision Warning (0.21)	Automatic Emergency Braking (0.38)	Fully Automated Vehicle (0.54)		
16	Lead Vehicle Accelerating					
17	Lead Vehicle Moving at Lower Constant Speed					
18	Lead Vehicle Decelerating					
19	Lead Vehicle Stopped					
20	Running Red Light	Cooperative Intersection Collision Avoidance Systems (0.36)	Automatic Emergency Braking (0.54)	Fully Automated Vehicle (0.72)		
21	Running Stop Sign					
22	LTAP/OD at Signalized Junctions					
23	Vehicle Turning Right at Signalized Junctions					
24	LTAP/OD at Non-Signalized Junctions					
25	Straight Crossing Paths at Non-Signalized Junctions					
26	Vehicle(s) Turning at Non-Signalized Junctions	None (0)	Automatic Emergency Braking (0.18)	Fully Automated Vehicle (0.36)		
27	Evasive Action with Prior Vehicle Maneuver					
28	Evasive Action Without Prior Vehicle Maneuver					
29	Animal Crash with Prior Vehicle Maneuver					
30	Animal Crash Without Prior Vehicle Maneuver					
31	Object Crash with Prior Vehicle Maneuver					
32	Object Crash Without Prior Vehicle Maneuver					
33	Vehicle Failure				Automatic Emergency Braking (0.09)	Fully Automated Vehicle (0.18)
34	Backing Up into Another Vehicle				Automatic Emergency Braking (0.54)	Fully Automated Vehicle (0.63)
35	Vehicle(s) Parking - Same Direction				Automatic Emergency Braking + Self-Parking System (0.81)	Fully Automated Vehicle (0.81)
36	Non-Collision Incident	None	None			

No.	Pre-Crash Scenario	CV-Only Safety Applications(CFR)	CV + AV Safety Applications Combined (CFR)	CV + Full Automation Combined (CFR)
37	Other	Combined Impacts of Safety Applications (0.09)	Automatic Emergency Braking (0.18)	Fully Automated Vehicle (0.27)

Table 4.6 CRF (Cumulative) Assumptions of the Fatal Crashes in Moderate Scenario

No.	Pre-Crash Scenario	CV-Only Safety Applications(CFR)	CV + AV Safety Applications Combined (CFR)	CV + Full Automation Combined (CFR)
1	Road Edge Departure with Prior Vehicle Maneuver	Road Departure Warning System (0.20)	Automatic Emergency Braking + Lane-Keeping Assist (0.40)	Fully Automated Vehicle (0.60)
2	Road Edge Departure Without Prior Vehicle Maneuver			
3	Road Edge Departure While Backing Up			
4	Control Loss with Prior Vehicle Action	Control Loss Warning (0.20)	Automatic Emergency Braking (0.30)	Fully Automated Vehicle (0.50)
5	Control Loss Without Prior Vehicle Action			
6	Pedestrian Crash with Prior Vehicle Maneuver	Vehicle to Pedestrian (Pedestrian) (0.30)	Automatic Emergency Braking (0.50)	Fully Automated Vehicle (0.70)
7	Pedestrian Crash Without Prior Vehicle Maneuver			
8	Pedalcyclist Crash with Prior Vehicle Maneuver	Vehicle to Pedestrian (Pedalcyclist) (0.20)	Automatic Emergency Braking (0.40)	Fully Automated Vehicle (0.60)
9	Pedalcyclist Crash Without Prior Vehicle Maneuver			
10	Vehicle(s) Turning - Same Direction	Blind Spot/Lane Change Warning (0.30)	Automatic Emergency Braking (0.40)	Fully Automated Vehicle (0.70)
11	Vehicle(s) Changing Lanes - Same Direction			
12	Vehicle(s) Drifting - Same Direction			
13	Vehicle(s) Making a Maneuver - Opposite Direction	Do Not Pass Warning (0.20)	Automatic Emergency Braking (0.30)	Fully Automated Vehicle (0.50)
14	Vehicle(s) Not Making a Maneuver - Opposite Direction			
15	Following Vehicle Making a Maneuver	Forward Collision Warning (0.23)	Automatic Emergency Braking (0.42)	Fully Automated Vehicle (0.60)
16	Lead Vehicle Accelerating			
17	Lead Vehicle Moving at Lower Constant Speed			
18	Lead Vehicle Decelerating			

No.	Pre-Crash Scenario	CV-Only Safety Applications(CFR)	CV + AV Safety Applications Combined (CFR)	CV + Full Automation Combined (CFR)
19	Lead Vehicle Stopped			
20	Running Red Light	Cooperative Intersection Collision Avoidance Systems (0.40)	Automatic Emergency Braking (0.60)	Fully Automated Vehicle (0.80)
21	Running Stop Sign			
22	LTAP/OD at Signalized Junctions			
23	Vehicle Turning Right at Signalized Junctions			
24	LTAP/OD at Non-Signalized Junctions			
25	Straight Crossing Paths at Non-Signalized Junctions			
26	Vehicle(s) Turning at Non-Signalized Junctions			
27	Evasive Action with Prior Vehicle Maneuver	None	Automatic Emergency Braking (0.20)	Fully Automated Vehicle (0.40)
28	Evasive Action Without Prior Vehicle Maneuver			
29	Animal Crash with Prior Vehicle Maneuver			
30	Animal Crash Without Prior Vehicle Maneuver			
31	Object Crash with Prior Vehicle Maneuver			
32	Object Crash Without Prior Vehicle Maneuver			
33	Vehicle Failure		Automatic Emergency Braking (0.10)	Fully Automated Vehicle (0.20)
34	Backing Up Into Another Vehicle		Automatic Emergency Braking (0.60)	Fully Automated Vehicle (0.70)
35	Vehicle(s) Parking - Same Direction		Automatic Emergency Braking + Self-Parking System (0.90)	Fully Automated Vehicle (0.90)
36	Non-Collision Incident		None	None
37	Other	Combined Impacts of Safety Applications (0.10)	Automatic Emergency Braking (0.20)	Fully Automated Vehicle (0.30)

Table 4.7 CRF (Cumulative) Assumptions of the Fatal Crashes in Aggressive Scenario

No.	Pre-Crash Scenario	CV-Only Safety Applications(CFR)	CV + AV Safety Applications Combined (CFR)	CV + Full Automation Combined (CFR)
1	Road Edge Departure with Prior Vehicle Maneuver	Road Departure Warning System		Fully Automated Vehicle

No.	Pre-Crash Scenario	CV-Only Safety Applications(CFR)	CV + AV Safety Applications Combined (CFR)	CV + Full Automation Combined (CFR)
2	Road Edge Departure Without Prior Vehicle Maneuver	(0.22)	Automatic Emergency Braking + Lane-Keeping Assist (0.44)	(0.66)
3	Road Edge Departure While Backing Up			
4	Control Loss with Prior Vehicle Action	Control Loss Warning (0.22)	Automatic Emergency Braking (0.33)	Fully Automated Vehicle (0.55)
5	Control Loss Without Prior Vehicle Action			
6	Pedestrian Crash with Prior Vehicle Maneuver	Vehicle to Pedestrian (Pedestrian) (0.33)	Automatic Emergency Braking (0.55)	Fully Automated Vehicle (0.77)
7	Pedestrian Crash Without Prior Vehicle Maneuver			
8	Pedalcyclist Crash with Prior Vehicle Maneuver	Vehicle to Pedestrian (Pedalcyclist) (0.22)	Automatic Emergency Braking (0.44)	Fully Automated Vehicle (0.66)
9	Pedalcyclist Crash Without Prior Vehicle Maneuver			
10	Vehicle(s) Turning - Same Direction	Blind Spot/Lane Change Warning (0.33)	Automatic Emergency Braking (0.44)	Fully Automated Vehicle (0.77)
11	Vehicle(s) Changing Lanes - Same Direction			
12	Vehicle(s) Drifting - Same Direction			
13	Vehicle(s) Making a Maneuver - Opposite Direction	Do Not Pass Warning (0.22)	Automatic Emergency Braking (0.33)	Fully Automated Vehicle (0.55)
14	Vehicle(s) Not Making a Maneuver - Opposite Direction			
15	Following Vehicle Making a Maneuver	Forward Collision Warning (0.25)	Automatic Emergency Braking (0.46)	Fully Automated Vehicle (0.66)
16	Lead Vehicle Accelerating			
17	Lead Vehicle Moving at Lower Constant Speed			
18	Lead Vehicle Decelerating			
19	Lead Vehicle Stopped			
20	Running Red Light	Cooperative Intersection Collision Avoidance Systems (0.44)	Automatic Emergency Braking (0.66)	Fully Automated Vehicle (0.88)
21	Running Stop Sign			
22	LTAP/OD at Signalized Junctions			
23	Vehicle Turning Right at Signalized Junctions			
24	LTAP/OD at Non-Signalized Junctions			
25	Straight Crossing Paths at Non-Signalized Junctions			
26	Vehicle(s) Turning at Non-Signalized Junctions			

No.	Pre-Crash Scenario	CV-Only Safety Applications(CFR)	CV + AV Safety Applications Combined (CFR)	CV + Full Automation Combined (CFR)
27	Evasive Action with Prior Vehicle Maneuver	None (0)	Automatic Emergency Braking (0.22)	Fully Automated Vehicle (0.44)
28	Evasive Action Without Prior Vehicle Maneuver			
29	Animal Crash with Prior Vehicle Maneuver			
30	Animal Crash Without Prior Vehicle Maneuver			
31	Object Crash with Prior Vehicle Maneuver			
32	Object Crash Without Prior Vehicle Maneuver			
33	Vehicle Failure		Automatic Emergency Braking (0.09)	Fully Automated Vehicle (0.22)
34	Backing Up Into Another Vehicle		Automatic Emergency Braking (0.66)	Fully Automated Vehicle (0.77)
35	Vehicle(s) Parking - Same Direction		Automatic Emergency Braking + Self-Parking System (0.99)	Fully Automated Vehicle (0.99)
36	Non-Collision Incident		None	None
37	Other	Combined Impacts of Safety Applications (0.11)	Automatic Emergency Braking (0.22)	Fully Automated Vehicle (0.33)

These CRFs are then applied to the original crash counts (by KABCO severity) and translated to the MAIS severity scale (using Table 4.2's values).

4.5 Crash Savings Results

Based on the results of this study, CV technologies, including V2V, V2I, and V2P, are estimated to save between \$23 billion to \$28 billion in economic costs each year, and as much as \$96 billion to \$117 billion in comprehensive costs each year in the U.S. Among the CV safety applications, the CICAS, mapped to intersection and traffic signal related pre-crash scenarios, is estimated to have the greatest potential to reduce crash costs, by preventing or mitigating the severity of crossing-path crashes, resulting in conservative estimated annual economic savings of \$9.1 billion, or \$34.1 billion annually in comprehensive cost savings.

Compared to the CV-based safety applications, AV technologies play a more significant role in improving traffic safety. The results are reasonable because AV technologies, particularly fully automated vehicles can avoid a human driver's incorrect response to warnings that non-automated CVs may provide (e.g., forward collision warnings rather than automatic emergency braking [IIHS 2016]). AEB is the most beneficial AV-based safety application, without being fully automated. AEB alone can save between \$23.5 billion and \$28.8 billion in economic costs and \$90 billion to \$110 billion in comprehensive costs annually.

The results also indicate a promising future of fully automated and connected vehicles in terms of safety benefits, which can save between \$97 billion to \$119 billion in economic costs and \$391 billion to \$477 billion in comprehensive costs. This suggests that about 75% of total (police-reported) collision costs could be saved if vehicles were made fully autonomous and connected.

Table 4.8 Annual Crash Counts of U.S. Light-Duty-Vehicle Pre-Crash Scenarios (using 2013 GES crash records)

No.	Pre-Crash Scenario	Crash Count per Year	Relative Frequency
1	Vehicle failure	44K	0.80%
2	Control loss with prior vehicle action	65K	1.18%
3	Control loss without prior vehicle action	393K	7.14%
4	Running red light	192K	3.49%
5	Running stop sign	36K	0.65%
6	Road edge departure with prior vehicle maneuver	85K	1.54%
7	Road edge departure without prior vehicle maneuver	441K	8.01%
8	Road edge departure while backing up	77K	1.40%
9	Animal crash with prior vehicle maneuver	3K	0.05%
10	Animal crash without prior vehicle maneuver	297K	5.39%
11	Pedestrian crash with prior vehicle maneuver	27K	0.49%
12	Pedestrian crash without prior vehicle maneuver	42K	0.76%
13	Pedalcyclist crash with prior vehicle maneuver	127K	2.31%
14	Pedalcyclist crash without prior vehicle maneuver	120K	2.18%
15	Backing up into another vehicle	22K	0.40%
16	Vehicle(s) turning – same direction	279K	5.07%
17	Vehicle(s) changing lanes – same direction	247K	4.48%
18	Vehicle(s) drifting – same direction	4K	0.07%
19	Vehicle(s) parking – same direction	95K	1.72%
20	Vehicle(s) making a maneuver – opposite direction	91K	1.65%
21	Vehicle(s) not making a maneuver – opposite direction	1.1M	20.21%
22	Following vehicle making a maneuver	202K	3.67%
23	Lead vehicle accelerating	268K	4.87%
24	Lead vehicle moving at lower constant speed	202K	3.67%
25	Lead vehicle decelerating	47K	0.85%
26	Lead vehicle stopped	136K	2.47%
27	LTAP/OD at signalized junctions	321K	5.83%
28	Vehicle turning right at signalized junctions	320K	5.81%
29	LTAP/OD at non-signalized junctions	125K	2.27%
30	Straight crossing paths at non-signalized junctions	78K	1.42%
31	Vehicle(s) turning at non-signalized junctions	9K	0.16%
32	Evasive action with prior vehicle maneuver	44K	0.80%
33	Evasive action without prior vehicle maneuver	65K	1.18%
34	Non-collision incident	393K	7.14%
35	Object crash with prior vehicle maneuver	192K	3.49%
36	Object crash without prior vehicle maneuver	36K	0.65%
37	Other	85K	1.54%
	Totals	5.5 Million/yr	100%

Table 4.9 Economic Costs and Comprehensive Costs of All U.S. Light-Duty-Vehicle Pre-Crash Scenarios (using 2013 GES crash records)

No.	Pre-Crash Scenario	Economic Costs (\$M, 2013 Dollars)	Comprehensive Costs (\$M, 2013 Dollars)
1	Vehicle failure	\$1,585	\$6,567
2	Control loss with prior vehicle action	\$14,425	\$70,886
3	Control loss without prior vehicle action	\$7,570	\$28,833
4	Running red light	\$1,193	\$4,070

5	Running stop sign	\$1,957	\$8,564
6	Road edge departure with prior vehicle maneuver	\$13,419	\$64,545
7	Road edge departure without prior vehicle maneuver	\$667	\$1,693
8	Road edge departure while backing up	\$27	\$91
9	Animal crash with prior vehicle maneuver	\$3,359	\$9,651
10	Animal crash without prior vehicle maneuver	\$2,652	\$14,567
11	Pedestrian crash with prior vehicle maneuver	\$5,086	\$28,778
12	Pedestrian crash without prior vehicle maneuver	\$925	\$3,857
13	Pedalcyclist crash with prior vehicle maneuver	\$1,221	\$5,666
14	Pedalcyclist crash without prior vehicle maneuver	\$2,094	\$5,502
15	Backing up into another vehicle	\$2,982	\$10,873
16	Vehicle(s) turning – same direction	\$550	\$1,795
17	Vehicle(s) changing lanes – same direction	\$6,948	\$20,366
18	Vehicle(s) drifting – same direction	\$5,222	\$14,640
19	Vehicle(s) parking – same direction	\$951	\$5,926
20	Vehicle(s) making a maneuver – opposite direction	\$6,086	\$30,212
21	Vehicle(s) not making a maneuver – opposite direction	\$121	\$529
22	Following vehicle making a maneuver	\$2,495	\$8,702
23	Lead vehicle accelerating	\$32,401	\$100,159
24	Lead vehicle moving at lower constant speed	\$6,319	\$21,815
25	Lead vehicle decelerating	\$7,167	\$21,337
26	Lead vehicle stopped	\$8,172	\$31,864
27	LTAP/OD at signalized junctions	\$883	\$2,296
28	Vehicle turning right at signalized junctions	\$5,102	\$19,310
29	LTAP/OD at non-signalized junctions	\$11,065	\$41,088
30	Straight crossing paths at non-signalized junctions	\$9,151	\$31,012
31	Vehicle(s) turning at non-signalized junctions	\$8	\$24
32	Evasive action with prior vehicle maneuver	\$177	\$666
33	Evasive action without prior vehicle maneuver	\$106	\$556
34	Non-collision incident	\$173	\$500
35	Object crash with prior vehicle maneuver	\$1,413	\$6,026
36	Object crash without prior vehicle maneuver	\$4	\$9
37	Other	\$5,423	\$21,879
	Annual Totals	\$169 billion	\$645 billion

Table 4.10 Annual Economic & Comprehensive Cost Savings Estimates for Fully Automated Light-Duty Vehicle Application under Three Scenarios (using 2013 GES Crash Records)

CV, AV and Fully Automated Safety Applications	Conservative Scenario		Moderate Scenario		Aggressive Scenario	
	Economic Costs Saved, \$M in 2013	Comprehensive Costs Saved, \$M in 2013	Economic Costs Saved, \$M in 2013	Comprehensive Costs Saved, \$M in 2013	Economic Costs Saved, \$M in 2013	Comprehensive Costs Saved, \$M in 2013
CV						

Total	\$23,308	\$96,125	\$25,897	\$106,800	\$28,486	\$117,480
CICAS	\$9,095	\$34,055	\$10,105	\$37,837	\$11,116	\$41,622
CLW	\$3,571	\$16,707	\$3,967	\$18,563	\$4,364	\$20,419
FCW	\$3,714	\$13,310	\$4,126	\$14,789	\$4,539	\$16,267
RDCW	\$2,311	\$11,183	\$2,567	\$12,425	\$2,823	\$13,668
V2P	\$2,043	\$10,261	\$2,270	\$11,399	\$2,497	\$12,541
BS/LCW	\$1,543	\$5,358	\$1,716	\$5,953	\$1,887	\$6,547
DNPW	\$1,031	\$5,251	\$1,146	\$5,834	\$1,260	\$6,416
AV						
Total	\$74,073	\$294,483	\$82,300	\$327,197	\$90,533	\$359,916
AEB	\$23,546	\$89,985	\$26,157	\$99,983	\$28,771	\$109,982
Self-Parking	\$3,508	\$10,565	\$3,897	\$11,740	\$4,287	\$12,914
LKA	\$1,154	\$5,591	\$1,283	\$6,213	\$1,411	\$6,833
L4 Automation	\$45,865	\$188,342	\$50,963	\$209,261	\$56,064	\$230,187
Total Safety Benefits	\$97,381	\$390,608	\$108,197	\$433,997	\$119,019	\$477,396
Original Costs (w/o CAV implementation)	\$ 169,099	\$644,854	\$ 169,099	\$644,854	\$ 169,099	\$644,854
CAV Benefits	58%	61%	64%	67%	70%	74%

Conclusions from GES Pre-Crash Scenario Estimates

The research described above seeks to comprehensively anticipate the safety benefits of various CV and AV technologies, in terms of economic and comprehensive cost savings in the U.S. The most recently available U.S. crash database (2013 NASS GES) was used, and results suggest that advanced CAV technologies may reduce current crash costs by at least \$390 billion per year (including pain and suffering damages, and other non-economic costs). These results rely on the three different effectiveness scenarios with a 100-percent market penetration rate of all CV- and AV-based safety technologies.

Of the eleven safety applications, the one with the greatest potential to avoid or mitigate crashes, but not yet on the market, is Full Automation of one's vehicle. A currently available technology, AEB, also offers substantial safety rewards, with an estimated economic savings of \$23.5 to \$28.8 billion each year, assuming full adoption across the U.S., along with current crash counts. Among the CV-based safety applications, CICAS is estimated to offer the greatest economic and comprehensive cost savings. Overall, AV-based technologies are expected to offer far more safety benefits than CV-based technologies, as expected, since automation proactively avoids human errors during travel, rather than simply warning human drivers about possible conflicts.

There is little doubt that various CAV technologies will offer significant safety benefits to transportation system users. However, the actual effectiveness of these technologies will not be known until sufficient real-world data have been collected and analyzed. Here, their effectiveness assumes 100-percent market access and use (thus technologies are available to all motorized vehicle occupants and are not disabled by those occupants), as well as different success rates under several assumption scenarios. Such assumptions come with great uncertainty surrounding the interaction between CAV systems and drivers/travelers. More on-road deployment and testing will be helpful to decrease the uncertainty of benefit analysis of CAV systems in terms of traffic safety improvement, alongside simulated driving situations. It is also important to note that connectivity is not needed in many cases, when AV cameras will suffice. However, CICAS does require a roadside device that is able to communicate quickly with all vehicles. NHTSA is likely to require DSRC on all new vehicles beginning in model year 2020 (Harding et al. 2014). Therefore, connectivity may become widely available much more quickly than high levels of automation, in terms of fleet mix over time. Older vehicles may be retrofitted with connectivity soon after, when costs are low (e.g., \$100 for add-ons to existing vehicles (Bansal and Kockelman 2015) and the benefits of connectivity more evident nation-wide.

It is also noteworthy that GES crash records have even more attributes than those used here, including road types and weather conditions at time of crash. Future work may do well to focus on anticipating technology-specific safety benefits with more hierarchical pre-crash scenarios, combined with road types and weather conditions. Furthermore, the database used in this study only contains GES crash records, therefore representing only U.S. driving context. For more detailed results, local crash databases, and databases in other countries, can be queried, which may suggest different benefit rankings and magnitudes.

4.6 Crash Estimates using Safety Surrogate Assessment Model (SSAM)

It is difficult to anticipate the crash benefits C/AV technologies will provide, especially without certain details of each crash. Another method for inferring crash-related benefits, beyond the US crash counts and pre-crash scenario categorization used above, is to simulate traffic flows with and without C/AV technologies on board and keep track of near-misses and other details that microsimulation models can detect. The FHWA's Safety Surrogate Assessment Model (SSAM) is a tool for tracking such metrics.

Introduction and Definitions

SSAM analyzes trajectory data, in the form of a “.tj” file from traffic-microsimulation software, such as VisSim, and identifies conflicts. Conflicts are defined as situation in which two vehicles will collide unless action is taken, and are categorized into Unclassified, Crossing, Rear End, and Lane Change. For each conflict identified, there are several surrogate safety measures that include the following: Minimum time-to-collision (TTC), minimum post-encroachment time (PET), initial deceleration rate (DR), maximum deceleration rate (MaxD), maximum speed (MaxS), maximum speed differential (DeltaS), and vehicle velocity change had the event proceeded to a crash (DeltaV).

Table 4.11 SSAM Measures and Definitions

SSAM Measure	Definitions
TTC	The minimum time-to-collision value observed during the conflict. This estimate is based on the current location, speed, and trajectory of two vehicles at a given instant.
PET	The minimum post encroachment time observed during the conflict. Post encroachment time is the time between when the first vehicle last occupied a position and the second vehicle subsequently arrived at the same position. A value of 0 indicates an actual collision.
MaxS	The maximum speed of either vehicle throughout the conflict (i.e., while the TTC is less than the specified threshold). This value is expressed in feet per second or meters per second, depending on the units specified in the corresponding trajectory file.
DeltaS	The difference in vehicle speeds as observed at tMinTTC. More precisely, this value is mathematically defined as the magnitude of the difference in vehicle velocities (or trajectories), such that if v_1 and v_2 are the velocity vectors of the first and second vehicles respectively, then $\Delta S = \ v_1 - v_2\ $. Consider an example where both vehicles are traveling at the same speed, v . If they are traveling in the same direction, $\Delta S = 0$. If they have a perpendicular crossing.
DR	The initial deceleration rate of the second vehicle. Note that in actuality, this value is recorded as the instantaneous acceleration rate. If the vehicle brakes (i.e., reacts), this is the first negative acceleration value observed during the conflict. If the vehicle does not brake, this is the lowest acceleration value observed during the conflict. This value is expressed in feet per second or meters per second, depending on the units specified in the corresponding trajectory file.
MaxD	The maximum deceleration of the second vehicle. Note that in actuality, this value is recorded as the minimum instantaneous acceleration rate observed during the conflict. A negative value indicates deceleration (braking or release of gas pedal). A positive value indicates that the vehicle did not decelerate during the conflict. This value is expressed in feet per second or meters per second, depending on the units specified in the corresponding trajectory file.

MaxDeltaV	The maximum DeltaV value of either vehicle in the conflict. This is a surrogate for the severity of the conflict, calculated assuming a <i>hypothetical</i> collision of the two vehicles in the conflict.
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The surrogate measures focused on in this paper are Max S, MaxDelta V, and MaxD. Focus is directed on Max S and MaxDeltaV because they are related to severity of a potential collision, and MaxD because it represents how well, on average, vehicles avoided collisions. From the SSAM Manual, TTC and PET are meant to indicate likelihood of a conflict, as PET = 0 indicates an actual collision, but they were not included in this analysis because of the nature of the EDMs. The vehicles are already following quite close to each other, producing lower TTC and PET values, which inflate the number of conflicts recognized by SSAM. Therefore, for driver models used in VisSim, TTC and PET do not give a good indication of the likelihood of a collision.

Urban Roadway Bottlenecks

Table 4.12 provides bottleneck conflict results while Table 4.13 summarizes the percentage decrease in total number of conflicts between 100% human-driven vehicles (HVs) and 100% AVs, for low, medium, and high flows. See Figures Figure 4.1Figure 4.3 for a plot of every conflict type at their respective flows.

Table 4.12 Bottleneck Conflict Results Disaggregated by Type

Flow Type	Percent Flow	Total	Unclassified	Crossing	Rear End	Lane Change
Low	100% HV	5	0	0	5	0
	25% AV	9	0	0	9	0
	50% AV	7	0	0	7	0
	75% AV	4	0	0	4	0
	100% AV	3	0	0	3	0
Medium	100% HV	137	0	0	125	12
	25% AV	115	0	0	106	9
	50% AV	85	0	0	79	6
	75% AV	50	0	0	42	8
	100% AV	17	0	0	8	9
High	100% HV	1972	0	0	1547	425
	25% AV	1741	0	1	1307	433
	50% AV	1393	0	0	915	478
	75% AV	1064	0	0	608	456
	100% AV	684	0	0	256	428

Table 4.13 *Percent Difference in Conflicts Between HVs and AVs*

Flow Type	Percent Decrease between 100% HV and 100% AV
Low	40%
Medium	88%
High	65%

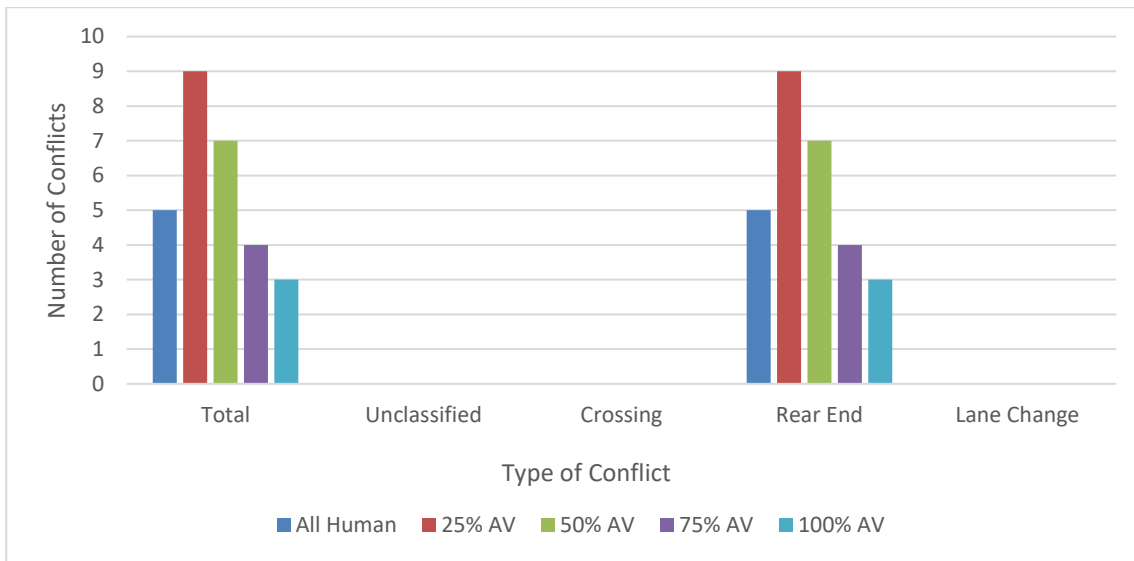


Figure 4.1 *Low-Flow Conflicts Disaggregated by Type*

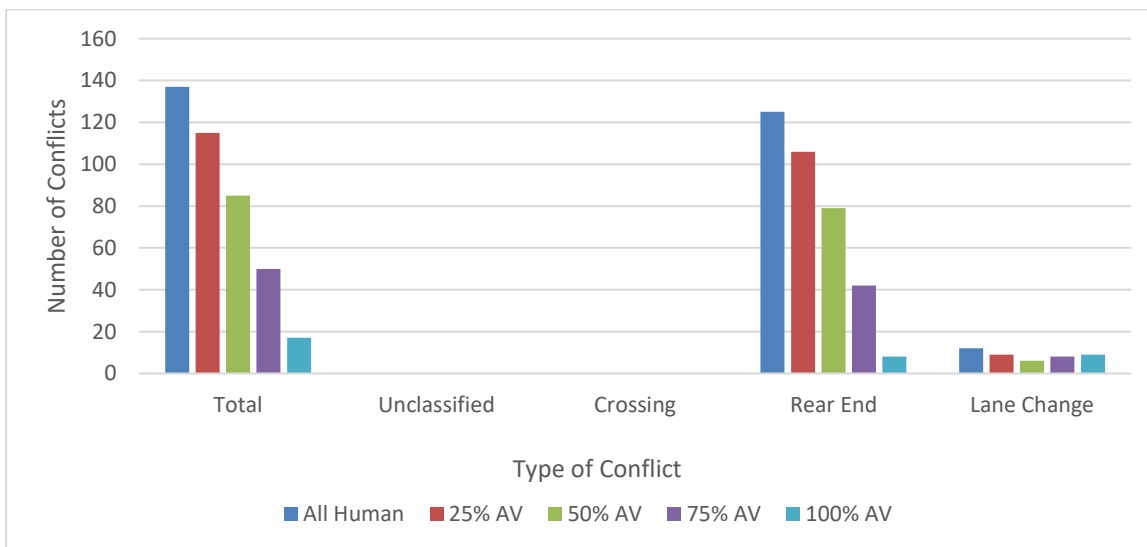


Figure 4.2 *Medium-Flow Conflicts Disaggregated by Type*

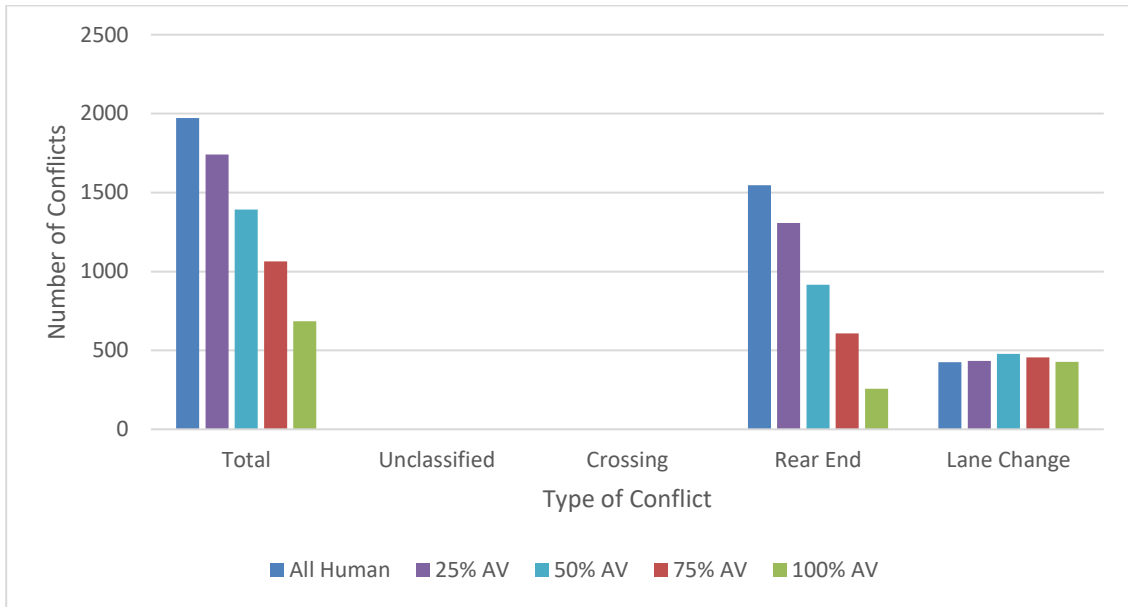


Figure 4.3 High-Flow Conflicts Disaggregated by Type

At low flow, the MaxDeltaV values are greater than only HVs with 25 and 50% AVs, but then decrease for the 75 and 100% AVs. At medium and high flow, the values are lower for all AV percentages, but only noticeably for 100% AVs. MaxS also decreases significantly between 100% HV and 75% AV/100% AV for all flow volumes. For example, at medium flow, the MaxS for all HVs is 29.09 m/s, while at 100% AVs it is 14.84 m/s, which is almost a 50% decrease. Table 4.14 displays the surrogate safety measures from the SSAM output, and Table 4.15 summarizes the percentage differences between the HV and AV EDMs.

Table 4.14 Bottleneck Surrogate Safety Measures (Number of Measures)

Mean Value	Variable	100% HV	25% AV	50% AV	75% AV	100% AV
Low	MaxS	25.56	29.38	27.55	20.72	16.52
	MaxDeltaV	3.96	5	4.71	3.62	2.53
	MaxD	-4.66	-5.49	-5.15	-1.76	-0.27
Medium	MaxS	29.09	29.18	27.61	25.51	14.84
	MaxDeltaV	5.18	5.13	4.5	4.5	2.54
	MaxD	-6.3	-6.2	-5.94	-6.09	-3.52
High	MaxS	20.92	20.24	18.83	17.47	14.7
	MaxDeltaV	4.71	4.69	4.14	3.83	2.98
	MaxD	-5.5	-5.56	-5.32	-4.96	-4.62

Table 4.15 Percent Differences in Safety Measures between HVs and AVs (Bottleneck, Number of Measures)

Percent Difference	Variable	25% AV	50% AV	75% AV	100% AV
Low	MaxS	15	8	-19	-35
	MaxDeltaV	26	19	-9	-36
	MaxD	18	11	-62	-94
Medium	MaxS	0	-5	-12	-49
	MaxDeltaV	-1	-13	-13	-51
	MaxD	-2	-6	-3	-44
High	MaxS	-3	-10	-16	-30
	MaxDeltaV	0	-12	-19	-37
	MaxD	1	-3	-10	-16

This data indicates that AVs are safer than HVs in a bottleneck situation, especially as the percentage of AVs increases. At 50% AVs, the data only agrees at medium and high flows, and at only 25% AVs the data provides mixed results. More simulations on a variety of bottleneck networks will need to be run to draw concrete conclusions.

Four-way Intersections

Table 4.16 provides data on four-way intersection conflicts disaggregated by type while Table 4.17 provides data on four-way intersection surrogate safety measures.

Table 4.16 Four-way Intersection Conflicts Disaggregated by Type (Number of Conflicts)

Human External Driver Model and AV External Drive Model					
Summary	Total	Unclassified	Crossing	Rear End	Lane Change
100% HV	25	0	23	0	2

25% AV	25	0	23	0	2
50% AV	24	0	22	0	2
75% AV	24	0	22	0	2
100% AV	24	0	22	0	2

Figure 4.4 summarizes the total number of conflicts predicted by SSAM, for the four-way intersection simulation. The data does not correspond to expected trends, based on the results seen from the other simulations. There is no variation in the number of conflicts between the different percentages of AV flow.

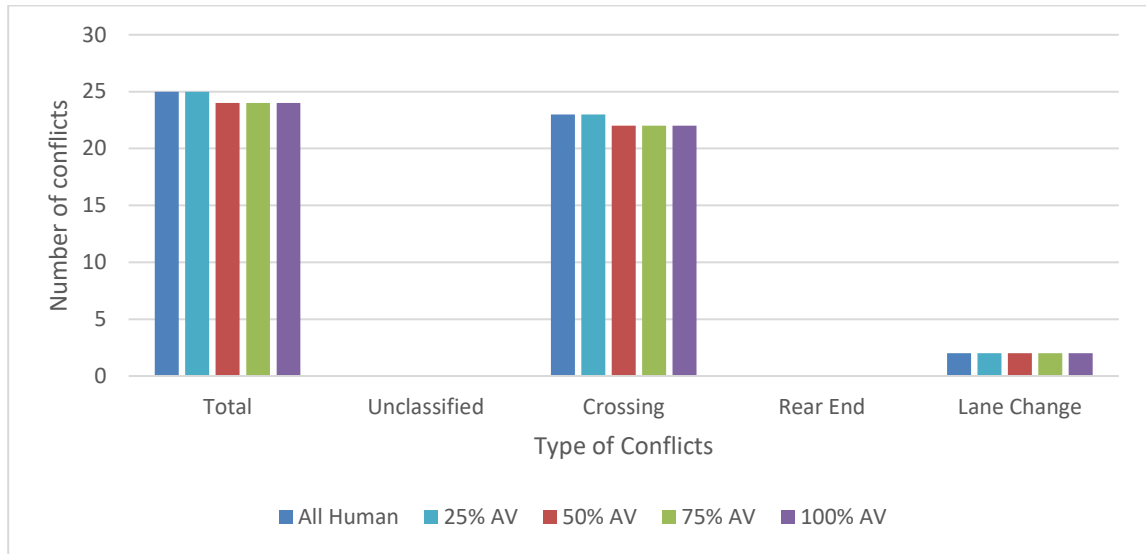


Figure 4.4 Four-way Conflicts Disaggregated by Type

Table 4.17 Four-way Intersection Surrogate Safety Measures (Number of Measures)

Mean Values	100% HV	25% AV	50% AV	75% AV	100% AV
MaxS	19.95	20.01	19.97	20.12	20.12
MaxDeltaV	13.34	13.36	13.69	13.64	13.64
MaxD	0.65	0.72	0.6	1.02	1.02

The severity of crashes does not vary much between the HVs and the varying percentages of AVs. However, there is an increase in MaxD for the 75% and 100% AVs. MaxD is the maximum deceleration of the second vehicle, and when positive indicates that the vehicle did not decelerate during the conflict. The mean MaxD for every simulation run generated a positive value, meaning on average, the second vehicle involved in the conflict did not decelerate. Though this is an undesirable action in the EDMs, it corresponds to the observation in VisSim, when the vehicles did not observe stop signs or conflict zones. The majority of conflicts were the Crossing type, which is why the MaxD is positive. Thus, the conflicts types can largely be ignored, however for any future simulations the EDMs will need to be adjusted in order to reasonably model AVs at intersections. Table 4.16 relates differences in safety measures between HVs and AVs.

Table 4.18 Percent Differences in Safety Measures between HVs and AVs (Four-way, Number of Measures)

Percent Difference	25% AV	50% AV	75% AV	100% AV
MaxS	0	0	1	1
MaxDeltaV	0	3	2	2
MaxD	11	-8	57	57

As it stands with current data, the results are inconclusive for this network, as the number of conflicts remained constant for each run, regardless of percentage of AV flow. There was also a decrease in safety, in terms of deceleration time (MaxD), for the 75 and 100% AV inputs.

On Freeway On-Ramps and Off-Ramps

Table 4.19 and Figure 4.5 provide on-ramp/off-ramp conflicts disaggregated by type.

Table 4.19 On-Ramp/Off-Ramp Conflicts Disaggregated by Type (Number of Conflicts)

Human External Driver Model and AV External Drive Model					
Summary	Total	Unclassified	Crossing	Rear End	Lane Change
100% HV	117	0	0	96	21
25% AV	119	0	0	97	22
50% AV	85	0	0	70	15
75% AV	81	0	0	65	16
100% AV	60	0	0	46	14

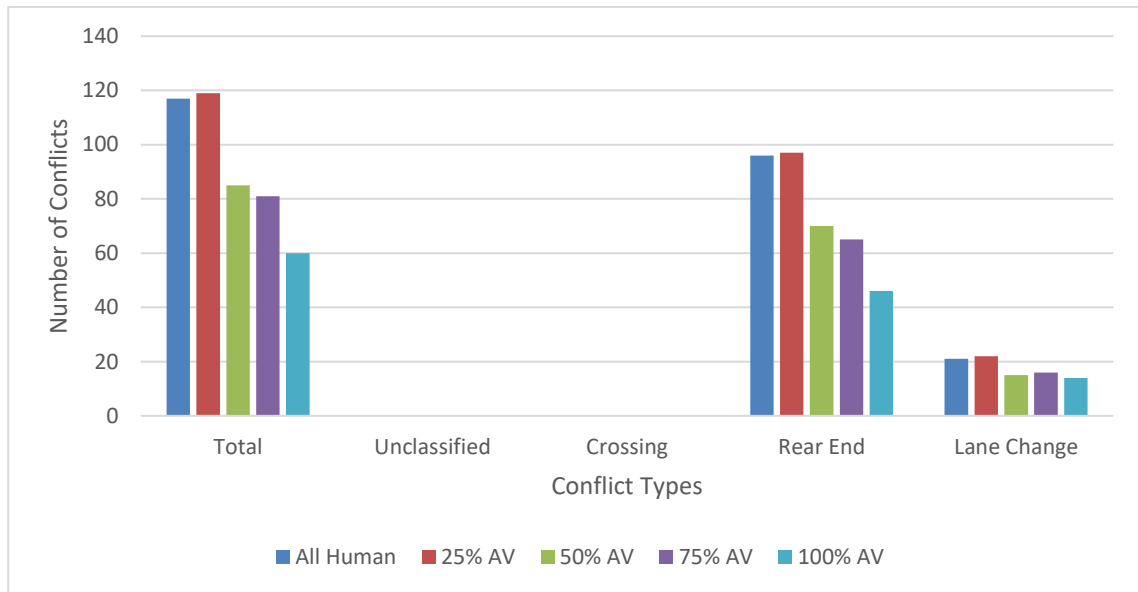


Figure 4.5 On-Off Ramp Conflicts Disaggregated by Type

For this network there was a slight increase of two conflicts during the 25% AV flow; however, this is an anomaly among the other data sets. In general, Table 4.20 shows that as the percentage of AV’s increases, the number of conflicts decreases, with the least number of conflicts occurring at 100% AVs. The most drastic decreases in conflicts occur with Rear End types. There was a slight decrease in the severity of crashes as the percentages of AVs increased, as well as a better deceleration response. The results indicate that AVs decrease the number of conflicts for networks involving entrance and exit ramps onto or off of a freeway.

Table 4.20 On-Off Ramp Surrogate Safety Measures (Number of Measures)

Mean Values	100% HV	25% AV	50% AV	75% AV	100% AV
MaxS	30.28	30.18	30.64	29.22	28.45
MaxDeltaV	4.07	4.32	4.41	3.71	3.23
MaxD	-3.72	-3.52	-3.51	-3.27	-2.66

Intersection of I-35 and Wells Branch Parkway

It was found through the simulations for the network intersection of I-35 and Wells Branch Parkway that the number of conflicts comprehensively decreased with the addition of AVs in the traffic. Figure 4.6 summarizes the conflicts across various concentrations of AVs.

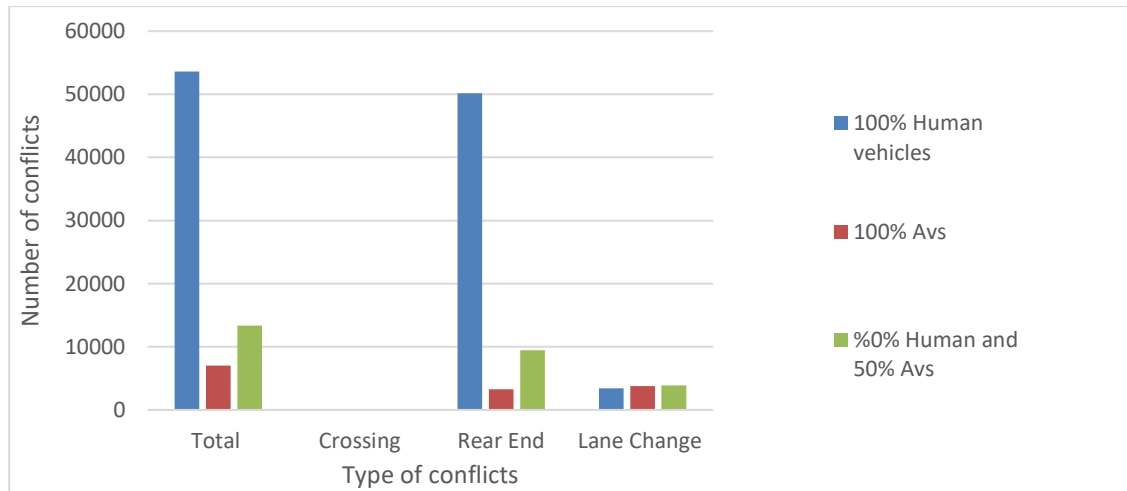


Figure 4.6 Intersection of I-35 and Wells Branch Parkway Conflicts Disaggregated by Type

At the specified flow, the MaxDeltaV and DeltaS values were found to decrease consistently with the increase in the concentration of AVs at this intersection. MaxS, also decreases significantly between 100% HV and 50% AV/100% AV. For example, the MaxS for all HVs is 19.28 m/s, while at 100% AVs it is 17.87 m/s, which is almost an 8% decrease. Similarly, the DeltaS for all HVs is 17.21 m/s, while at 100% AVs it is 9.36 m/s, which is almost a 45% decrease. Finally, the MaxDeltaV for all HVs is 9.07 m/s, while at 100% AVs it is 4.94 m/s, which is almost a 45% decrease. Tables Table 4.21 and Table 4.22 summarize the total number of conflicts and other measures for the various scenarios predicted by SSAM.

The following results were observed for 100% HVs at the intersection of I-35 and Wells Branch Parkway.

Table 4.21 Intersection of I-35 and Wells Branch Parkway Conflict Summary (Number of Conflicts)

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	53605	0	0	50176	3429
Run 1	11440	0	0	11106	334
Run 2	2632	0	0	2262	370
Run 3	1617	0	0	1284	333
Run 4	1697	0	0	1292	405
Run 5	3350	0	0	2995	355
Run 6	1176	0	0	921	255
Run 7	1143	0	0	898	245
Run 8	27168	0	0	26719	449
Run 9	1576	0	0	1230	346
Run 10	1806	0	0	1469	337

Table 4.22 Intersection of I-35 and Wells Branch Parkway Surrogate Safety Measures (Number of Measures)

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.07	0.07
PET	0	3.8	0.04	0.04
MaxS	0	34.5	19.28	6.01
DeltaS	0	24.07	17.21	23.02
DR	-8.39	3	-3.92	7.05
MaxD	-8.44	3	-6.45	3.79
MaxDeltaV	0	13.71	9.07	6.51

Table 4.23 and Table 4.24 provide the results for 100% AVs for the intersection of I-35 and Wells Branch Parkway, while Tables Table 4.25 and Table 4.26 provide the results for 50% AV and 50% HVs at that intersection.

Table 4.23 Intersection of I-35 and Wells Branch Parkway Conflict Summary (Number of Crashes)

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	7035	0	3	3278	3754
Run 1	825	0	1	392	432
Run 2	787	0	0	356	431
Run 3	653	0	0	315	338
Run 4	749	0	0	365	384
Run 5	704	0	0	310	394
Run 6	783	0	1	376	406
Run 7	478	0	0	175	303
Run 8	563	0	0	251	312
Run 9	868	0	1	407	460
Run 10	625	0	0	331	294

Table 4.24 Intersection of I-35 and Wells Branch Parkway Surrogate Safety Measures (Number of Measures)

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.4	0.29
PET	0	4.8	0.28	0.27
MaxS	1.45	32.73	17.87	14.56
DeltaS	0	25.58	9.36	23.45
DR	-8.19	3.37	-4.29	12.28
MaxD	-8.33	3.37	-5.08	12.54
MaxDeltaV	0	13.99	4.94	6.6

Table 4.25 Intersection of I-35 and Wells Branch Parkway Conflicts Summary (Number of Conflicts)

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	13350	0	2	9477	3871
Run 1	1325	0	0	925	400
Run 2	1759	0	0	1275	484
Run 3	1139	0	0	816	323
Run 4	1169	0	0	803	366
Run 5	2108	0	0	1542	566
Run 6	1390	0	0	974	416
Run 7	1048	0	1	733	314
Run 8	1021	0	0	736	285
Run 9	1404	0	1	1010	393
Run 10	987	0	0	663	324

Table 4.26 Intersection of I-35 and Wells Branch Parkway Surrogate Safety Measures (Number of Measures)

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.24	0.22
PET	0	4.8	0.17	0.18

MaxS	0	32.34	18.31	11.3
DeltaS	0	29.66	11.85	27.45
DR	-8.23	3.32	-3.64	8.84
MaxD	-8.36	3.32	-5.23	8.63
MaxDelta V	0	15.51	6.25	7.69

It was found through the simulations for the network intersection of I-35 and 4th Street that the number of conflicts comprehensively decreased with the addition of AVs in the traffic. Figure 4.7 summarizes the conflicts across various concentrations of AVs.

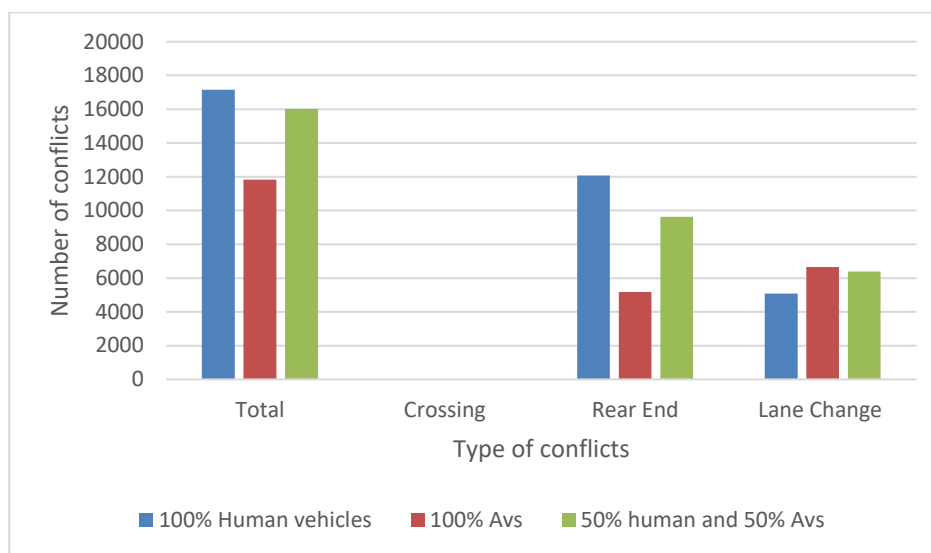


Figure 4.7 Number of Conflict Types Aggregated by Simulation Type

Intersection of I-35 and 4th Street

At the specified flow, the MaxDeltaV and DeltaS values were found to decrease consistently with the increase in the concentration of AVs at the intersection of I-35 and 4th Street. MaxS, however, increased slightly for increasing AVs concentration. For example, the MaxS for all HVs is 15.3 m/s, while at 100% AVs it is 15.83 m/s, which is almost a 3% increase. The DeltaS for all HVs is 10.41 m/s, while at 100% AVs it is 8.20 m/s, which is almost a 22% decrease. Finally, the MaXDeltaV for all HVs is 5.49 m/s, while at 100% AVs it is 4.32 m/s, which is almost a 22% decrease. TablesTable 4.27 and Table 4.28 summarize the total number of conflicts and other measures for the various scenarios predicted by SSAM. The following results were observed for 100% AVs at the intersection of I-35 and 4th Street. TablesTable 4.29 andTable 4.30 provide the results for 100% HVs at this intersection.

Table 4.27 Intersection of I-35 and 4th Street Conflicts Summary (Number of Conflicts)

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	11833	0	2	5171	6660
Run 1	1189	0	0	536	653
Run 2	1199	0	0	519	680
Run 3	1251	0	1	554	696
Run 4	1156	0	0	526	630
Run 5	1283	0	0	560	723
Run 6	1112	0	0	463	649

Run 7	1189	0	0	521	668
Run 8	1162	0	1	493	668
Run 9	1185	0	0	505	680
Run 10	1107	0	0	494	613

Table 4.28 Intersection of I-35 and 4th Street Surrogate Safety Measures (Number of Measures)

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.35	0.26
PET	0	4.6	0.29	0.37
MaxS	0	29	15.83	28.14
DeltaS	0	27.56	8.2	28.75
DR	-8.17	3.5	-4.6	12.39
MaxD	-8.35	3.5	-5.18	12.4
MaxDeltaV	0	14.66	4.32	8.02

Table 4.29 Intersection of I-35 and 4th Street Conflicts Summary (Number of Conflicts)

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	17156	0	1	12067	5088
Run 1	1145	0	0	702	443
Run 2	1687	0	1	1136	550
Run 3	1550	0	0	1062	488
Run 4	2511	0	0	1932	579
Run 5	1251	0	0	787	464
Run 6	1805	0	0	1335	470
Run 7	1591	0	0	1113	478
Run 8	1910	0	0	1349	561
Run 9	1289	0	0	830	459
Run 10	2417	0	0	1821	596

Table 4.30 Intersection of I-35 and 4th Street Surrogate Safety Measures (Number of Measures)

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.22	0.2
PET	0	4.8	0.17	0.18
MaxS	0	31.72	15.3	22.58
DeltaS	0	28.57	10.41	27.85
DR	-8.37	3.1	-3.88	9.87
MaxD	-8.5	3.1	-5.19	10.07
MaxDeltaV	0	14.29	5.49	7.82

The following results were observed for 50% AV and 50% HVs at this intersection (Tables Table 4.31 and Table 4.32).

Table 4.31 Intersection of I-35 and 4th Street Conflict Summary (Number of Conflicts)

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	16012	0	2	9629	6381

Run 1	1726	0	0	1027	699
Run 2	1485	0	1	873	611
Run 3	1767	0	0	1093	674
Run 4	1508	0	0	906	602
Run 5	1552	0	0	898	654
Run 6	1460	0	0	890	570
Run 7	1724	0	1	1072	651
Run 8	1668	0	0	991	677
Run 9	1683	0	0	1024	659
Run 10	1439	0	0	855	584

Table 4.32 Intersection of I-35 and 4th Street Surrogate Safety Measures (Number of Measures)

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.28	0.24
PET	0	4.8	0.22	0.29
MaxS	0	29.82	15.62	24.86
DeltaS	0	31	9.37	29.34
DR	-8.5	3.5	-3.88	10.29
MaxD	-8.5	3.5	-5.18	10.11
MaxDeltaV	0	15.99	4.94	8.18

Intersection of Manor Road and E M Franklin Avenue

The simulations for the network intersection of Manor Road and E M Franklin Avenue revealed that the number of conflicts increased as the concentration of AVs increased from 0% to 50%, but then decreased as the concentration of AVs reached 100%. Figure 4.8 summarizes the number of conflicts across various concentrations of AVs.

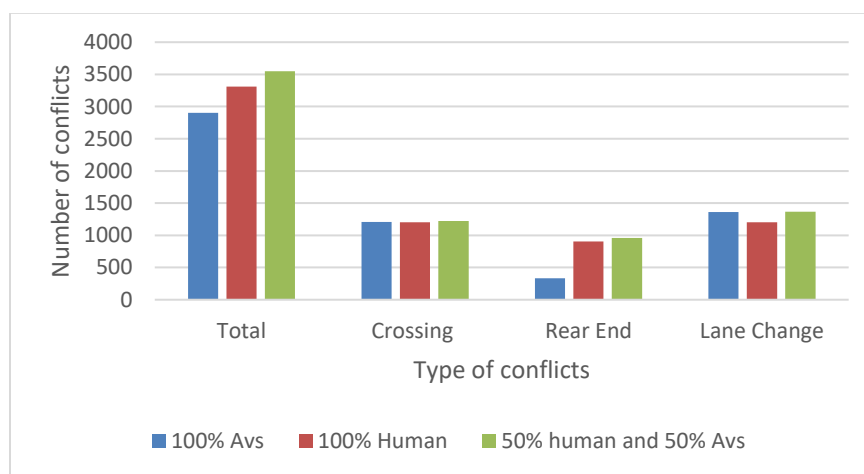


Figure 4.8 Conflicts at Intersection of Manor Road and E M Franklin Avenue

At the specified flow, the MaxDeltaV and MaxS values were found to decrease consistently with the increase in the concentration of AVs at this intersection. DeltaS, however, increased slightly for increasing AV concentration. For example, the MaxS for all HVs is 20.82 m/s, while at 100% AVs it is 20.43 m/s, which is almost a 2% decrease. The DeltaS for all HVs is 20.27 m/s, while at 100% AVs it is 20.57 m/s, which is almost a 1.5% increase. Finally, the MaXDeltaV for all HVs is 30.61 m/s, while at 100% AVs it is 10.84 m/s,

which is almost a 65% decrease. Tables Table 4.33 and Table 4.34 summarize the total number of conflicts and other measures for the various scenarios predicted by SSAM.

Table 4.33 *Intersection of Manor Road and E M Franklin Avenue Conflicts Summary (Number of Conflicts)*

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	2901	0	1208	331	1362
Run 1	303	0	123	34	146
Run 2	275	0	111	34	130
Run 3	316	0	111	45	160
Run 4	286	0	115	32	139
Run 5	278	0	105	35	138
Run 6	317	0	138	39	140
Run 7	255	0	114	21	120
Run 8	291	0	135	28	128
Run 9	261	0	109	23	129

Table 4.34 *Intersection of Manor Road and E M Franklin Avenue Surrogate Safety Measures (Number of Measures)*

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.16	0.15
PET	0	3.2	0.09	0.07
MaxS	3.31	26.67	20.43	9.86
DeltaS	0.39	40.87	20.57	111.26
DR	-7.75	3.09	-1.55	12.23
MaxD	-8.1	3.09	-1.92	14.26
MaxDeltaV	0.21	22.21	10.84	30.99

The following results were observed for 100% HVs at the intersection of Manor Road and E M Franklin Avenue (Tables Table 4.35 and Table 4.36).

Table 4.35 *Intersection of Manor Road and E M Franklin Avenue Surrogate Safety Measures (Number of Conflicts)*

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	3311	0	1201	905	1205
Run 1	365	0	128	97	140
Run 2	283	0	109	68	106
Run 3	446	0	144	147	155
Run 4	277	0	109	65	103
Run 5	353	0	119	114	120
Run 6	345	0	134	88	123
Run 7	276	0	109	55	112
Run 8	327	0	117	97	113
Run 9	327	0	116	102	109
Run 10	312	0	116	72	124

Table 4.36 Intersection of Manor Road and E M Franklin Avenue Surrogate Safety Measures (Number of Measures)

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.14	0.14
PET	0	2.4	0.07	0.04
MaxS	2.27	27.71	20.82	6.31
DeltaS	1.08	43.19	20.27	110.09
DR	-7.66	2.59	-1.56	9.43
MaxD	-8.23	2.59	-2.19	12.45
MaxDeltaV	0.55	23.26	10.66	30.61

The following results were observed for 50% HVs and 50% AVs at the intersection of Manor Road and E M Franklin Avenue (Tables Table 4.37 and Table 4.38).

Table 4.37 Intersection of Manor Road and E M Franklin Avenue Surrogate Safety Measures (Number of Conflicts)

Summary	Total	Unclassified	Crossing	Rear End	Lane Change
Total	3549	0	1223	960	1366
Run 1	372	0	121	100	151
Run 2	296	0	104	76	116
Run 3	392	0	128	123	141
Run 4	335	0	127	75	133
Run 5	344	0	116	83	145
Run 6	384	0	138	94	152
Run 7	307	0	113	79	115
Run 8	378	0	133	112	133
Run 9	366	0	119	108	139
Run 10	375	0	124	110	141

Table 4.38 Intersection of Manor Road and E M Franklin Avenue Surrogate Safety Measures (Number of Measures)

SSAM Measure	Min	Max	Mean	Variance
TTC	0	1.5	0.13	0.13
PET	0	2.6	0.07	0.04
MaxS	3	27.71	20.51	7.41
DeltaS	0.87	41.16	19.66	104.76
DR	-8.24	2.52	-1.68	10.1
MaxD	-8.36	2.52	-2.38	13.3
MaxDeltaV	0.44	22.14	10.35	29.04

4.7 Summary

In summary, the VisSim simulations and the subsequent SSAM analyses suggest that AVs may be safer on selected networks in comparison with HVs. It was observed that the number of crashes and their severity

decreases as the share of AVs in the traffic stream rises. The results were not completely consistent in trend. Certain measures, such as DeltaS and MaxDeltaV, showed unexpected patterns for some conditions. These discrepancies were minor, however, and no major anomalies were encountered. The reason for the observed discrepancies could be the difference in the behavior of AVs for different road networks; the AV and HV model used for this analysis may also require better calibration to provide more realistic results.

CHAPTER 5 DEMONSTRATION OF CV APPLICATIONS PERTAINING TO TRAFFIC MANAGEMENT OPERATIONS

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5.1 Introduction

This chapter explains work that leveraged the technologies of the United States Department of Transportation (USDOT) CV program and applications developed by Southwest Research Institute (SwRI), to introduce the benefits of connected vehicles to a broad audience through a series of hands-on demonstrations, discussed in detail in Section 5.4. These technologies include the dedicated short-range communication (DSRC) radios that are contained within the infrastructure-based roadside device, or roadside unit (RSU), and the vehicle-based onboard device, or onboard equipment (OBE). Additionally, SwRI has developed a portable system that contains an OBE, antennas, power interface, and Android-based tablet. This system, the portable onboard device (POD), enables any vehicle to become a “connected vehicle,” bringing this technology out of the lab environment and into more realistic environments, which can then be used for hands-on demonstrations. These technologies are described in more detail in Section 5.2.

This work introduced a number of connected and automated vehicle technologies through hands-on demonstrations.

Two demonstrations were conducted within this work. The first was conducted at the UT Austin J.J. Pickle Research Center, in Austin, Texas in December 2015, and the second was conducted on the campus of SwRI as well as Interstate 410 and surrounding roadways in San Antonio, Texas, held in June 2016. These demonstrations involved both vehicle- and infrastructure-based CV technologies, and demonstrated six separate CV applications, one of which also incorporated a fully autonomous Class VIII Freightliner at the SwRI test track. These demonstrations are described in more detail in Section 5.4. Over the past decade, SwRI has performed in excess of \$40 million in research and development related to CAV technologies for commercial, military, and state and federal government clients. SwRI-developed CV applications such as curve speed warnings, emergency brake warnings, bridge over-height warnings, and wrong-way driver alerts, have been deployed in Florida, Michigan, New York, and Texas. SwRI also performs testing and certification of CV-related hardware, such as DSRC radios, and is heavily involved in national standardization efforts related to CV technology. SwRI has fielded fourteen fully autonomous vehicle platforms, performing hardware and software integration, and has developed a large variety of automated vehicle enabling technologies (multi-modal perception, sensor fusion, world modeling/situational awareness, absolute and relative localization, global and local motion planning, vehicle control) for commercial vehicle manufacturers and the U.S. Army, Navy, Marine Corps, as well as several European defense ministries. SwRI-developed autonomy software is platform agnostic and is configurable to work in both on-road and off-road scenarios. SwRI has commercialization rights of our perception, localization, and navigation autonomy software. Figure 5.1 depicts SwRI technologies and resources.



Figure 5.1 SwRI CAV Technologies and Resources

SwRI also has extensive experience participating in many standards groups as liaisons, voting members, and authors of standards documents. Our team understands both the depth and breadth of standards and has extensive hands-on experience applying standards in practice in pilot deployments as well as in operational traffic management systems.

5.2 Roadside and Vehicle DSRC Hardware and Applications

The USDOT CV program consists of both hardware and software applications and tools. The hardware is focused on the DSRC technology, although other communication technologies are under study, and these devices are installed either as statically mounted infrastructure devices, or as mobile devices installed in vehicles. CV application development has primarily been focused in one of three domains: safety, mobility, and environment. And the tools for development include the Systems Engineering Tool for Intelligent Transportation (SET-IT) tool for application development within the Connected Vehicle Reference Implementation Architecture (CVRIA) , and the Cost Overview for Planning Ideas and Logical Organization Tool (CO-PILOT) for estimating CV pilot deployment costs . The following sections describe in more detail the hardware, applications, and tools used in this work.

Roadside Unit (RSU)

SwRI has previously helped deploy RSUs along I-410 in San Antonio and implement applications which would send static signage to vehicles as well as detect over-height vehicles and warn them. This existing hardware was used in some of the demonstrations described below to show some of the potential remote aggregation capabilities of a system such as a district traffic management center and the increased volume and resolution of the CV data that will be available as OEMs begin deploying vehicles with this technology. Figure 5.2 (a) and b(b) provide examples of RSU devices and Figure 5.3 shows the installation locations.



Figure 5.2 Example of RSU (a)

Example of RSU (b)

Source: <http://cohdawireless.com/Products/Hardware.aspx>

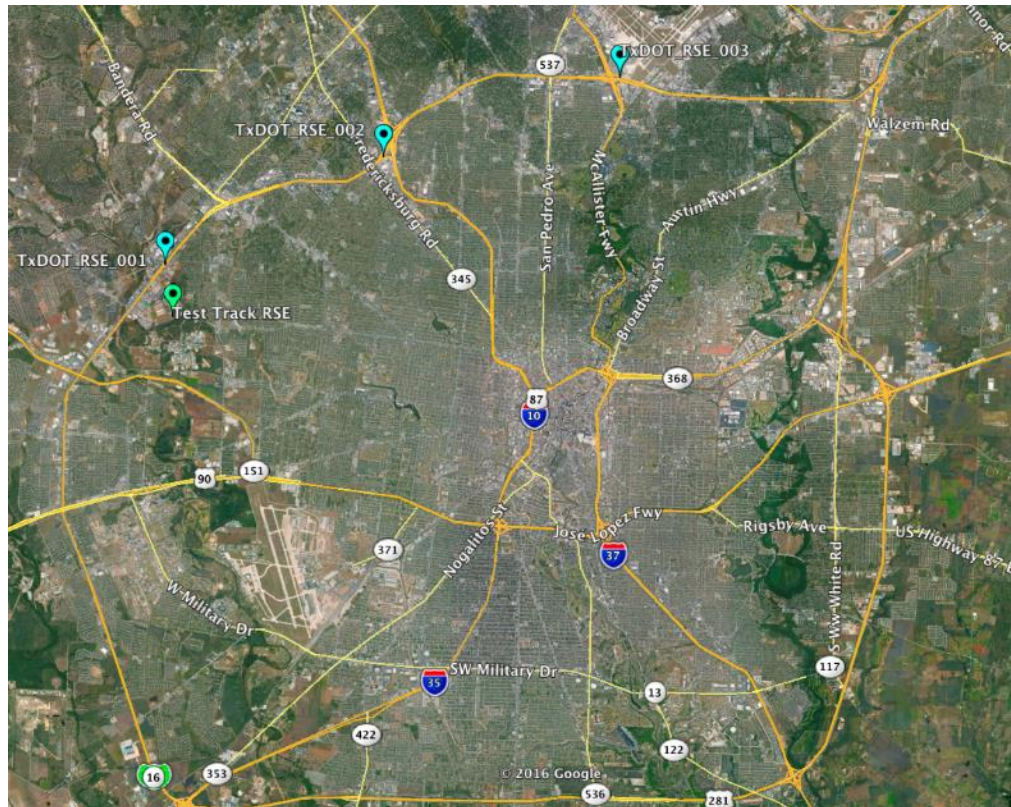


Figure 5.3 San Antonio RSU Installation Locations

Vehicle: Onboard Equipment (OBE)

The vehicle OBE provides the vehicle-based processing, storage, and communications functions necessary to support connected vehicle operations. The DSRC radio(s) supporting V2V and V2I communications are a key

component of the vehicle OBE. This communication platform is augmented with processing and data storage capability that supports the connected vehicle applications. Figure 5.4-Figure 5.6 demonstrate the architecture and equipment.

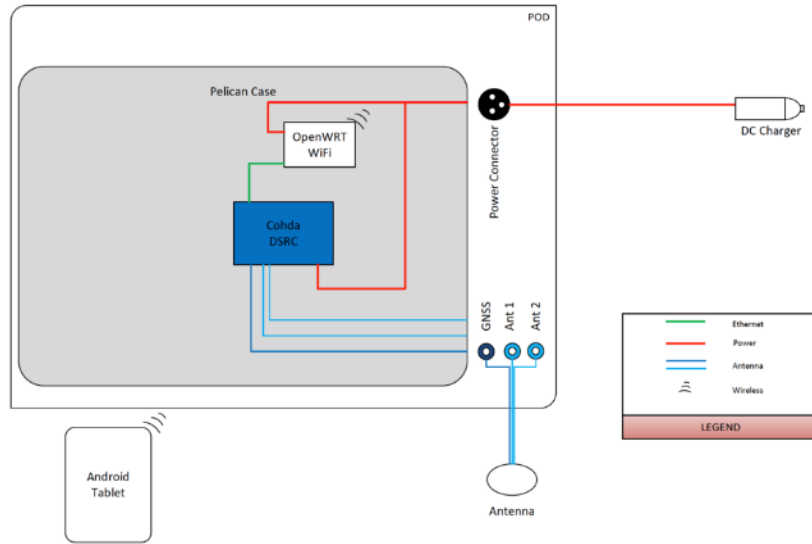


Figure 5.4 SwRI POD Architecture



Figure 5.5 SwRI PODS on Test Bench



Figure 5.6 SwRI Pod Internal

5.3 Connected Vehicle Applications

Emergency Vehicle Alert (EVA)

Emergency vehicles, like ambulances, police cars, fire trucks, and construction vehicles, broadcast out an EVA when they are activated. Connected vehicles receiving the EVA will analyze it to determine the emergency vehicle's direction of travel, distance, and speed, which in a real-world deployment would enable the driver, or an automated vehicle control system, to take an appropriate action, such as slow down, pull over, or continue with no change. This demonstration will display the EVA using a tablet interface inside a demonstration vehicle.

All five SwRI PODs can send and receive EVA messages. Each POD can be individually configured as an emergency vehicle for: Ambulance, Police, and Fire. The receiving POD determines from BSM the location, direction, and speed of the emergency vehicle. Figure 5.7 depicts an EVA demonstration.



Figure 5.7 EVA

Electronic Emergency Brake Lights (EEBL)

A connected vehicle will broadcast an “emergency braking” message to other vehicles when the system detects a deceleration greater than a defined threshold. This message is intended to warn other CVs that are located behind the vehicle, so they may take immediate action by reducing their speed. This application is intended to prevent the kind of sudden traffic compression, and subsequent crashes, seen in today’s non-CV traffic systems. Figure 5.8 provides an example of an EEBL message.

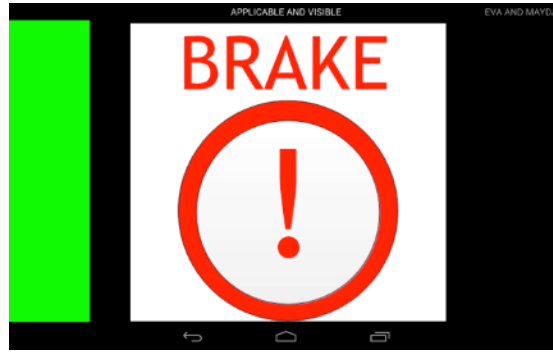


Figure 5.8 SwRI Tablet Display EEBL Message

Static Wrong-way Driving Detection

Connected vehicle systems have the ability to detect wrong-way drivers (WWD) using information reported by a vehicle’s BSM. One way to do this is for an RSU to check the reported heading of a vehicle against the previously-defined correct heading for traffic on a segment of road. SwRI can simulate a vehicle entering the wrong direction using our San Antonio test track, SwRI’s RSU, and vehicles equipped with PODs. The RSU receives the vehicle BSMs and compares the reported heading against the road segment’s correct heading, in a process often referred to as geo-fencing or geo-coding. The RSU can then broadcast a roadside service announcement specifically to the WWD vehicle, as well as other vehicles within communication range (Figure 5.9).

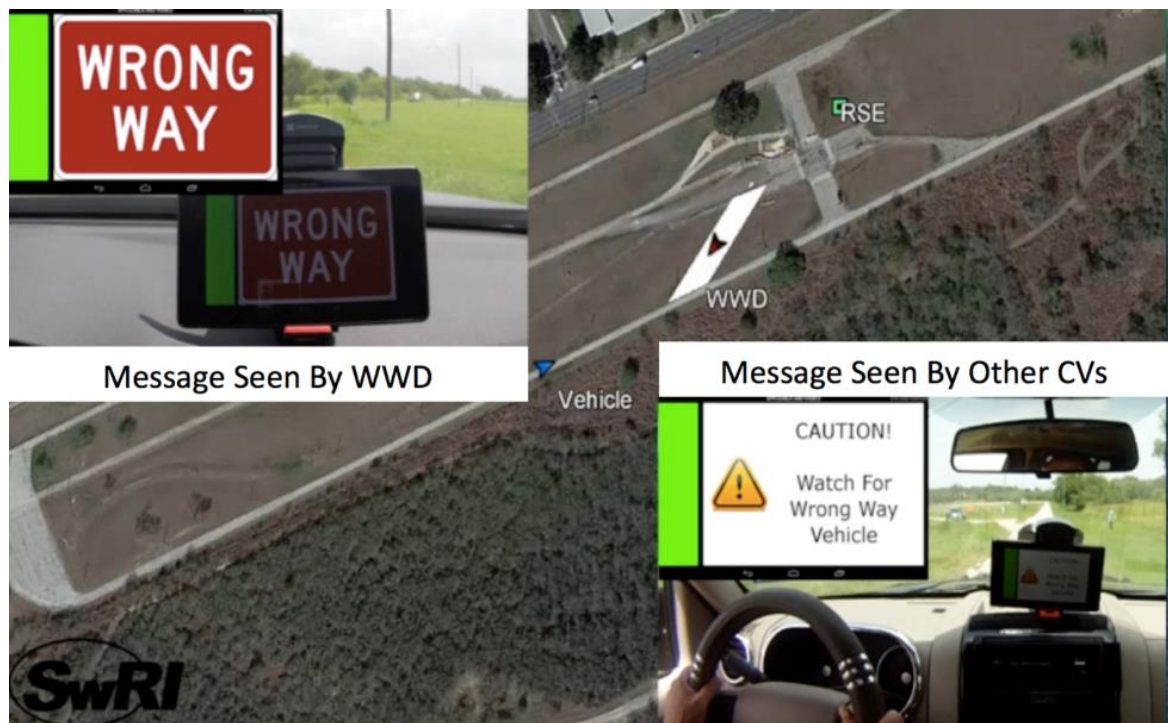


Figure 5.9 Connected Vehicle WWD Messages Sent by RSU

Newly Developed Applications

This CV application enables vehicles or infrastructure devices (such as RSUs) to pass along (propagate) messages they have received. This would be very useful, for example, in a scenario where RSU coverage is

sparse or otherwise unavailable and would enable CVs to continue to be informed of important events without RSU coverage. V2V message propagation is also viable for this application. Although this application is best demonstrated over large areas with many vehicles, we will demonstrate it by driving one CV into an area that is out of range of an RSU. We will then have one CV drive within range of the “hidden” CV, and this “middle” vehicle will relay (propagate) messages from the hidden CV to the RSU at the SwRI test track. Figure 5.10 maps the simulated CVs along I-410.



Figure 5.10 Simulated CVs along I-410 in San Antonio Showing Potential for Message Propagation between RSUs

Road Condition Monitoring (RCM)

According to current estimates, potholes cause approximately \$6.4 billion in damage annually, making timely detection and repair of degraded roadways a significant concern for citizens and governments alike. Current methods for detection of poor road conditions consist of manual surveying, which is limited by the available resources of a traffic management entity. While the prevalence of smartphones has increased the ability for individuals to report road condition issues, the use of CV communication protocols presents a unique opportunity to enable vehicles to identify regions of pavement that require immediate maintenance, and to observe trends in pavement conditions over time. The necessary technologies to accomplish this, such as accelerometers, GPS-based localization systems, and CV DSRC are becoming more widely available, enabling new applications to be developed to enhance the collective situational awareness of the vehicles themselves, and of the traffic system as a whole.

SwRI has developed a method for utilizing incoming accelerometer and GPS data to quantify road roughness, which can be scaled across various spatial windows that reflect different aspects of road health. For example, a smaller spatial window will detect shorter-term anomalies in road condition, such as might be caused by a pothole or piece of debris in the road, while a larger window will detect more general roughness on a segment of road, which may indicate road surface deterioration. Figure 5.11 shows RCM hardware evolution.

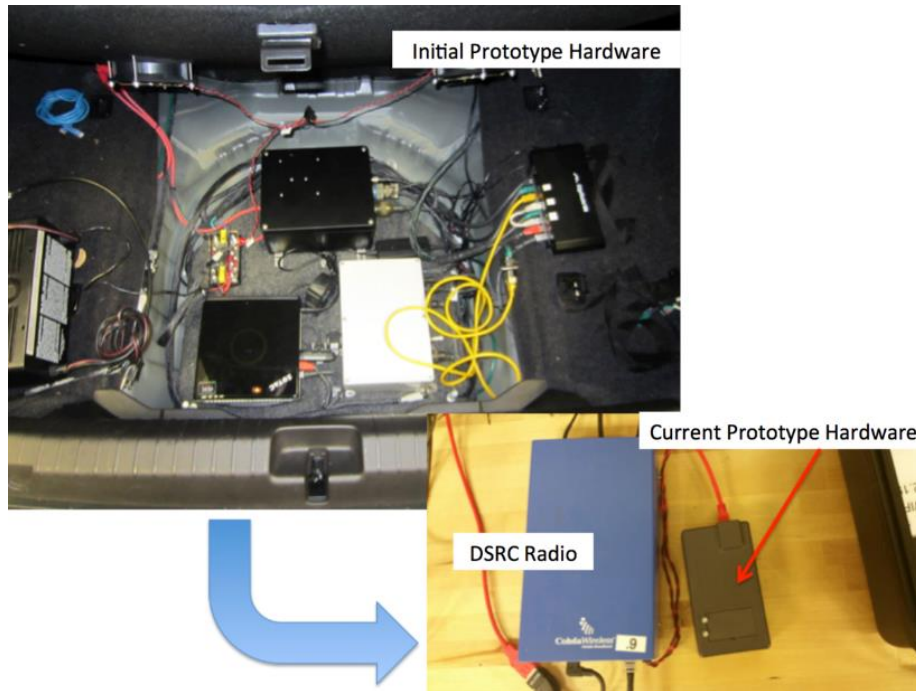


Figure 5.11 RCM Hardware Evolution

Because the response of an individual accelerometer will be affected by the specific dynamics of a vehicle, including tire and suspension response, the Dynamic Distributed Road Rating (DDRR) system is first trained using the accelerometer data from a specific vehicle installation. This training is performed by driving the vehicle through a variety of speeds on smooth roads to identify the system’s baseline response (as shown in Figure 5.13). Once completed, the vehicle is able to identify anomalous road pavement conditions, and communicate this data to other CV-equipped vehicles or to an RSU. This is reflected in the “vehicle” portion of Figure 5.12. Figure 5.13 provides a reading distribution from the system.

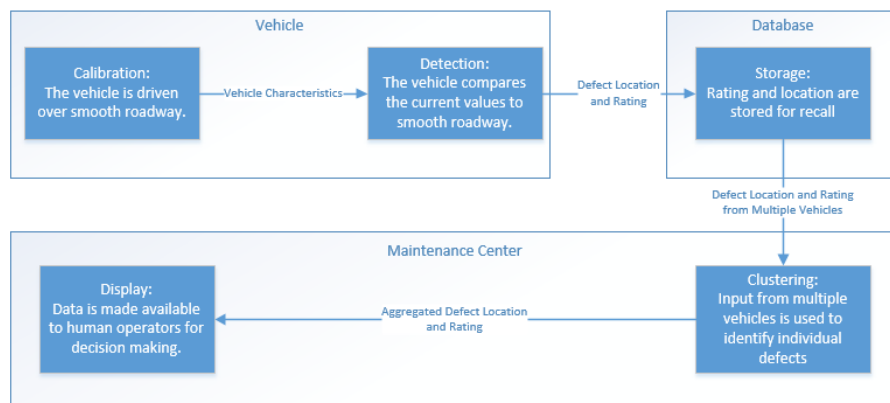


Figure 5.12 High-level Overview of the DDRR System.

Note: Blocks represent processing steps and arrows represent transmitted data.

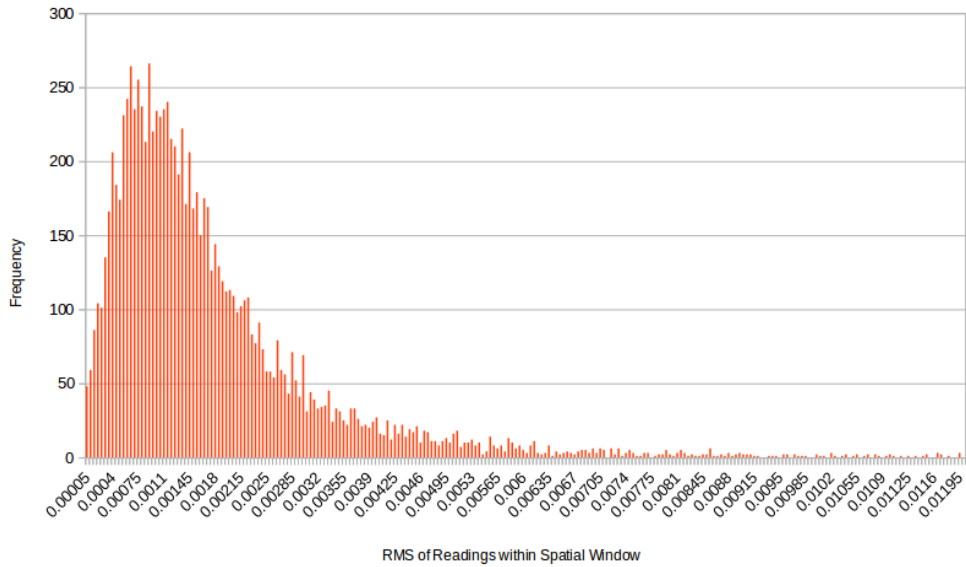


Figure 5.13 *The Distribution of Readings from the DDDR System.*

Note: This distribution can be analyzed using standard statistical methods to identify anomalous pavement conditions.

Data that have been received by another vehicle or an RSU can be utilized to illustrate the road conditions across a broader geographic area. The SwRI-developed method performs a clustering operation on collected road condition reports, which allows uniform display of roadway condition independent of traffic distribution. This clustered data can then be displayed using a tool such as an intensity-weighted heatmap, as shown in Figure 5.14, or with individual events called out, such as in Figure 5.15 (Storage, Clustering, and Display in Figure 5.12).

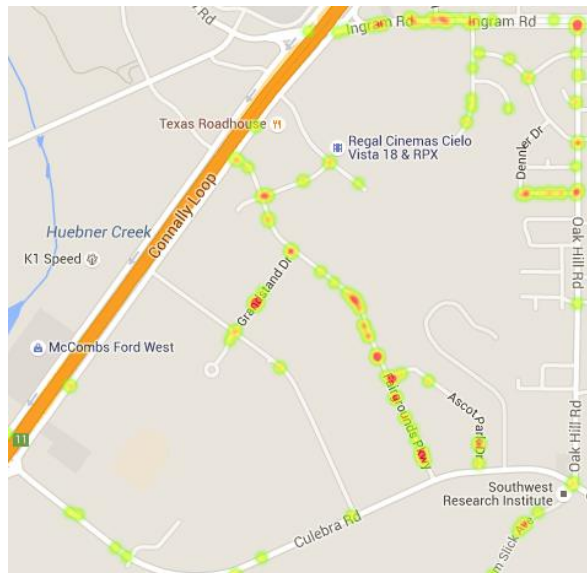


Figure 5.14 *Heatmap Display of Road Condition in San Antonio, TX*

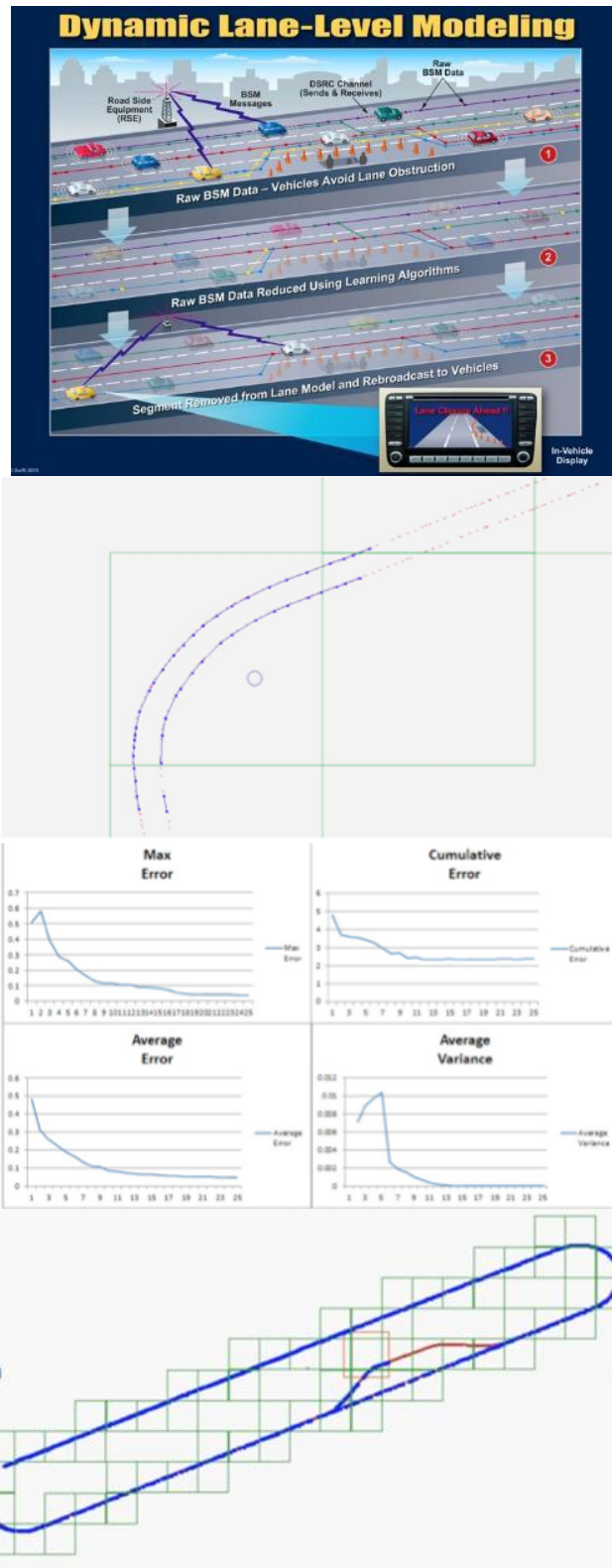


Figure 5.15 Showing Precise Location of Anomalous Events

Dynamic Wrong-way Driving Detection

Vehicles that are equipped with the SwRI-developed portable onboard device (POD) system, which will be transmitting basic safety messages (BSMs) at 10 Hz, to drive the correct direction on our test track and through our four-way signalized intersection. The RSU located at the SwRI test track will be running a SwRI-developed machine-learning algorithm, essentially listening to the BSMs and learning the location of lanes and their correct direction of travel (Figure 5.16). Once this learning is accomplished, any connected vehicle traveling the wrong way, will be identified as a WWD, and the WWD warnings, as previously demonstrated, will be initiated.

Figure 5.16 Dynamic Lane Learning



SwRI's R&D efforts on this program focused around the intelligent aggregation of basic vehicle state data such as GPS position, heading, and speed, passively collected by nearby infrastructure-based DSRC equipment using existing hardware solutions developed for CV deployments. This aggregated data was then processed using SwRI-developed learning algorithms and condensed into a set of sparse GPS waypoints that represents the lane-level roadway model. This set of waypoints can then be broadcast out by the RSU and received by DSRC-equipped vehicles for use in numerous safety and mobility applications. The lane-level model can also be rebroadcast by vehicles to other vehicles that are not within range of the RSU, or could be broadcast and received using cellular communications, thus greatly expanding the number of vehicles that can benefit from the map data.

As vehicles repeatedly pass over lane segments, the stationary RSU collects the vehicles' BSM data, which will vary slightly from vehicle to vehicle as individual drivers may pass over a given lane segment in different positions within the lane, and due to small variations in GPS accuracy. However, the more frequently vehicles pass over the same lane segment, the more data the learning algorithm has to analyze, and the faster it can converge on a steady-state model of the lane. This iterative process results in an increasingly accurate representation of the centerline of a lane segment, which can be updated dynamically simply through the altered behavior of drivers. The algorithms SwRI has developed can detect this altered behavior after a threshold of vehicles have traversed the same segment, and the lane model can be updated and rebroadcast quickly without centralized control of the process.

BSM data sets are evaluated as groups of line segments that correspond to "path history" points as defined in SAE J2735. SwRI began with an assumption that once a sufficient number of vehicles pass over a given lane segment that a normal distribution of GPS points within the lane width will begin to emerge. The learning algorithms begin by grouping line segments together and then calculate the perpendicular distance and angle of separation with all other line segments for a given segment of lane. After candidate groups have been identified, outlier segments are identified using Chauvenet's criterion, and removed, and the mean absolute error calculated. It is desirable to minimize this error, which is then assumed to be the center of the lane for that location. This does not necessarily mean the absolute center of the physical lane has been identified, just that the center path driven by a number of vehicles has reached convergence based on this method. This method, however, is susceptible to halting on local minima, and so a minimum group size is required before the process is allowed to halt.

Histograms are then calculated for each group to determine if and where significant peaks exist. Selected potential lane segments must be within one lane width of a root segment. When all lane segment groups have been evaluated, the roadmap will have been populated with high-likelihood lane-level.

5.4 Demonstrations

Winter 2017, J.J. Pickle Research Campus

In December 2015, the team organized a demonstration of the applications described above at the J.J. Pickle Research Campus in Austin, TX. A quarter-mile stretch of road was closed off to normal traffic on the campus's south side where the team conducted demonstrations to an audience of TxDOT staff and UT Austin faculty and staff, as shown in Figure 5.17. These demonstrations enabled the attendees to ride in connected vehicles during the demonstrations to view first-hand how various CV applications might be implemented.

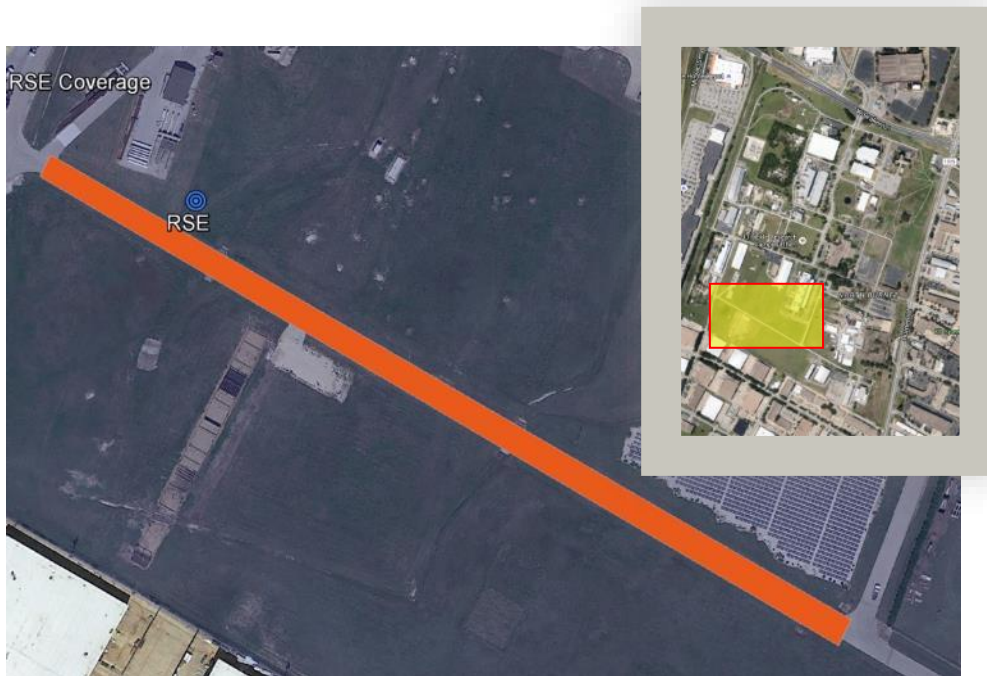


Figure 5.17 Winter Demonstration Venue Showing J.J. Pickle Research Campus (Inset), and Detail Location of Test Road and Temporary RSU

Attendees who were not riding in vehicles could view the demonstrations from a safe viewing area, labeled “Base” in Figure 5.18, and could see various DSRC hardware as well as a large TV screen that showed the real-time locations of the vehicles on a Google Earth map overlay.



Figure 5.18 Winter Demonstration Venue Showing Effective RSU Coverage Area, Viewing Area, and CV Vehicles During a Demonstration

Spring 2016, SwRI and San Antonio Roadways

In June 2016, the team organized a second set of demonstrations, this time in San Antonio, TX. These demonstrations enabled the team to highlight the installed base of RSU devices in San Antonio, with one located on SwRI’s campus and three installed along Interstate 410 between Culebra Road and US-281, as shown in Figure 5.19. Specifically, the road condition monitoring, message propagation, and dynamic WWD

detection and alert demonstrations were able to take advantage of these RSUs and demonstrate the power of these CV applications in a larger geographic area than was possible during the winter demonstration.

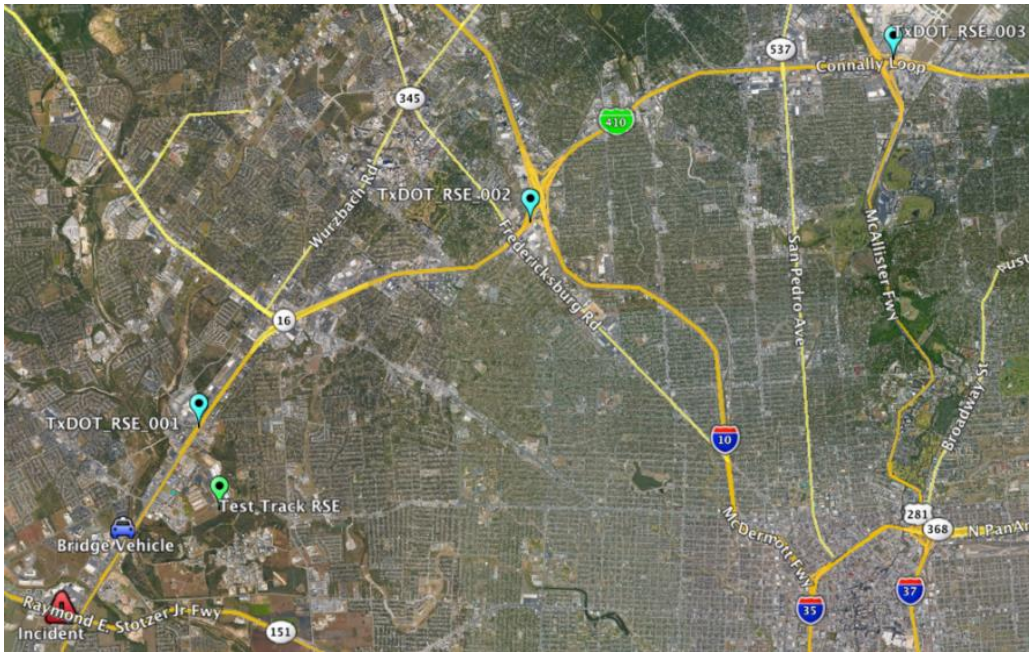


Figure 5.19 Spring Demonstration Venue Showing the Campus of SwRI and a Portion of Interstate 410 Instrumented with RSUs

On SwRI’s Test Track: Dynamic WWD Detection and Alert with AV Safe Stop

SwRI demonstrated a new method for implementing WWD Detection utilizing machine learning algorithms and how an automated vehicle can be safely stopped before becoming a hazard to right-way drivers. To accomplish this, SwRI used two vehicles that are equipped with the SwRI-developed portable onboard device (POD) system, which transmitted BSMs at 10hz, to drive the correct direction on the test track and through our four-way signalized intersection, as shown in Figure 5.20 and Figure 5.21. The RSU located at the SwRI test track ran a SwRI-developed machine-learning algorithm, essentially listening to the BSMs and learning the location of lanes and their correct direction of travel. Once this learning is accomplished, any connected vehicle traveling the wrong way was identified as a WWD, and the WWD warnings, as previously demonstrated, was initiated. In this instance, SwRI utilized a fully autonomous Class VIII Freightliner as the WWD vehicle, and upon receiving the WWD alert from the RSU, the vehicle came to a controlled (safe) stop, prior to entering the main lanes of right-way driver traffic.

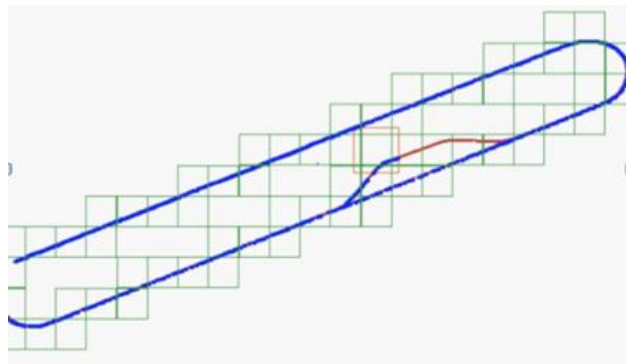


Figure 5.20 Dynamic Lane Learning at SwRI's Test Track

SwRI was also able to showcase one of its fully autonomous vehicles, a Class VIII Freightliner (shown in Figure 5.22, during the dynamic WWD demonstration. The Freightliner was sent along a route as a WWD, and once the local RSU detected this and warned the vehicle of its WWD status, the vehicle was autonomously brought to a controlled (safe) stop before it could enter the primary route for “right-way” drivers.

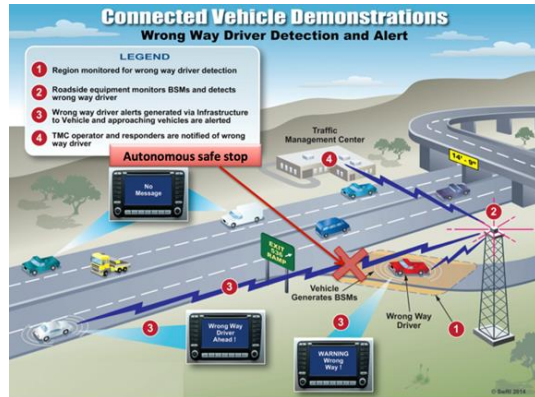


Figure 5.21 SwRI's Autonomous Freightliner Stops Once Identified as a WWD

Figure 5.22 SwRI Autonomous Freightliner

This simulates an autonomy-capable vehicle approaching a highway the wrong direction on an exit ramp, either in an autonomous driving mode or under human control, and upon notification by the RSU, which sends out a trusted and verified message, the vehicle will slow and stop prior to entering the main lanes of the highway. Additionally, at the SwRI test track, a large TV screen displayed a Google Earth map showing semi-live updates on from mobile (off-campus) demonstrations, including Road Condition Monitoring and Message Propagation. This display gave attendees a sense of the type of data that could be available to a transportation agency such as TxDOT, with even sparse deployment of CVs and RSUs.

On and Around Loop 410 in San Antonio

SwRI utilized the installed base of RSUs in San Antonio to demonstrate road condition monitoring and message propagation. The Road Condition Monitoring demonstration was conducted using a team of vehicles, which took participants onto San Antonio streets and I-410. In the vehicle, an Android tablet displayed the real-time data “rough roads” and “pot holes.” Roughness events that exceed a threshold were cached onboard until the vehicle comes within range of an RSU, at which time the data was sent to the RSU and forwarded on to SwRI computers at the test track and displayed as a heat map of locations and severity, as show in Figure 5.23. This data could be shared with other vehicles to warn or advise of rough roads and would be very valuable to a transportation agency for real-time maintenance awareness.



Figure 5.23 Road Condition Monitoring Tablet and Heat Map Displays

Message Propagation: This CV application enables vehicles or RSUs to pass along (propagate) messages they have received. This would be very useful, for example, in a scenario where RSU coverage is sparse or otherwise unavailable and would enable CVs to continue to be informed of important events without RSU coverage. This application is best demonstrated over large areas with many vehicles; however, SwRI demonstrated it by driving one CV into an area that is out of range of the SwRI RSU, with a second CV positioned within range of the first (hidden) CV. This second (bridge) vehicle relayed (propagate) messages from the hidden CV to the RSU at the SwRI test track, and its message was displayed on the TV over a Google Earth map overlay, along with message propagation meta-data such as the number of hops taken, in this case just one, and the time it took to propagate from source to destination, as shown in Figure 5.24.

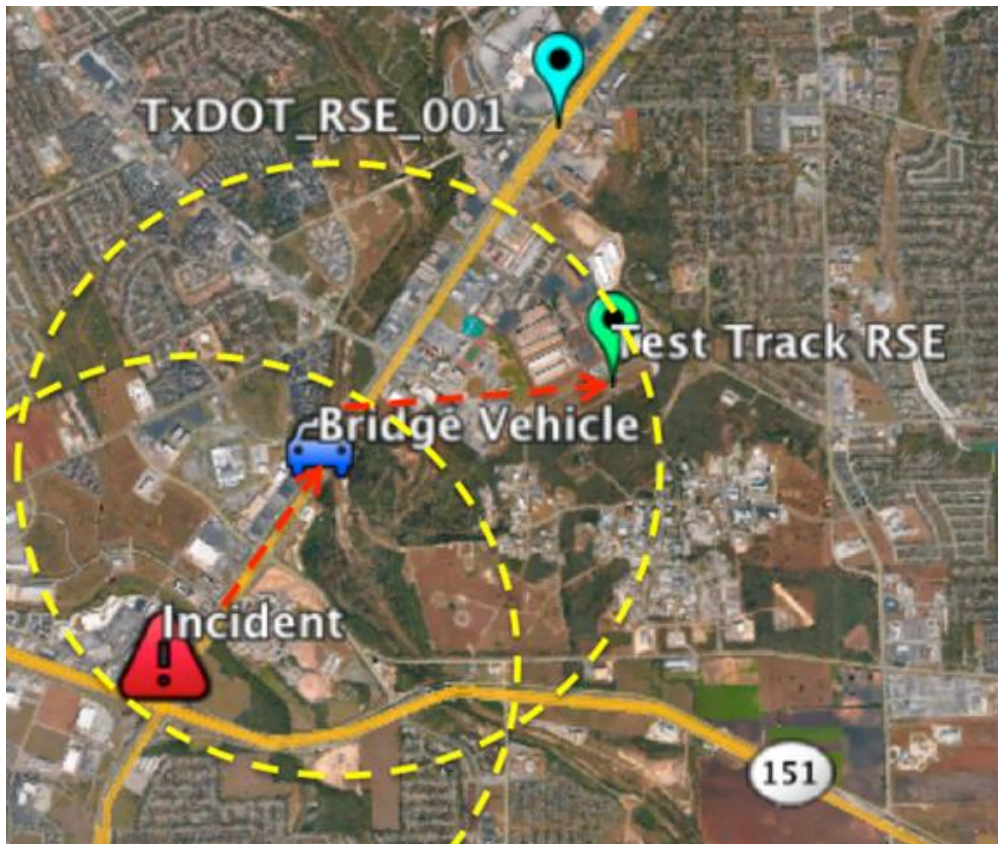


Figure 5.24 Message Propagation Demonstration Configuration

CHAPTER 6 TECHNOLOGY IMPLEMENTATION: GENERATING AND INTEGRATING INERTIAL MEASUREMENT DATA WITH FLOW MODELS FOR TRAFFIC MONITORING

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6.1 Introduction

Transportation research is currently at a tipping point: the emergence of new transformative technologies and systems, such as vehicle connectivity, automation, shared-mobility, and advanced sensing is rapidly changing the individual mobility and accessibility. This will fundamentally transform how transportation planning and operations should be conducted to enable smart and connected communities. The transportation systems can be substantially improved, and become safer, more efficient and reliable, thanks to the emergence of connected and autonomous vehicle technology. Dynamic routing and traffic-dependent navigation services are already available for users. Such applications need to estimate the present traffic situation and that of the near future at a forecasting horizon based on measurement data available in real-time, possibly supplemented with past data on traffic patterns. Using this measurement data and prior information, one can estimate the state of traffic on a road network, which consists in estimating all the traffic variables (e.g., cars density, speed), everywhere in the network, at the current time. This estimation requires the fusion of traffic data and traffic models, which are typically formulated as partial differential equations (PDEs).

In this chapter, we identify two possible improvements to the problem of traffic state estimation (that is, creating traffic maps and forecasts from traffic measurement data) that directly result from the presence of connected autonomous vehicles (CAVs). These improvements can be summarized as follows:

- Using vehicle connectivity to generate traffic measurement data automatically, relying on the currently available traffic monitoring infrastructure. In the present case, our objective is to investigate the use of Inertial Measurement Units (IMUs), which can act as position sensors, while preserving user privacy. These IMUs can send traffic measurement data over Bluetooth to currently available Bluetooth traffic readers.
- Since these IMU sensors generate trajectory estimates, which typically differ from the measurement data generated by both GPS sensors and fixed traffic sensors, our objective is to design a computational scheme that can integrate the trajectory estimates generated by the IMU sensors into traffic flow model, to generate traffic maps.

6.2 Background

Most car navigation systems estimate the car position using satellite-based positioning systems, such as the Global Positioning System (GPS) (Figure 6.1). Other satellite-based systems are available, such as the Global Navigation Satellite (GLONASS) system, or the upcoming Galileo System, though such systems are not currently offering worldwide coverage.

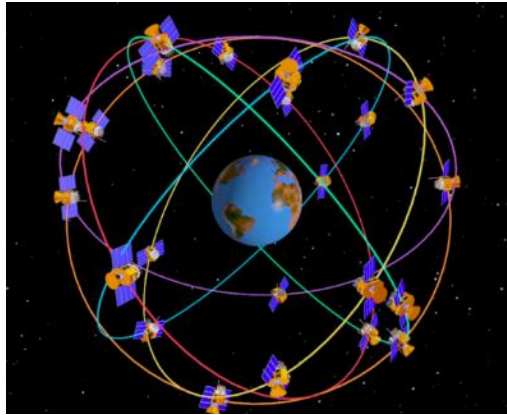


Figure 6.1 Illustration of a Constellation of GPS Satellites Orbiting the Earth

GPS positioning systems operate as follows: a set of satellites transmit pulses at regular time intervals, which can be received by a GPS receiver. If four satellites signals are simultaneously received by the user, the user can determine its position and time by solving a system of four equations with four unknowns, where the equations correspond to the times required for the signals of the satellites to reach the GPS receiver, and the unknowns correspond to the position on Earth (longitude, latitude and altitude), as well as the current time.

GPS satellites operate on two communication channels (L1 and L2), operating at a very high frequency, on the order of 1GHz. The L1 channel carries the Navigation Message, which is transmitted at a very slow rate of 50 bits per second (bps, or Baud). It is a 1500-bit sequence, and therefore takes 30 seconds to transmit. This Navigation Message includes information on the Broadcast Ephemeris (satellite orbital parameters), satellite clock corrections, almanac data (a crude ephemeris for all satellites), Ionosphere information (which is used to correct the delays received by the receiver in function of the state of the Ionosphere, an atmospheric layer located between 60km and 1000km altitude), and satellite health status.

While GPS systems are relatively inexpensive and accurate (up to tens of meters in usual conditions), they have several drawbacks for traffic sensing applications:

- The positioning information is affected by random noise, particularly in urban environments. This random noise is caused by the unwanted reflections of the satellite signals on buildings, which affect the accuracy at which one can precisely time when the signal of each satellite was received, and therefore causes positional errors (canyon effect). In urban environments, these errors can be on the order of tens of meters, which can cause for example a vehicle equipped with a GPS to appear to be driving on another street. This can result in a loss of precision for traffic purposes: while the mapping of the vehicle to the road network is usually correct, it may be that the fluctuations in the estimated position (from the GPS measurements) cause high uncertainty in travel time estimates between two consecutive intersections. Similarly, when monitoring traffic in urban environments, the GPS uncertainty prevents one from accurately distinguishing vehicles stopped in traffic, or parked vehicles (such as vehicles waiting for a passenger). Higher resolution GPS systems are available; for example, Real-Time Kinematics (RTK) GPSs use measurements of the phase of the GPS signals emitted by satellites to pinpoint the position of a receiver with greater accuracy. As of 2016, however, these devices cost hundreds of dollars, and require minutes to tens of minutes to properly lock on GPS satellites.
- While the generation of absolute position data (longitude, latitude, and altitude) is desirable from a positioning standpoint, it inherently affects the privacy of the user when part of a traffic monitoring system. Indeed, classical traffic monitoring architectures (such as the architecture used in the Mobile Millennium experiment at UC Berkeley) for GPS-based traffic sensing rely on GPS position

measurements sent by users to a given centralized server, as illustrated in Figure 6.2. As can be seen from this figure, the traffic data generated by vehicles (in the form of velocity and position measurements) is first sent to a third-party server (over the cellular network), which attempts to anonymize the data (for example by stripping the phone number associated with the GPS position information), and subsequently transmits this data to computer servers that perform the traffic state estimation (using possibly other traffic feeds, such as from fixed traffic sensors or other sources of traffic information). The major issue associated with this architecture is that the third party has access to all information about the user, and therefore has to be trusted.

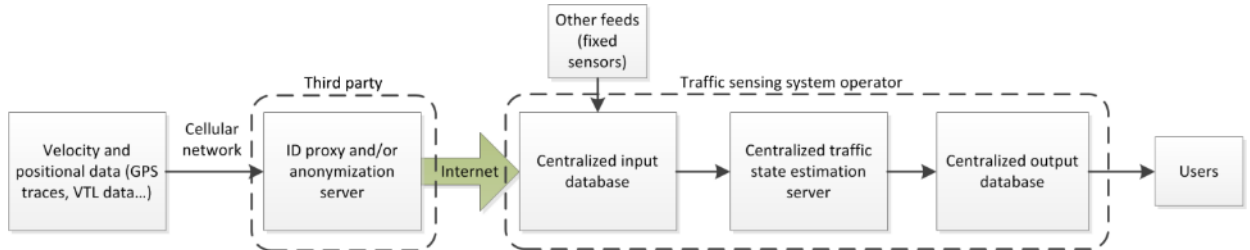


Figure 6.2 Architecture of Classical Traffic Monitoring Systems (Probe-Vehicle Based).

Note: In this system, traffic measurement data is sent to an anonymization server, which holds sensitive information.

Figure 6.3 outlines a different type of traffic monitoring architecture based on a short-range wireless radio network. In this architecture, the data generated by vehicles is processed in a distributed manner by the fixed radio nodes themselves.

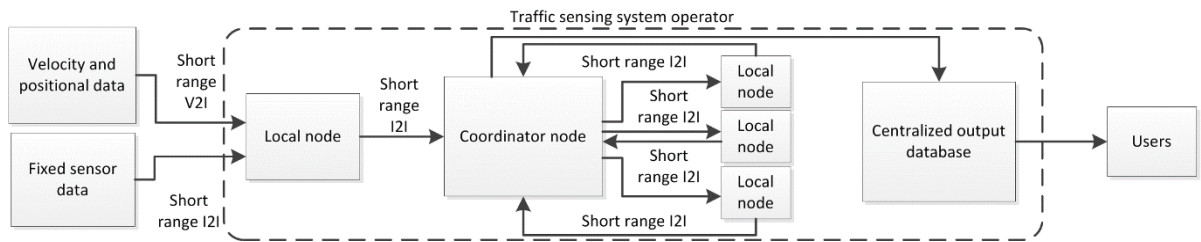


Figure 6.3 Architecture of a Distributed Probe-Based Traffic Flow Monitoring System, which Guarantees User Privacy.

Note: Unlike current systems, the measurement data is not centralized, and local nodes only have access to local measurements.

The advantage of such a system is that privacy is guaranteed by design, since only a distributed attack on the radio nodes would allow an adversary to gain information on the location of users.

Bluetooth or WiFi readers are widely used across the United States and the world to generate traffic measurements. They operate as follows: a vehicle carrying a Bluetooth or WiFi enabled device (for example, a Bluetooth-enabled cellphone, or a WiFi-enabled tablet) drives between two different readers. Each reader captures the MAC (Medium Access Control) of the device by performing a scan. The MAC is unique to each device; therefore, the operator of the sensing infrastructure can match the MAC addresses collected by the readers and determine the travel time required to go between one reader to the other.

The main issue associated with Bluetooth or WiFi readers is their inherent tradeoffs. The devices cannot be installed too far apart from each other, as the probability of matching vehicles decreases when the distance between readers increases (since vehicles are less and less likely to take the route between the two readers). A notable exception is highways, since most users can only take one route between two readers. Similarly,

Bluetooth or WiFi readers cannot be installed too closely to each other, as this would result in added uncertainty, due to the detection range of the Bluetooth or WiFi signals, in the order of tens of meters. Thus, the proposed IMU system can interface directly with Bluetooth readers, providing an additional and complementary data feed to this system

6.3 IMU-based Traffic Flow Monitoring

Inertial Measurement Units

An Inertial Measurement Unit, or IMU, consists of the combination of an accelerometer, a gyrometer (or gyroscope), and possibly a magnetometer, in a single device. IMUs are commonly used in aerospace engineering to estimate the position of aircrafts or spacecrafts by monitoring the accelerations and rotations of the vehicle in which the IMU is located. IMUs are also used in connected and autonomous vehicles to monitor their acceleration and attitude with respect to the ground.

The accelerometer of an IMU measures the proper acceleration, which is the acceleration of an object with respect to a free-falling frame. The proper acceleration (sometimes referred to as g-force) is different from the actual acceleration of the object (sometimes called coordinate accelerations). In this work, we are not interested in matching the accelerations to causes (external forces), since we only want to reconstruct vehicle trajectories.

The gyrometer (or gyroscope) of an IMU measures the rate of rotation of an object with respect to an inertial frame. Newtonian mechanics postulate that all inertial frames are in uniform translation with respect to each other, and therefore have no rotation motion with respect to one another. Such frames are approximated by frames that use reference points that are very far away from us (for example stars or galaxies). The gyroscopes measure the rate of rotation of an object with respect to these frames, by measuring the Coriolis pseudoforce caused by the rotation on a test object.

The magnetometer is a device that monitors the direction and amplitude of the local magnetic field and can therefore be used as a directional reference by tracking the direction of the magnetic North. Given that vehicles are built with high amounts of steel, which is ferromagnetic (and thus strongly perturbs magnetic field lines), the measurements of the magnetometer are in practice too unreliable to be used as a directional reference.

Fabrication of a Bluetooth IMU Device

To facilitate the integration of the IMU with a vehicle, we chose to build our own IMU system using hardware components, integrated in a printed circuit board (PCB). The objective was initially to use the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 RF protocol to transmit position data to a given wireless sensor network, and as a result, the system has a slot for an 802.15.4 XBee transceiver. An early prototype of the system is shown in Figure 6.4

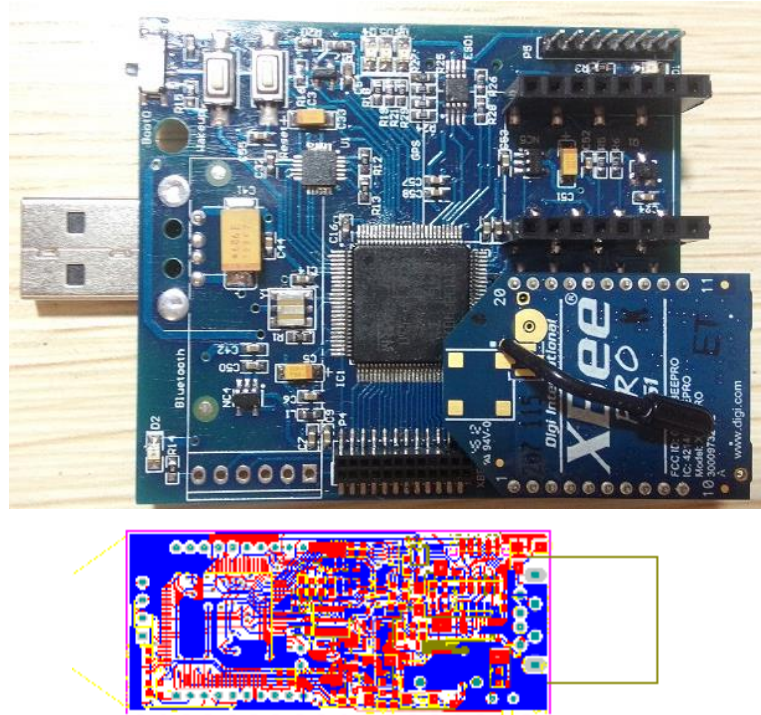


Figure 6.4 Top: Early IMU Prototype. Bottom: Second Iteration of the PCB Layout

The early prototype shown in Figure 6.4 is built around an ARM Cortex M4 processor, handling an IMU connected to the processor using the inter-integrated circuit (I2C) protocol, a type of digital communication protocol. A Bluetooth module (located under the system) is connected to the processor using serial communication, which is another form of digital communication. The USB port is used to supply regulated current to the system, and as a way to rigidly attach the IMU to the vehicle. The final version (shown in the bottom of Figure 6.4) is slightly larger to accommodate the GPS antenna and SD card slot. The final iteration of the IMU prototype is shown in Figure 6.5. This figure also shows the different peripherals connected to the main processor.

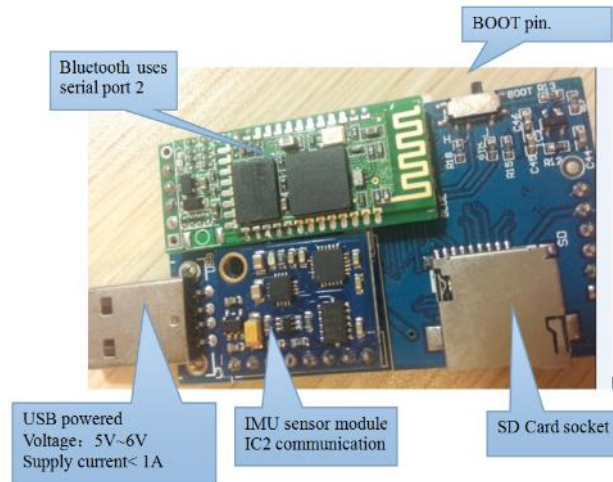


Figure 6.5 Bluetooth, IMU, and SD Card Peripherals of the Developed Sensor

To validate the performance of the sensor in trajectory reconstruction, we also included a GPS system (which is only used for validation). The GPS has its own antenna, and also communicates to the main processor using serial communication. It is shown in Figure 6.6.

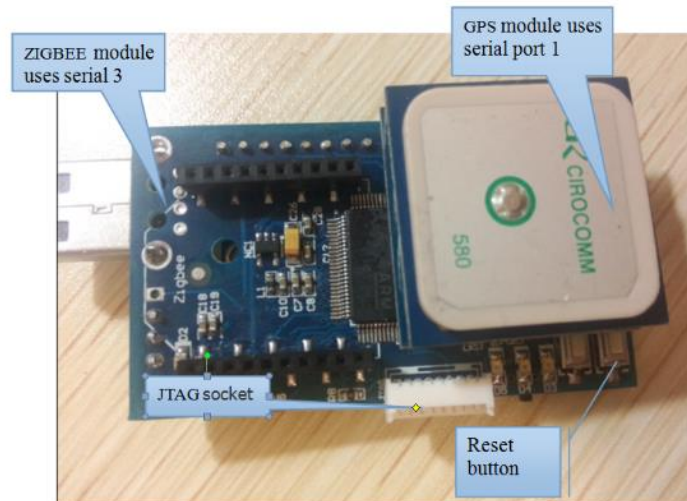


Figure 6.6 GPS and JTAG Programming Interface of the Sensor

To program this sensor, we use a Joint Test Action Group, an electronics industry association formed in 1985 for developing a method of verifying designs and testing printed circuit boards, (JTAG) interface. JTAG interfaces are commonly used for developing printed circuit boards and have standard connectors for programming the device. The JTAG interface and JLink programmer used to upload the code to the memory of the microcontroller is shown in Figure 6.7

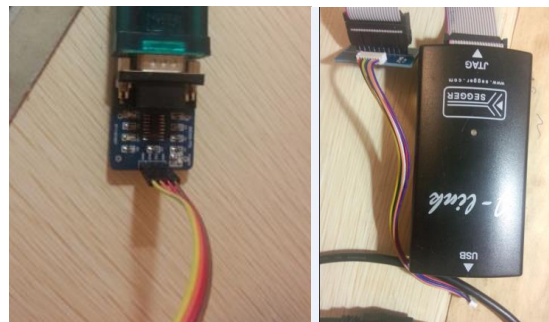


Figure 6.7 JTAG Programming System. Left: RS232 Interface. Right: JLink Programmer.

Validation of the Different Components

The second set of activities consists of developing software to interface with the sensor and communicate with its different subsystems (for example, Bluetooth, GPS, and IMU). This requires the development of software libraries. These libraries allow the microcontroller to establish a connection with its peripherals, retrieve the data they generate (for the GPS and IMU), configure their performance characteristics (for example, the rate at which they send measurement data or their scales), and output this data (such as by sending them to a Bluetooth-enabled device, or by storing them in a micro SD card).

Since embedded systems have an emphasis on performance and low cost (with respect to other consumer electronics), they tend to be unreliable, which requires an intensive debugging process.

The different components have subsequently been tested by installing the device in a vehicle, connecting it either to a free USB port, or to a USB car charger. An example of installation is shown in Figure 6.8.



Figure 6.8 IMU Device Installed in a Vehicle, with Power Supplied through a USB Car Charger

The Bluetooth connectivity was subsequently tested by installing a Bluetooth terminal application (in the present case the BT Simple Terminal app developed for Android) on a smartphone (Samsung Galaxy Mega 2) and paired with the device. The default pairing code chosen (1234) is static for simplicity, although more sophisticated and secure pairing schemes could be created.

The inertial measurement data consists in a vector with six components:

$$a = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix},$$

which correspond to the vector of proper acceleration measured in the set of coordinates defined by the IMU sensor, and

$$g = \begin{bmatrix} g_x \\ g_y \\ g_z \end{bmatrix},$$

which correspond to the rotation vector, measured in the set of coordinates defined by the IMU sensor.

Note that the rate at which data is generated by the sensor is a function of the dynamics that we want to track. For land vehicles, the spectrum of the accelerations and rotation rates contains frequencies that are relatively low, on the order of a few Hz. Therefore, we choose a sampling rate of 10Hz, which is sufficiently high to cover all significant frequency components of the signal (by Shannon's sampling theorem). The sampling rate should also be as low as possible, since the random noise affecting the signal increases with higher sampling rates. Figure 6.9 illustrates the reception of data on a smartphone over Bluetooth.

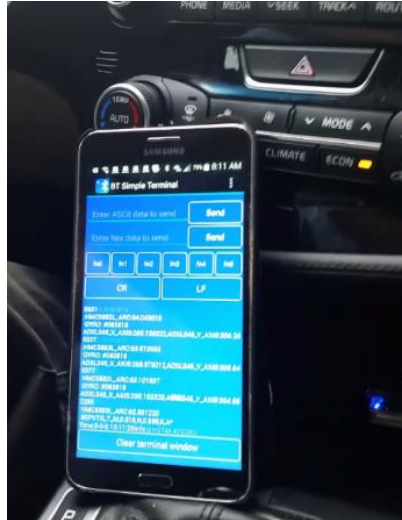


Figure 6.9 Illustration of Inertial Data Reception on a Bluetooth-enabled Smartphone

Inertial Data Validation

We conducted some tests to validate the performance of the IMU component of the system, by performing a few checks:

- The norm of the acceleration vector $a = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}$ should be close to the value of g (acceleration of gravity at the surface of the Earth)
- We align each of the three axes of the IMU in the direction of the vertical to check that each of the axes has a correct acceleration measurement. The variability of the acceleration measurement between axes is caused by factory calibration and accelerometer bias
- The norm of the acceleration vector is shown in Figure 6.10. As this figure illustrates, the norm is very close to the acceleration of gravity g (about 980 cm/s^2), and within the 2% error specified in the IMU parameters. The x-axis corresponds to the time sample, over an experiment time of 75 seconds (with 10 measurements per second).

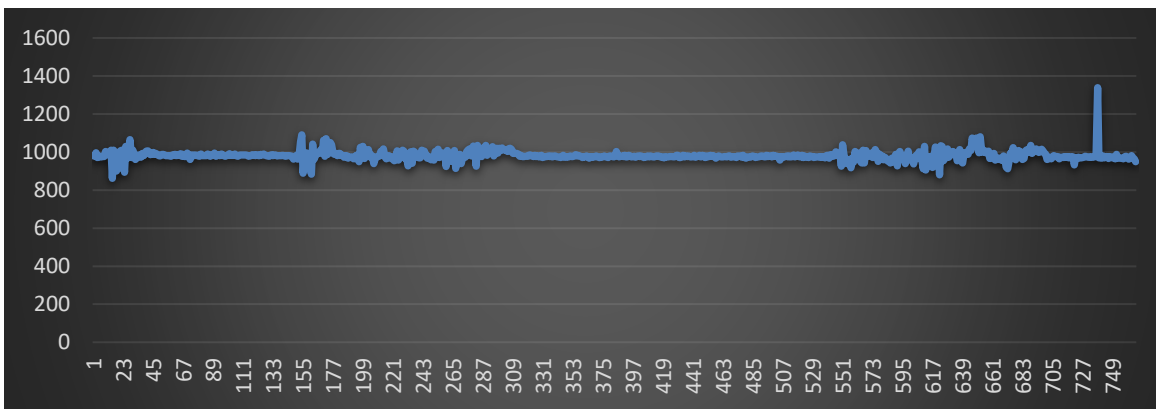


Figure 6.10 Norm of the Acceleration Vector (Units: cm/s^2)

As this figure demonstrates, the proper acceleration is always very close to 1000 cm/s^2 , which corresponds to the acceleration of gravity on Earth.

Figure 6.11 and Figure 6.12 show examples of raw acceleration and rotation rate measurement data, obtained from the accelerometer and gyrometer.

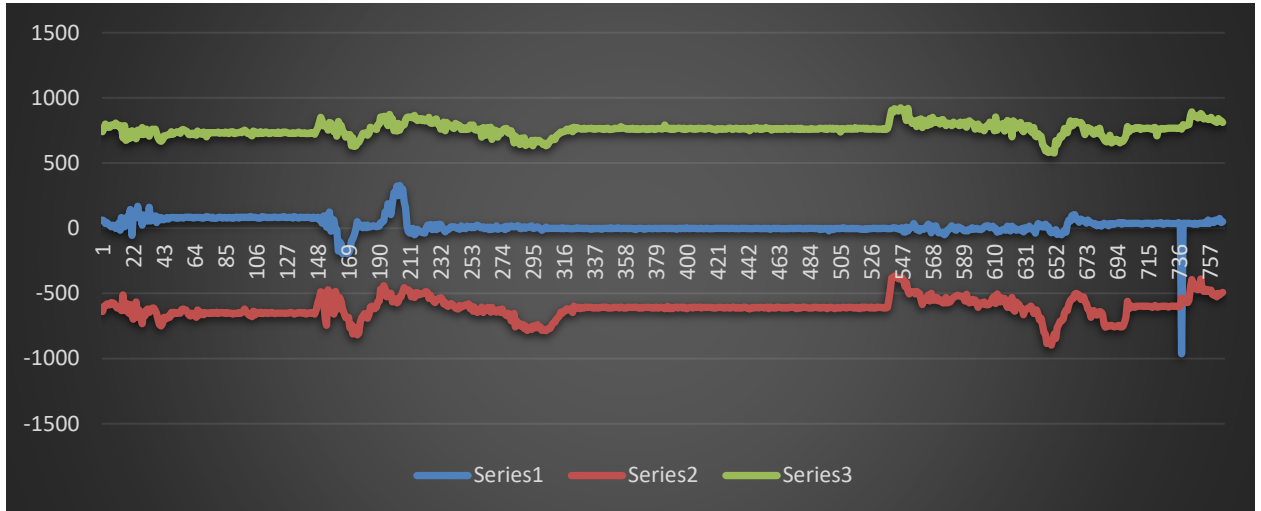


Figure 6.11 Acceleration (Unit:m/s²) along the Three Axes of the Accelerometer during a Car Trip.

Since the axes of the accelerometer were not perfectly aligned with the natural axes of the vehicles (longitudinal, lateral and vertical), the signal is difficult to interpret.



Figure 6.12 Rotation Rate Measurement Data (Units: cdeg/s)

GPS Free Auto Calibration of IMU Onboard Vehicles

In Figure 6.11 and Figure 6.12, the IMU is not aligned with the coordinate axes of the vehicles, which are defined as follows:

- Longitudinal axis: x-axis
- Lateral axis: y-axis
- Vertical axis: z-axis

The axes of the IMU are not necessarily aligned with the aforementioned axes. The relationship between the coordinates of the acceleration and rotation rate vectors in the vehicle axes and in the IMU axes is encoded by a rotation matrix R :

$$\begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} = R \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix},$$

where A corresponds to the coordinates of the acceleration vector in the vehicle frame, and a corresponds to the coordinates of the acceleration vector in the IMU frame. This misalignment is one of the main issues of retrofitting an IMU to a vehicle. Unlike a GPS, an IMU requires calibration, which makes the retrofit too complex. We thus investigated a way to perform this calibration automatically.

Procedure: Let $R_{g \rightarrow c}(\mathbf{t})$, $R_{g \rightarrow s}(\mathbf{t})$, and $R_{s \rightarrow c}(\mathbf{t})$ be the rotation matrices transforming respectively the vehicle coordinates into the ground coordinates, the IMU sensor coordinates into the ground coordinates, and the IMU sensor coordinates into the vehicle coordinates. Our objective is to determine $R_{s \rightarrow c}$, which is assumed here to be constant ($R_{s \rightarrow c}$ is only representing the coordinate change between the IMU and the vehicle, and unless the IMU is rotated with respect to the vehicle, this transformation remains constant). Since we do not have GPS or magnetometer data, $R_{g \rightarrow s}$ (which corresponds to the mapping between the IMU coordinates and the ground coordinates) cannot be determined univocally, though this does not affect the self-calibration principle.

Using the above definitions, we have that $R_{s \rightarrow c}(t) \times R_{g \rightarrow s}(t) = R_{g \rightarrow c}(t)$ (by the composition of rotations). We assume that the pitch and roll attitude of the vehicle with respect to the ground is most of the time zero, given that most of the time, the vehicle lies flat on the surface of the Earth; that is, the vehicle does not have any roll angle (or tilt with respect to its longitudinal axis) or pitch angle (with respect to its lateral axis).

With this assumption, we have that $R_{s \rightarrow c}(t)$ is (on average) a rotation matrix of a pure yaw, of the form:

$$\begin{bmatrix} \cos(\alpha) & -\sin(\alpha) & 0 \\ \sin(\alpha) & \cos(\alpha) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Determining $R_{g \rightarrow c}(t)$ (up to a rotation with respect to the z axis of the Earth frame) can be done by fusing (combining) the accelerometer and gyrometer data, using a complementary filter or a Kalman filter. Note that since no heading measurement is assumed to be available, this rotation matrix will be known up to a rotation around the vertical direction (the z -axis of the Earth frame). While the IMU contains a magnetometer, which could be used to obtain the heading of the vehicle, the presence of metal in a car greatly affects the accuracy of the readings of this device, and we chose to ignore its measurement data for the present application. Therefore, the two above equations do not allow us to determine the attitude of the device with respect to the vehicle $R_{s \rightarrow c}(t)$ uniquely. To determine $R_{s \rightarrow c}$ uniquely, we can leverage the residuals of the acceleration measurements. Indeed, the proper acceleration of the vehicle will be (in the frame of the vehicle, neglecting the Coriolis acceleration due to the rotation of the vehicle around its z -axis¹):

$$\begin{bmatrix} a_x = \frac{dv}{dt} \\ a_y = v g_z \\ a_z = g \end{bmatrix} = R_{s \rightarrow c} \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}$$

where a_x , a_y , a_z , a_x , a_y , a_z , and g_z respectively denote the acceleration components in the vehicle coordinates, the acceleration components in the sensor coordinates, the velocity of the vehicle in the Earth frame, and the rotation rate of the vehicle along the z axis in the vehicle coordinates.

¹ The Coriolis acceleration is on the order of $v \cdot \omega$, where ω is the yaw rate of the vehicle and v is the speed of the vehicle (in the Earth frame). For usual vehicles speeds and yaw rates, the effect of the Coriolis acceleration is negligible.

Since the gyro measures the rate of rotation, we use the following approach: if the rate of rotation is approximately zero², the second term in the above equation is approximately zero, which gives us an additional measurement constraint, enabling us to compute the rotation matrix $R_{\frac{c}{c}}$.

We validated the performance of this algorithm in reconstructing the correct value of $R_{\frac{c}{c}}$ by computing the acceleration in the Earth Frame. The results are shown in Figure 6.13. As this figure demonstrates, the algorithm correctly converges to a state in which both a_x and a_y are zero, as expected.

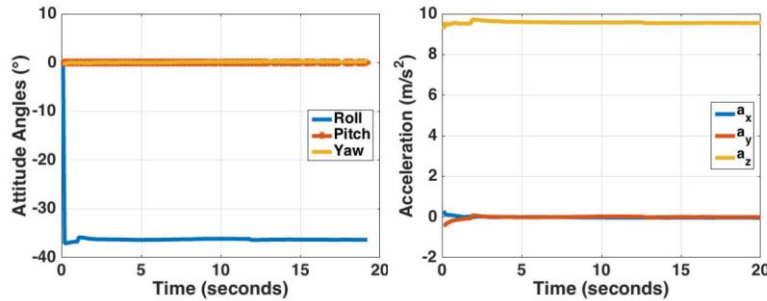


Figure 6.13 Convergence of the Attitude Angle Estimates (attitude of the IMU device with respect to the vehicle) Derived from the Rotation Matrix $R_{\frac{c}{c}}$

Trajectory Estimation Using Calibrated IMU Measurements

We performed a test involving a single IMU onboard a vehicle to evaluate the ability of the system to reconstruct the trajectory, from inertial measurements.

6.4 Fast Computational Scheme for Integrating IMU Data into the LWR Traffic Flow Model

In traffic flow theory, different typologies of “slow” vehicles (or platoons) can be modeled as moving bottlenecks. These obstructions in traffic streams are usually associated with the presence of buses in urban traffic, and trucks or simply slower vehicles on highways. All these situations, indeed, are characterized by a partially blocked road (typically the right lane), causing a capacity reduction. The concept of moving bottleneck can be extended to fixed bottlenecks, which represent static (spatially) and time varying capacity restrictions caused for example by traffic lights and traffic incidents.

Some of the main challenges of modeling moving bottlenecks consist of identifying and modeling features regarding their speed (depending on the traffic conditions and on the maximum speed of the vehicle), their discharging flow (maximum rate at which vehicles overtake) and the entity of queue hold-back. Several studies have highlighted the importance of the effects of moving bottlenecks on traffic (Munoz and Daganzo 2002; Daganzo and Laval 2005) and have developed methodologies to include them into existing traffic models. Gazis and Herman developed in 1992 a model based on the conservation of flow, unconditional existence of the flow-density relation, and independence of capacity state from the bottleneck state. The first complete formulation based on the Lighthill–Whitham–Richards (LWR) model was proposed few years later by Newell (1993; 1998), where the moving bottleneck is assumed to behave as in a scaled-down version of the freeway’s fundamental diagram, not influenced by the bottleneck speed. In recent years, more comprehensive formulations of the moving bottleneck problem have been proposed by Munoz and Daganzo (2002), Leclercq et al. (2004), and Daganzo and Laval (2005). Other studies have focused on numerical

² To check if the rotation rate is approximately zero, we are thresholding for the norm two of the rotation vector in the device frame. The rotation of the Earth is negligible with respect to the measurement uncertainty of the gyrometer, and thus we can assume that a fixed object on Earth is associated with a zero-rotation vector.

methods to solve the fixed and moving bottleneck problems within the LWR model (Lebacque et al. 1998; Giorgi et al. 2002; Leclercq 2007).

Motivated by the problem of traffic state estimation using IMUs, we derive an algorithm based on the Hamilton Jacobi representation of the LWR model to simultaneously compute the state of the system (density map) and the moving bottleneck trajectories. The method we propose is very fast, and improves computational times by almost two orders of magnitude with respect to current methods based on the Cell Transmission Model (CTM).

The idea behind forward simulation of traffic with unknown exogenous trajectories is to perform state estimation, as follows. The IMUs provide us with trajectory measurements, which are known. The initial and boundary conditions of the problem are however unknown. In this chapter, our objective is to compute the trajectories of given vehicles, assuming that the initial conditions of the problem are known, which is the converse problem. This converse problem can be used to solve the original problem, as part of a classical estimation framework, for example, based on Particle Filtering or Ensemble Kalman Filtering:

- Define candidate initial and boundary conditions, in some feasible set.
- Compute the trajectories of the moving bottlenecks representing the IMU equipped vehicles, using these initial and boundary conditions (propagation).
- Use actual trajectory measurements from IMUs to select and filter the initial and boundary condition candidates (update) and use these updated candidates back in 1.

The problem of computing the trajectories and parameters (passing flows) associated with moving bottlenecks is not easy, since the bottlenecks both influence and are influenced by traffic. Thus, in order to compute the density map associated with a general problem (involving initial, boundary conditions and bottlenecks), we have to simultaneously compute the solution to the LWR model and the corresponding trajectories of the bottlenecks, which is usually computationally intensive, since we have to map the solution on the complete computational domain. In this chapter, we focus on moving bottleneck problems in which the passing flow is zero, that is, vehicles that are representative of traffic, though the method introduced here could be extended to the case in which the passing flow is nonzero. We also assume that the IMU vehicles have the same performance as the rest of the traffic.

The algorithm we propose is based on an extension of the semi-analytical solutions to arbitrary Hamilton-Jacobi equations introduced in (Mazaré et al. 2011). Using semi-explicit solutions, we show that the trajectories of an arbitrary number of fixed and moving bottlenecks can be marched forward in time simultaneously for a very low computational cost. Indeed, if the piecewise affine initial conditions contain n_i blocks, the piecewise affine upstream and downstream boundary conditions contain n_u and n_d blocks respectively, and i bottlenecks are considered, the future evolution of each bottleneck can be computed by at most (n_u+n_b+2) calculations of explicit functions, which determine the future value of the solution to the Hamilton-Jacobi equation along the trajectory of the bottleneck. Once this set of calculations is done, the future evolution of the moving bottleneck is completely determined, in function of the difference between the current value of the solution to the Hamilton Jacobi equation along the trajectory, and its future value along the predicted trajectory. This process is marched forward in time and allows one to simultaneously compute the parameters associated with all moving and fixed bottlenecks of the problem, without having to compute the solution everywhere.

Once the parameters and trajectories of all moving and fixed bottlenecks are known, one can use this information to efficiently compute the solution of the problem everywhere using the Lax-Hopf algorithm (which was shown to be faster than the Godunov scheme if solutions are only required at the time horizon in Claudel and Bayen (2010)).

6.5 Analytical Solutions to the Hamilton-Jacobi Partial Differential Equation (PDE)

The LWR PDE

Given a one-dimensional uniform section of highway, limited by x_0 upstream and x_n downstream. For a given time t and position x we define the local traffic density $k(x,t)$ in vehicles per unit of length, and the instantaneous flow $q(x,t)$ in vehicles per unit time. The conservation of vehicles on the highway is written as follows (Lighthill and Whithman 1956; Richards 1956; Garavello and Piccoli 2006):

$$\frac{\partial k(t, x)}{\partial t} + \frac{\partial q(t, x)}{\partial x} = 0$$

For first-order traffic flow models, flow and density are related by the *Fundamental Diagram* (FD); in this article we adopt triangular FD (Daganzo 1994). The FD is a positive function defined on $[0, k_j]$, where k_j is the maximal density (jam density). It ranges in $[0, q_{max}]$ where q_{max} is the maximum flow (capacity). It is assumed to be differentiable with derivative $Q'(0) = v > 0$ (free-flow speed) and $Q'(k_j) = w < 0$ (congested wave speed).

The Moskowitz Function

The Moskowitz function expresses the cumulated vehicle count $N(x,t)$ and it represents the continuous vehicle count at location x and time t . In the Moskowitz framework one assumes that all vehicles are labeled by increasing integers as they pass the entry point x_0 of a highway section, and that they cannot pass each other. If the latest car that passed an observer standing at location x and time t is labeled n , then $N(x,t)=n$.

Replacing k and q with N yields to Hamilton-Jacobi PDE (Newell 1993; Daganzo 2005, Daganzo 2006; Claudel and Bayen 2010):

$$\frac{\partial N(x, t)}{\partial t} - Q\left(-\frac{\partial N(x, t)}{\partial x}\right) = 0$$

The Generalized Lax-Hopf Formula

From Aubin et al. (2008), the solution associated with the value condition function c , denoted by N_c , is the infimum of an infinite number of functions of the value condition:

$$N_c = \inf\{c(t - T, x - Tu) + TR(u)\} \text{ s. t. } (u, T) \in [v_f] \times R_+ \text{ and } (t - T, x - Tu) \in \text{Dom}(c)$$

where c corresponds to:

$$c(x, t) = \begin{cases} N_{ini}(x) & t = 0 \\ N_{up}(t) & x = x_0 \\ N_{down}(t) & x = x_n \end{cases}$$

And $R(u)$, which is the Legendre-Fenchel transform associated with the fundamental diagram, is defined as:

$$R(u) = \sup_{k \in [0, k_j]} (Q(k) - u \cdot k)$$

This equation is well known in the Hamilton-Jacobi literature and often referred to as Lax-Hopf formula (Aubin et al. 2008; Evans 1998).

Fast Algorithm for Triangular Fundamental Diagram

Assuming a triangular fundamental diagram, the calculation of its convex transform R yields to:

$$\forall u \in [w, v_f], R(u) = k_c(v_f - u)$$

Hence, the solution components associated with the initial and boundary conditions can be expressed as follows.

Initial Conditions:

If $0 \leq k_i \leq k_c$, the initial condition imposes a free-flow state.

$$N_{c_{ini}}(x, t) = \begin{cases} k_i(tv_f - x) + b_i & : x_i + tv_f \leq x \leq x_{i+1} + tv_f \\ k_i(tv_f - x) + b_i + x_i(k_c - k_i) & : x_i + tw \leq x \leq x_{i+1} + tv_f \end{cases}$$

else, if $k_c \leq k_i \leq k_j$:

$$N_{c_{ini}}(x, t) = \begin{cases} k_i(tw - x) - tk_jw + b_i & : x_i + tw \leq x \leq x_{i+1} + tw \\ k_c(tw - x) - tk_jw + x_{i+1}(k_c - k_i) + b_i & : x_{i+1} + tw \leq x \leq x_{i+1} + tv_f \end{cases}$$

Upstream Boundary Condition:

For an upstream boundary condition N_{up} defined as: $N_{up}^j(t) = q_j t + d_j$ with $d_j = -q_j t + \sum_{l=0}^{j-1} (t_{l+1} - t_l) q_j^l$, the solution component can be expressed as:

$$N_{c_{up}^j}(x, t) = \begin{cases} d_j + q_j \left(t - \frac{x - x_0}{v_f} \right) & : x_0 + v_f(t - t_{j+1}) \leq x \leq x_0 + v_f(t - t_j) \\ d_j + q_j t_{j+1} + k_c \left((t - t_{j+1})v_f - (x - x_0) \right) & : x_0 \leq x \leq x_0 + v_f(t - t_{j+1}) \end{cases}$$

Downstream Boundary Condition:

For a downstream boundary condition N_{down}^j , defined as $N_{down}^j(t) = p_j t + b_j$ with $b_j = -p_j t + N_{ini}^{(n-1)}(x_n) + \sum_{l=0}^{j-1} (t_{l+1} - t_l) q_j^l$, the solution component can be expressed as:

$$N_{down}^j(x, t) = \begin{cases} b_j + p_j t - \left(\frac{p_j}{w} + k_j \right) (x_n - x) & : x_n + w(t - t_j) \leq x \leq x_n + w(t - t_{j+1}) \\ b_j + p_j t_{j+1} + k_c \left((t - t_{j+1})v_f + x_n - x \right) & : x_n + w(t - t_j) \leq x \leq x_n \end{cases}$$

Derivation of Internal Conditions for Multiple Bottlenecks

The algorithm used to compute the trajectory of the vehicle is leveraging the semi-analytic properties of the solutions of the Hamilton Jacobi equation, to enable one to compute the solution at a given point without having to march a grid forward in time.

- 1) Choose an arbitrary time step Δt (Δt should be sufficiently large to have favorable computational time characteristics, and sufficiently small to use in step 2 to:
- 2) Calculate the values of the Moskowitz function for: $M(x_0, t_0) = M_0$ and $M(x_0 + v_{max}\Delta t, t_0 + \Delta t) = M_1$, where (x_0, t_0) corresponds to the position of the moving bottleneck in the end of the previous time interval, and v_{max} corresponds to the maximum speed of the moving bottleneck.
- 3) If $M_1 \neq M_0$, do a line search on the domain $\{(t_0 + \Delta t, x_0 + v\Delta T), \forall v \in [0, v_{max}]\}$ to identify v such that $M(x_0 + \Delta t v) = M_0$.

4) Update trajectory and go to 2.

In the above, $u = v_{max}$ stands for the free-flow speed, k_c is the critical density and n_l is the number of lanes.

Once complete, the above process allows us to determine the solution to an arbitrary number of moving bottlenecks, which can be used to represent trajectory data generated by IMU equipped vehicles. We illustrate the performance of this algorithm by computing the density map associated with 11 distinct IMU trajectories in Figure 6.14.

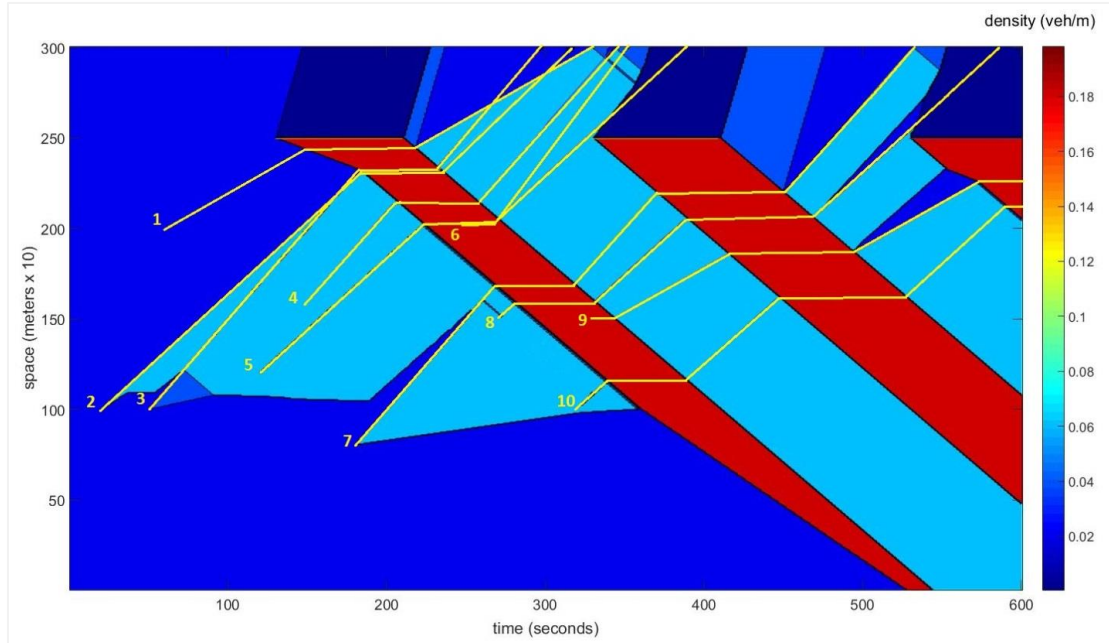


Figure 6.14 Example of Simulation of Several Moving Bottlenecks.

Note: The trajectory of each bottleneck is modeled by a yellow line, and the corresponding density is represented as a color map.

6.6 Summary

The algorithm that we developed consists in a new semi-analytic numerical scheme that can be used to compute the solutions within the LWR traffic flow model given initial, upstream and downstream boundary conditions, and an arbitrary number of moving bottlenecks, which can be associated with different types of vehicles. The moving bottlenecks can be used to encode the trajectories of IMU equipped vehicles, for state estimation purposes.

This numerical scheme is based on a Hamilton-Jacobi formulation of the LWR model, and results from the properties of the solutions to Hamilton-Jacobi equations, and in particular the infomorphism property. Being semi-analytic, it is very accurate (though not exact due to the piecewise linear approximation of the trajectories of the moving bottlenecks), and very fast, since it allows one to determine the trajectories of all moving bottlenecks without having to compute the solution on the entire computational domain, making it very adapted to traffic estimation problems resulting from the integration of large amounts of vehicle trajectory data (generated by GPSs or IMUs).

Through the use of IMU and computational algorithms, traffic states can be estimated from within a CV-system framework. One capability demonstrated here is successful operations without dependence on GPS

data. Multiple, moving bottlenecks along a section of roadway can be tracked, which enables effective system-wide traffic optimization strategies.

CHAPTER 7 LEGAL ENVIRONMENT OF SELF-DRIVING VEHICLES WITH CAVS

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7.1 Background

The law has been cited as one of the primary obstacles to the effective and efficient integration of connected and/or autonomous vehicles (C/AV) onto public roadways (Davidson and Spinoulas 2015). For states where testing and limited deployment of C/AVs is underway, there is enthusiasm, as well as some caution, about further integration of the benefits and capabilities of automated transportation onto the transportation network. Policymakers are eager to learn more about the intersection of this new wave of technology with the existing legal infrastructure. Questions that policymakers want to know include whether existing law prohibits or impedes testing or deployment of the technology or if greater legal oversight is desirable. Within the U.S., in light of the limited federal regulation of C/AV transportation currently, there are questions about the most useful role of states and local governments in overseeing this new technology without creating a patchwork of different rules and regulations that will need to be reconciled between jurisdictions.

7.2 U.S. Federal Laws, Regulations and Policies

Our analysis of the intersection of the law and C/AVs starts with a review of the legal developments that have occurred within the U.S. regulating this emerging technology. This is broken down into developments at the federal level, state level, and internationally emerging to address various aspects of C/AV safety and intersect with legal responsibility.

U.S. Congress

The U.S. Congress has introduced multiple bills since 2015 regarding C/AVs. None of these have passed into law. 2017 saw a large number of bills created, although none have yet passed out of committees or a conference committee for a final vote.

The U.S. Senate Committee on Commerce, Science and Transportation held a hearing on June 14, 2017 regarding the release of bipartisan principles for self-driving vehicle legislation. Those principles are reproduced in Figure 7.1.

In July 2017, the U.S. House of Representatives Committee on Energy and Commerce's Subcommittee on Digital Commerce and Consumer Protection introduced an unnumbered bill regarding highway AV testing and deployment (U.S. Congress, 2017). The legislation proposes to clarify the federal and state roles for regulating Highly Automated Vehicles (HAVs). The legislation requires NHTSA to publish rulemaking and a safety priority plan for HAVs, and requires submission of safety assessment certifications by HAV manufacturers (although it does not stipulate if the term "manufacturer" means only original equipment manufacturers or includes technology companies or after-market manufacturers).

Prioritize Safety:

- As with conventional vehicles, federal standards will be important to self-driving vehicle safety.
- Legislation must consider both the near-term and long-term regulatory oversight of these vehicles, recognizing that new safety standards governing these vehicles should eventually be set.
- Promote Continued Innovation and Reduce Existing Roadblocks:
- Currently, there is a body of regulations governing conventional vehicles, developed over decades, that does not directly address self-driving vehicles. Developing new standards takes significant time.
- Legislation must allow the life-saving safety benefits of self-driving vehicle technology to move forward as new standards development is underway.
- Legislation must find ways to preserve and improve safety while addressing incompatibility with old rules that were not written with self-driving vehicles in mind.

Remain Tech Neutral:

- Self-driving vehicles are likely to take different forms, use diverse technologies, serve consumers with varying capability levels, and follow multiple business models.
- Legislation must be technology neutral and avoid favoring the business models of some developers of self-driving vehicles over others.

Reinforce Separate Federal and State Roles:

- Traditionally, the federal government has regulated the vehicle itself, while states have regulated driver behavior.
- Legislation must clarify the responsibilities of federal and state regulators to protect the public and prevent conflicting laws and rules from stifling this new technology.
- Legislation must be based on the existing relationship between federal and state regulators and their current separation of authority but make necessary targeted updates for new challenges posed by the current regulatory environment with respect to self-driving vehicles.

Strengthen Cybersecurity:

- Cybersecurity should be a top priority for manufacturers of self-driving vehicles and it must be an integral feature of self-driving vehicles from the very beginning of their development.
- Legislation must address the connectivity of self-driving vehicles and potential cybersecurity vulnerabilities before they compromise safety.
- Educate the public to encourage responsible adoption of self-driving vehicles: Government and industry should work together to ensure the public understands the differences between conventional and self-driving vehicles.
- Legislation must review consumer education models for self-driving vehicles and address how companies can inform the public on what self-driving vehicles can and cannot do based on their level of automation and their individual capabilities.

Figure 7.1 Principles for Bipartisan Legislation on Self-Driving Vehicles (US Congress, 2017)

On July 25, 2017, the U.S. House introduced the Safely Ensuring Lives Future Deployment and Research in Vehicle Evolution Act (Self Drive Act) H.R. 3388. H.R. 3388 was reported out by the House Committee on Energy and Commerce on September 5, 2017 and referred to the Senate Committee on Commerce, Science and Transportation on September 6, 2017. The bill, clarifies federal and state roles and preempts states or political sub divisions to maintain, enforce, prescribe or continue in effect laws or regulations regarding the design, construction or performance of HAVs, automated driving systems of components of automated driving systems, unless such law or regulation is identical to any prescribed within this chapter. It requires NHTSA

to issue within 18 months rules on submission of safety assessment certifications on how safety is being addressed by manufacturers of highly automated vehicles or automated driving systems. For highly automated vehicles, NHTSA should identify elements that may require performance standards including human machine interface, sensors, and actuators, and consider process and procedure standards for software and cybersecurity as necessary (US House 2017 (b)).

The act also amends Chapter 3001 of Subtitle VI of Title 49 USC by adding a new section on rear seat occupant alert systems. The Secretary shall, no later than 2 years after the date of enactment of this section, issue a final rule requiring all new passenger motor vehicles weighing less than 10,000 pounds gross vehicle weight to be equipped with an alarm system to alert the operator to check rear designated seating positions after the vehicle motor or engine is deactivated by the operator.

The Act requires manufacturers to develop written cybersecurity plans. The Act would also create a Highly Automated Vehicle Advisory Council six months after the enactment of the act. Membership is to be diverse and will be determined by the USDOT Secretary (US House 2017 (b)).

On July 26, 2017 the U.S. House introduced H.R. 3416 to establish in the National Highway Traffic Safety Administration a Rural and Mountainous Advisory Council to make recommendations regarding the testing and deployment of highly automated vehicles and automated driving systems in areas that are rural, remote, mountainous, insular, or unmapped (U.S. House, 2017 (c)). The council would be convened by NHTSA within six months of the bill's enactment. Members will be appointed by the Secretary for 3 years. The Committee will undertake information gathering, develop technical advice, and present best practices or recommendations to the Secretary. The council will terminate six years after enactment. Within Section 1 automated driving system, dynamic driving task, highly automated vehicle and operation design domain are defined. The bill notes that if SAE revises definitions, it will notify the Secretary who is required to publish these within the federal register for comment. The Secretary will then notify SAE that if it has determined that the definition does not meet the need for motor vehicle safety or is otherwise inconsistent with United States Code, the existing Section 1 definition shall remain in effect. If the Secretary does not reject a definition revised by SAE it will amend regulations and standards as necessary.

On July 28, 2017, the U.S. House introduced H.R. 3401 to amend chapter 301 of subtitle VI of title 49, United States Code, to update or provide new motor vehicle safety standards for highly automated vehicles, and for other purposes. The bill defines automated driving systems, dynamic driving tasks, highly automated vehicles and operational design domain. The bill requires the Secretary to issue final rules no later than 24 months requiring the submission of safety assessment certifications regarding how safety is being addressed by each entity developing HAVs or ADS. (U.S. Congress, 2017 (d)). In the interim, the bill would require that safety assessment letters are submitted to NHTSA under its policy issued in September 2016 or under any successor guidance. If this bill moves forward, amendment to NHTSA's September 2017 guidance, which now only has voluntary safety self-assessment guidance, where entities can choose to submit or not submit, will be necessary.

On July 28, 2017, the U.S. House introduced H.R. 3411 to amend chapter 301 of subtitle VI of title 49, United States Code, to update or provide new motor vehicle safety standards for highly automated vehicles, and for other purposes. (U.R. Congress, 2017 (e)). The bill proposes an automated driving system cybersecurity council that will be convened within six months of the bill's enactment. Set by the Secretary, representation will be diverse and capped at 30 members. In the same fashion as HR 3416, this bill notes that if SAE revises definitions, it will notify the Secretary who is required to publish these within the federal register for comment. The secretary will then notify SAE that if it has determined that the definition does not meet the need for motor vehicle safety or is otherwise inconsistent with United States Code, the existing Section 1 definition shall remain in effect. If the Secretary does not reject a definition revised by SAE it will amend regulations and standards as necessary.

On September 8 the Senate Commerce Committee circulated a draft AV bill called the American Vision for Safer Transportation through Advancement of Revolutionary Technologies Act, (AV START Act – S.1885). The bill has similarities to the House's SELF Drive Act, but also some major departures within specific sections. Most notably including addressing trucking, the definitions section includes brackets pertaining to a

vehicles weight, so inclusion of trucks and buses is considered within this bill. The draft bill makes major differences in the approach to preemption, with AV laws and regulations enacted by states considered to be pre-empted if they pertain to any of nine subject areas of the Safety Evaluation Report that this bill requires (Eno, 2017).

In July 2017 the house introduced HR 3440 Highly Automated Information Sharing Advisory Council (Shares Act) that would establish a council to make recommendations on the development of a framework to allow manufacturers of HVS to share information relating to testing and deployment. The act as at writing was still referred to a subcommittee.

Federal Agency Policy

The US Department of Transportation (USDOT) and the National Highway Traffic Safety Administration (NHTSA) are the primary agencies charged with overseeing C/AVs and both are making significant headway in overseeing and guiding the development and use of C/AV technology.

NHTSA has issued three policy documents since 2013. The latest policy statement was issued in May 2017 titled [insert name]. In October 2016 NHTSA issued a policy on Cybersecurity (Cybersecurity Best Practices for Modern Vehicles, October 2016) and in September 2016, NHTSA issued policy guidance, which encapsulated some of the challenges outlined in its 2013 policy and added new elements (Federal Automated Vehicles Policy: Accelerating the Next Revolution in Roadway Safety). All of these documents have been *deliberately issued* as policy (rather than regulation) given the changing dynamic of technologies and public-sector groups within this field, with the goal of encouraging technological development, while also setting up the rationale for a playing field that was not a patchwork to lead to more statutes and regulations.

NHTSA's "Preliminary Statement of Policy Concerning Automated Vehicles" published in 2013 acknowledged the challenges faced by regulatory agencies developing performance requirements for, and ensuring the safety and security of, vehicles with increased levels of automation and automated control functions. In the statement, NHTSA outlined the Agency's C/AV research plan in accordance with concurrent technological developments in the automotive sector and defines the four/five levels of vehicle automation (depending on whether you follow the Society of Automotive Engineers (SAE) or NHTSA). NHTSA also encourages states to play the primary role in overseeing the "licensing, testing, and operation of self-driving vehicles on public roads" but adds that it does not believe that "self-driving vehicles are ready to be driven on public roads for purposes other than testing" (NHTSA 2013, p.10).

Under the National Traffic and Motor Vehicle Act of 1966 ("Safety Act"), NHTSA was statutorily directed by Congress to conduct research, promulgation, and enforcement of Federal Motor Vehicle Safety Standards (FMVSS). NHTSA releases information on the safety features of new vehicles, called the New Car Assessment Program (NCAP). This includes comparative performance ratings to encourage vehicle manufacturers to improve the safety of their vehicles voluntarily. For example, NHTSA identifies if vehicles are equipped with advanced technology features like electronic stability control (ESC), lane departure warning (LDW), and forward collision warning (FCW), and would likely include C/AV technology in its NCAP 5-star rating system (NHTSA 2013).

Given this role, NHTSA has the power to preempt state actions related to C/AV regulations and operational activities regarding design standards but is unlikely to do so at this point in time if the State actions are administrative in nature (Lindsay et al. 2014). In general, the preemption provision provided in the Safety Act authorizes NHTSA to intervene in state activities should vehicles and equipment not comply with the standards in place at the time of manufacture (ULC 2014). Accordingly, the preliminary statement of policy recommends eight principles for states with respect to overseeing C/AV operation and use (again, reserving oversight of the actual design features for federal regulation). While non-binding, these principles highlighted the agency's concern at that time about premature, prescriptive regulation of the design of C/AVs by the states which could stifle innovation or conflict with a "significant regulatory objective at this time" (NHTSA 2013).

The September 2016 policy publication set out USDOT's expectations of industry for the immediate short term to test and deploy HAVs. Unlike the 2013 policy, this new 2016 policy was aimed at Level 3-and-above

vehicles (under SAE J3016 definitions). NHTSA created the new term *highly automated vehicle (HAV)*, and most importantly re-set its stratification to mirror SAE International’s J3016 levels (the global industry reference for defining the six levels of automated/autonomous driving). A vehicle performance section set out best practices for safe pre-deployment, design, development, and testing of HAVs, and defined deployment as the operation of an HAV by members of the public who were not agents or employees of the designer, developer, or manufacturer of the HAV (NHTSA, 2016 (a)). The policy also confirmed the model state policy articulated in the 2013 policy: state responsibilities will include licensing of drivers (human) and motor vehicle registration, law and traffic enforcement, inspections, and motor vehicle liability and insurance rules. NHTSA noted that this was to ensure the creation of a consistent national framework, rather than a patchwork of laws that could be incompatible with one another.

The model state policy in the guidance outlines federal and state roles. NHTSA responsibilities include the following (NHTSA, 2016e, p. 38):

- Setting FMVSS for new motor vehicles and motor vehicle equipment (to which manufacturers must certify compliance before they sell their vehicles)
- Enforcing compliance with the FMVSS
- Investigating and managing the recall and remedy of non-compliances and safety-related motor vehicle defects and recalls on a nationwide basis
- Communicating with and educating the public about motor vehicle safety issues
- Issuing guidance for vehicle and equipment manufacturers to follow, such as the Vehicle Performance Guidance for HAVs presented in this Policy

State responsibilities include the following:

- Licensing (human) drivers and registering motor vehicles in their jurisdictions
- Enacting and enforcing traffic laws and regulations
- Conducting safety inspections, where states choose to do so
- Regulating motor vehicle insurance and liability

NHTSA noted that these general areas of responsibility should remain largely unchanged for HAVs. The federal government would continue to be responsible for regulating motor vehicles and equipment, and the states will retain traditional responsibilities for regulating human drivers and most aspects regarding the operation of motor vehicles. NHTSA however, noted that as vehicle equipment increasingly performs “driving tasks,” each state DOT’s exercise of its authority/responsibility in regulating equipment safety would increasingly encompass tasks that would be similar to the “licensing” but now for a non-human driver, where the hardware and software that performs part or all of the driving tasks previously performed by a human driver.

States were encouraged to evaluate their current laws and any implementing regulations to reduce and address unnecessary impediments to the safe testing, deployment, and operation of HAVs, including updating any references to a human driver when appropriate. States could experiment with different policies and approaches to create consistent standards to contribute to the development of the best approaches and policies to achieve uniform regulatory objectives.

Elements of the model state framework are placed into eight thematic areas with key recommendations shown in Table 7.1

Table 7.1 Key Recommendations

Recommendation	Description
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Administrative	Identify a lead agency responsible for consideration of HAV testing, and create a committee, with stakeholder representation. The lead agency should take steps to use or establish statutory authority to implement a framework and regulations and examine its existing laws in five areas: licensing/registration including application processes for testing), driver education and training, insurance and liability, enforcement of traffic laws/regulations, and administration of vehicle inspections.
Application for testing	Create an application process that follows federal standards and rules, and identifies the process, vehicles, operators/testers and safety and compliance plans and insurance provision.
Jurisdictional permission to test	Lead agency should involve law enforcement prior to responding to the testing request. The test authorization should include a permit carried in vehicle and registration/titling of vehicle.
Testing by manufacturer / other entity	Vehicles used in test should be operated by an authorized user who has received training regarding its capabilities and limitations, and crashes should be reported.
Deployed vehicles and drivers	To facilitate the transition from human-driven vehicles with safety technologies to fully automated vehicles, gaps in current regulations should be identified and addressed by states.
Deployed vehicles' registration and titling	HAV technologies that allow a vehicle to be operated without a human driver should be identified on title and registration documents. Aftermarket installation of HAV technologies should be reported to the motor vehicle agency.
Law enforcement	Law enforcement and first responders will need to create training and education for how HAVs will affect their duties, including interaction with operators, or users of service.
Liability and Insurance	States should consider how to allocate liability among HAV owners, operators, passengers, manufacturers, and others when a crash occurs.

In October 2016 NHTSA (NHTSA, 2016 (b)) released a new policy on best practices for cybersecurity in modern vehicles. This policy, which covers all motor vehicles, recommended a layered approach to cybersecurity, with the goal to reduce the probability of a cyber-attack's success and diminish unauthorized access ramifications. NHTSA notes that it is important for the automotive industry to make vehicle cybersecurity an organization priority, which should include proactively adopting and using any available guidance and establishing internal processes and strategies to ensure that systems will be reasonably safe under expected real-world conditions. NHTSA stated that the approach should be built upon:

- risk-based prioritization,
- provide for timely detection and rapid response,
- create methods to 'design-in' rapid recovery from an incident, and
- institutionalize methods for adopting lessons learned.

NHTSA encouraged use of the International Organization for Standardization ISO 2700 series of standards and other best practices used in other technology sectors for developing protocols and approaches (NHTSA, 2016 (b)). The cybersecurity policy also recommended "penetration testing and documenting," which has stages that employ qualified testers who were not involved in development and are incentivized to unearth vulnerabilities. In summary, NHTSA set out at pages 17–20 a series of fundamental vehicle cybersecurity protections that it recommended.

NHTSA recommends that the industry consider the Center for Internet Security's Critical Security Controls for Effective Cyber Defense (CIS CSC's) recommended approaches for:

- performing cybersecurity gap assessment,

- developing implementation roadmaps,
- effectively and systematically executing cybersecurity plans,
- integrating controls into vehicle systems and business operations, and
- reporting and monitoring progress through iterative cycles.

NHTSA's policy also recommends that companies developing or integrating safety-critical vehicle systems:

- create corporate leadership teams to foster a culture prepared to handle increasing cybersecurity challenges,
- prioritize cybersecurity by allocating resources and facilitating direct and seamless communications related to product cybersecurity, and
- enable independent voices for cybersecurity-related considerations during the development and vehicle safety design process (NHTSA, 2016e, p.10).

The cybersecurity policy also suggested that the industry develop a risk-based approach to assess vulnerabilities and potential impacts within their supply-chain of operations. At a minimum, NHTSA recommended that organizations consider cybersecurity risks to safety-critical vehicle control functions and personally identifying information (PII). They suggest using the CIS CSC approach with some modifications, including asking the following questions during documentation processes:

- What are the functions?
- What are the implications if they were compromised?
- What are the potential safety hazards that could be exposed by these vulnerabilities?
- What is the safety risk to society and the value risk to the organization?
- What can be done to minimize exposure to the potential loss or damage?
- What design decisions could be made with respect to the risk assessment process?
- Who/what are the threats and vulnerabilities?

Penetration testing and documentation is also recommended and should include stages that deploy qualified testers who have not been part of the development team, and who are "incentivized" to identify vulnerabilities. The automotive industry is also encouraged to establish procedures for documentation and review of cybersecurity-related activities.

In September 2017 NHTSA issued a new draft of policy for highly automated vehicles called Automated Driving Systems 2.0 A Vision for Safety. As before this was introduced as a policy document and not through NHTSA's rulemaking authority process. The document was also responding to comments that had been provided on the 2016 NHTSA policy document. This new document fully replaces the 2016 policy and will be updated annually. The policy is split into two sections. Section one has *voluntary* guidance which details ADS safety elements and ends with a voluntary safety self-assessment component. Section two covers technical assistance to the states. The policy states that:

"The purpose of this Voluntary Guidance is to help designers of ADSs analyze, identify, and resolve safety considerations prior to deployment using their own, industry, and other best practices. It outlines 12 safety elements, which the Agency believes represent the consensus across the industry, that are generally considered to be the most salient design aspects to consider and address when developing, testing, and deploying ADSs on public roadways. Within each safety design element, entities are encouraged to consider and document their use of industry standards, best practices, company policies, or other methods they have employed to provide for increased system safety in real-world conditions. The 12 safety design elements

apply to both ADS original equipment and to replacement equipment or updates (including software updates/upgrades) to ADSs” (NHTSA, 2017).

A new schematic for automation levels was created (Figure 7.2).

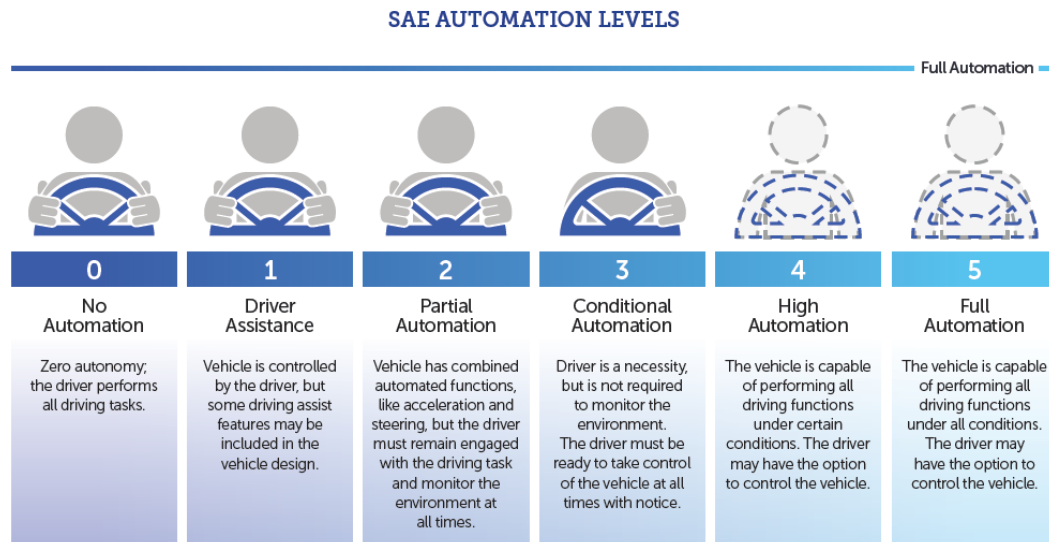


Figure 7.2 SAE Automation Levels (NHTSA, 2017)

Many sources have noted that there is a difference between “autonomous” and “automated” vehicles.³ The adoption of the different SAE automation levels by the federal government (and by some of the states) should help the public recognize that human-driven automated vehicles with automated features, such as the Tesla “Autopilot”, are not necessarily “autonomous” vehicles.

Twelve ADS Safety Elements with brief descriptions are outlined in this 2017 policy, with some new elements to include: fallback minimal risk condition, data recording, human machine interface and post-crash ADS behavior. Table 7.2 outlines the ADS safety elements.

Table 7.2 NHTSA’s 2017 Policy ADS Safety Elements (NHTSA, 2017)

Safety Element		Brief Descriptor
1	System safety	A robust design and validation process based on systems engineering approach to design ADSs free of unreasonable safety risks. Including a hazard and safety risk assessment for overall vehicle design integration. Design decisions should be linked to assessed risk that impact safety-critical system functionality.
2	Operational design domain	Define and document ODD for each ADS available on their system including: road types, geographic area, environmental conditions, speed range and domain constraints.
3	Object and event detection and response	Detection by driver or ADS circumstances relevant to immediate driving task and implementation of driver system response. Document process for assessment, testing and validation, crash avoidance and variety of behavioral competencies for ADSs.
4	Fallback minimal risk condition	Process for transitioning to a minimal risk condition when a problem is encountered and ADS cannot operate safely. At higher automation, where human driver is not available, ADS must fall back into minimal risk condition without driver intervention.

³ Glancy, p. 629-630, <http://scholarship.law.umn.edu/cgi/viewcontent.cgi?article=1013&context=mjlst>

5	Validation methods	As scope, technology and capabilities widen, entities are encouraged to develop validation methods to appropriately mitigate safety risks associated with ADS approach.
6	Human machine interface	At minimum the ADS should be capable of informing the human operator/occupant through indicators that the ADS is ADS functioning properly, i.e. is currently engaged or unavailable, experiences malfunction and/or requests control from ADS to the operator.
7	Vehicle cybersecurity	Encouraged to follow a robust product develop process based on systems engineering approach to minimize safety risks due to cybersecurity threats and vulnerabilities. Documentation encouraged, including changes, design choices, analysis and testing. Groups involved with ADSs should consider adopting a coordinated vulnerability reporting/disclosure policy
8	Crashworthiness	As vehicle mix may be operating (those with/without ADS), entities should consider scenarios of non-ADS vehicle crashing into ADS equipped vehicle and how to protect.
9	Post-crash ADS behavior	In testing or deployment consider how to return ADS to a safe state immediately after an incident, e.g. moving to a safe spot. If vehicle is a connected vehicle, communication with a relevant entity is encouraged to share and reduce harm resulting from a crash.
10	Data recording	Entities engaged in testing/deployment are encouraged to establish a process for data collection and validation to establish crash causes leading to fatalities/injuries. ADS data recommended to be stored and available for retrieval for crash reconstruction.
11	Consumer education and training	Develop, document, and maintain employee, dealer, distributor and consumer education and training programs to address anticipated differences in use and operation of ADS vehicles.
12	Federal state and local laws	Document how federal, state and local traffic laws and updates will be integrated in in vehicle design and ADSs.

The final piece of section one is the voluntary safety self-assessment. The difference between this requirement and the previous NHTSA 2016 policy is that entities will not be required to submit this safety assessments. These are now entirely voluntary.

Section two of the document detailed federal and state roles, USDOT strongly encourages states to allow USDOT alone to regulate the safety design and performance aspects of ADS technology. If a state does pursue ADS performance-related regulations, they ‘should consult with NHTSA’. However, given that this is a guidance document and not prescriptive requirements, states could choose not to consult with NHTSA since NHTSA is not fully preempting this space.

State responsibilities as detailed have not changed, and comprise licensing, traffic laws, inspections and insurance. Best practices for legislatures have four major bullets:

- Provide a technology neutral environment
- Provide licensing and registration procedures
- Provide reporting and communications for public safety official
- Review traffic laws and regulations that could serve as barriers to operation of ADS.

Other, more specific laws, rules, reports, and significant proposals are discussed in more detail below.

Congress allocated over \$25 million to the USDOT for the modernization of the National Automotive Sampling System (NASS) in 2012 as part of continued research into advanced automotive safety technology. The funding purpose was to ensure that the modernization of NASS could assist in decision-making at the federal, state and jurisdictional levels for what was expected to be a faster-than-anticipated outflow of C/AV/HAV technologies (NHTSA, 2015a). NHTSA proposed substantial changes to two existing systems: a) general estimates and b) crashworthiness data. NHTSA proposed deployment of the new Crash Report

Sampling System in 2016 at 60 sites, and the Crash Investigation Sampling Systems in 2017 at 24 sites (NHTSA, 2015a).

In April 2016, NHTSA issued a request for public comments on safety related defects and emerging automotive technologies. The docket summary notes:

This proposed Enforcement Guidance Bulletin sets forth NHTSA's current views on emerging automotive technologies—including its view that when vulnerabilities of such technology or equipment pose an unreasonable risk to safety, those vulnerabilities constitute a safety-related defect—and suggests guiding principles and best practices for motor vehicle and equipment manufacturers in this context. (NHTSA, 2016a)

The request was issued to gather comments concerning the proposed guidance for motor vehicle and equipment manufacturers in developing and implementing new and emerging automotive technologies, safety compliance programs, and other business practices in connection with such technologies.

In 2015, USDOT and NHTSA proposed that they would not require EDRs at this point in time, although they have promulgated a rule that requires standardized requirements for voluntary installation of EDRs (49 CFR Part 563). The interfaces for downloading EDR data will most likely be in the passenger compartment and the interface locations will not be accessible to individuals unless they have access to the passenger compartment. The proposal requires public access to information on the protocol for downloading EDR data; however, the Agency feels that this will not result in public access or intrusion into C/AV EDR data (NHTSA 2015).

Moreover, NHTSA feels that the access to data in EDRs will be a matter of state law. With C/AVs, access will continue to be possible in only limited situations. Many of these same data are routinely collected during crash investigations, but they are based on estimations and reconstruction instead of direct data (NHTSA 2013).

The standard approach for acquiring crash data is through the use of event data recorders (EDRs), which enable vehicles to collect various data from the car and can provide a valuable picture of the vehicle's state leading up to an accident. The federal government does not mandate EDRs, though NHTSA estimates that approximately 96% of model year 2013 passenger cars are already equipped with EDR capability (NHTSA 2012b). NHTSA previously estimated in a 2006 NPRM that by 2010 over 85% of vehicles would have EDRs installed in them, and warned that if the trend did not continue, the agency would revisit their decision and possibly make installation a requirement (NHTSA 2006).

When it comes to determining fault or liability in an HAV collision, there is a problem with access. Investigating fault may require access to an HAV's proprietary "machine learning" data and algorithms. This is what technology manufacturers wish to protect. Legislators and agencies need to evaluate carefully whether mandating access to proprietary data is fair and/or necessary. If this problem is solved now among the stakeholders, it can save everyone time and money later on. If responsibility is legislated to be mainly on the manufacturers and the federal government, manufacturers may avoid the insecurity of a state-by-state-legal liability patchwork.

The FAST Act passed in December 2015, includes at Section 24302 a limitation on the data retrieval from EDRs. Any data retained by an EDR, regardless of when the motor vehicle in which it is installed was manufactured, is defined as the property of the owner. For a leased vehicle the lessee of the vehicle is considered the owner (§24302 (a)). Under Section b, data recorded or transmitted by an EDR may not be accessed by a person other than an owner or a lessee unless:

- 1) a court or other judicial or administrative authority having jurisdiction authorizes the retrieval of the data; and to the extent that there is retrieved data, it is subject to the standards for admission into evidence required by court or administrative authority;
- 2) an owner or lessee of the vehicle provides written, electronic, or recorded audio consent for data retrieval for any purpose, including diagnosing, servicing, or repair, or by agreeing to a subscription that describes how data will be retrieved and used;

- 3) the data is retrieved pursuant to an investigation or inspection authorized under section 1131(a) or 30166 of Title 49, United States Code, and the personally identifiable information of the vehicle's owner or lessee and the vehicle identification number (VIN) is not disclosed in connection with the retrieved data, except that the VIN may be disclosed to the certifying manufacturer;
- 4) the data is retrieved for the purpose of determining the need for, or facilitating, emergency medical response in response to a crash; or
- 5) the data is retrieved for traffic safety research, and the personally identifiable information of the vehicle's an owner or lessee and the VIN is not disclosed in connection with the retrieved data.

EDRs are not mandated by the federal government, although approximately 96% of model year 2013 passenger cars are already equipped with EDR capability according to NHTSA estimates (NHTSA, 2012). Prior to passage of the FAST Act, NHTSA put forth a proposal indicating that they would not require EDRs, although they chose to promulgate a rule mandating standardized requirements for voluntary installation of EDRs (49 CFR Part 563). The proposal requires public access to information on the protocol for downloading EDR data; however, NHTSA stated that they did not believe access to protocol information would result in public access or intrusion into the C/AV/HAV EDR data itself (NHTSA, 2015).

Furthermore, in 2013, NHTSA noted that it believed access to EDR data would be a matter of state law. Within C/AV/HAVs, data access would only continue to be possible in limited situations. Much of the same data are routinely collected during crash investigations but are based on estimations and reconstruction rather than on direct data (NHTSA, 2012b).

The Fast Act also requires the USDOT to submit a report to Congress on the operations of the Council for Vehicle Electronics, Vehicle Software and Emerging Technologies (Electronics Council), which was established in the Moving Ahead for Progress in the 21st Century Act (MAP-21) passed in 2012 to provide a forum for research, rulemaking, and enforcement officials to coordinate and share information internally on advanced vehicle electronics and new technologies (Pub. L. No. 114-94 §31402, 129 Stat. 1312 [2015]).

7.3 Other Legislative Developments

Rulemakings and Proposed Rules

Rulemakings on airwaves for vehicular radar use, vehicle-to-vehicle communications technology, and wi-fi spectrum sharing are important for understanding potential legislative development around AVs. Reports from federal agencies are also useful when attempting to forecast future legislation.

Rulemaking on New Airwaves for Vehicular Radar Use

On July 13, 2017 the FCC announced it had unlocked new airwaves for vehicular radar use (FCC, 2017). According to the FCC, access to this additional spectrum will enable innovation; allow these radar devices to better distinguish between objects in areas close to the vehicle; and improve performance for applications such as lane change warnings, blind spot detection, parking aids, "stop and follow," "stop and go," autonomous braking, and pedestrian detection, and is consistent with spectrum available internationally, so avoids the needs to customize radars for different markets. The order amends Amendment of Parts 1, 2, 15, 90 and 95 of the Commission's Rules to Permit Radar Services in the 76-81 GHz Band (FCC, 2017 a).

Proposed Rulemaking for Vehicle-to-Vehicle Communications Technology

In May 2015, US Transportation Secretary Anthony Foxx announced that NHTSA will advance the schedule for issuing a proposal to require vehicle-to-vehicle (V2V) communication devices in new light vehicles (NHTSA 2015d). In September 2015, NHTSA issued a notice of proposed rulemaking (NPRM) mandating that V2V communications be required for heavy vehicles, such as freight and buses. As such, NHTSA will determine the best course of action with regard to the exercise of its regulatory and research authority within this context (NHTSA 2015).

With respect to this proposed rulemaking, NHTSA had originally planned for an Agency Decision by 2016. However, substantial feedback following a request for information from August 2014's Advance NPRM allowed NHTSA to signal its intentions to deploy a limited amount of V2V devices earlier than originally anticipated. A key focus of this early rulemaking was expected to focus on enhancing existing advanced safety technologies. According to the most recent press release, NHTSA is working on a regulatory proposal that would require V2V devices to be consistent with applicable legal requirements, Executive Orders, and federal guidance. The Agency planned to send a proposal to the Office of Management and Budget for review by the end of 2015 (NHTSA 2015).

Proposed Rulemaking and Legislation on Wi-Fi Spectrum Sharing

In October 2014, NHTSA received approval from the FTC after the Department specifically addressed three lingering concerns expressed by the Commission, which targeted V2V systems and the ability for connected technology to track consumers, provide information about driving habits without consent, and ensure overall security (FTC 2013). The Commission supported the decision based upon "NHTSA's commitment to 'protect[ing] individual safety...while also promoting the technology'... rooted in the framework of the Fair Information Practice Principles" (FTC 2014, p.8). Nevertheless, existing limitations over the reserved use of the Wi-Fi spectrum for dedicated short-range communications (DSRC) have raised serious concerns over potential for interference when transmitting and receiving information on the same or similar frequencies (GAO 2014).

In general, V2V communication devices developed specifically for C/AVs currently operate on a lightly controlled band of the Wi-Fi spectrum at the 5.8–5.9 GHz frequency. This reserved band and spectrum supports the safety applications that require fast response times needed for mitigating crashes and advanced safety applications. Since 2003, NHTSA and the USDOT have reserved use of this band for the purposes of developing, researching, and testing V2V communication devices as part of ongoing research into Intelligent Transportation Systems (ITS) programs.

The FCC is investigating the opportunity for opening this "unlicensed information infrastructure" in order to meet the growing need for increased access to Wi-Fi for the public at large. In Congress, H.R.821, or the "Wi-Fi Innovation Act," was reintroduced in 2015 by Sens. Cory Booker (D-NJ) and Marco Rubio (R-FL) to open the 5GHz band for Wi-Fi use. The bill directs the FCC and National Telecommunications and Information Administration to test the feasibility of spectrum sharing for Wi-Fi devices in line with the Executive Office's goal for freeing up 500 megahertz of spectrum by 2020 (Sonni 2015).

In August 2015, the USDOT released its "DSRC Spectrum Sharing Plan" in an effort to test feasibility and safety impact of devices sharing the 5.8–5.9 GHz band of Wi-Fi spectrum (NHTSA 2015). Through a partnership with the FCC and the NTIA, the USDOT plans to test and determine the safety impact of wireless devices sharing the same spectrum. The potential for interference on the Wi-Fi spectrum is one of the many concerns raised by stakeholders over onboard V2V devices and after-market conversion (NHTSA 2015).

Vehicle-to-Vehicle (V2V) Communications and Liability Reports

If widely deployed and adopted, V2V technologies could provide warnings to drivers for as many as 76% of potential multi-vehicle collisions involving at least one passenger (light) vehicle (GAO 2015). In addition, V2V technology has tremendous potential to improve the effectiveness of advanced safety applications, as well as provide the foundation for increased levels of vehicle automation, by fusing with existing vehicle safety features.

In October 2014, NHTSA published four cybersecurity reports that describe the agency's initial work to support the goals outlined in its Automotive Cybersecurity Research Program. Under Presidential Decision Directive 63, which looks at ways for public and private sector partners to share information about physical and cyber threats to critical infrastructure, NHTSA and the automotive industry formed an Information Sharing and Analysis Center (ISAC) in 2014 to help the industry proactively and uniformly address cybersecurity threats. Today, ISACs are used in over a dozen critical infrastructure areas, such as surface transportation, finance, and energy (NHTSA 2014). NHTSA believes an automotive industry ISAC is a critical

piece of vehicle cybersecurity infrastructure, as manufacturers and suppliers are in the best position to identify weaknesses in their own products (NHTSA, 2015).

As outlined in the DSRC Spectrum Sharing Plan, NHTSA was to pursue its regulatory efforts into 2016 and proposed to seek comments on various aspects of the architecture, including the protocols that will ensure interoperability and security (DOT 2015). Manufacturers continue to remain concerned whether V2V communications for advanced safety control system, which operate outside of the driver's full control, increase legal risk when compared with onboard warning systems (NHTSA 2014). NHTSA has made explicit that it does not view "V2V warning technologies as creating new or unbound liability exposure for the industry" (NHTSA 2013, p. 5).

The benefits presented by studies and models for V2V systems will depend on the extent of the deployment and adoption by consumers and the effectiveness of the technological interoperability and vehicle-to-driver interface (RAND 2012). With respect to C/AVs, both the USDOT and NHTSA acknowledge that V2V technology and functionality require additional research and development to produce FMVSS-level test procedures for V2V communication devices and safety applications.

NHTSA feels quite confident that no changes to the Safety Act will be required since the existing law is pliable enough to provide the agency with the broad authority necessary to regulate C/AVs and related equipment, which includes V2V communications from OEMs and most aftermarket equipment with V2V capabilities. According to the V2V Readiness report, NHTSA considers the following items subject to the agency's regulatory authority: any integrated original equipment used for V2V communications or safety applications reliant on V2V communications; any integrated aftermarket equipment used for V2V communications or safety applications reliant on V2V communications; some non-integrated aftermarket equipment, depending on its nature and apparent purpose; software that provides or aids V2V functions and software updates to all of this equipment; and some roadside infrastructure (V2I) to the extent it relates to safety (NHTSA 2014).

In September 2015, NHTSA and the Big 10 Automakers outlined an agreement to include AEB in all new cars starting manufacture year (MY) 2018 (NHTSA 2015a). In October NHTSA put a request for public comment in the Federal Register on Crash Warning System Data Collection (NHTSA 2015b). This follows from an October 9, 2015 NHTSA request for approval on new information collection (NHTSA 2015c).

In November 2015, USDOT as part of its Joint Program Office noted it would provide a total of \$42 million to three applicants seeking pilot projects that demonstrate the feasibility and safety of connected vehicle technology (USDOT 2015a). These three sites include New York, NY (urban testing); Tampa, FL (fringe and transitional area testing), and the State of Wyoming (emissions and rural testing). This pilot program will include the installation of V2I instruments along public and private ROW.

In November 2015 the USDOT deployed a pilot program in New York City for the ITS Testing Wave One: New York City Fleet, V2V and V2I for Urban Roadways (USDOT 2015). USDOT will provide both the City and NYDOT with \$20 million for testing, and will collect data for up to 10,000 cars, buses and limousines. A primary focus is the role of fleets and buses on efficiency, safety, and viability. These vehicles will be retrofitted with the technology in hopes of reducing traffic congestion, curbing greenhouse gas emissions, and making drivers and pedestrians safer on the roads (USDOT 2015b).

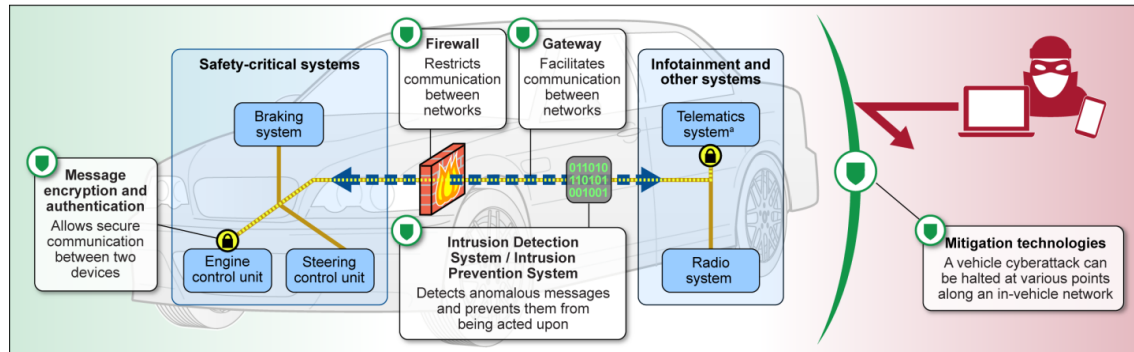
NHTSA issued on November 5, 2015 a final agency decision recommending the use of (a) crash imminent breaking and (b) dynamic break support as key features for Automatic Emergency Breaking (AEB) for consumers purchasing cars after manufacture year 2018 through NHTSA's New Car Assessment Program (NCAP) (Federal Register 2015).

In April 2016 (NHTSA, April 2016) NHTSA issued a request for public comments on safety related defects and emerging automotive technologies. According to the docket summary: "This proposed Enforcement Guidance Bulletin sets forth NHTSA's current views on emerging automotive technologies—including its view that when vulnerabilities of such technology or equipment pose an unreasonable risk to safety, those vulnerabilities constitute a safety-related defect—and suggests guiding principles and best practices for motor vehicle and equipment manufacturers in this context." NHTSA's notice solicited comments from the public,

motor vehicle and equipment manufacturers, and other interested parties concerning the proposed guidance for motor vehicle and equipment manufacturers in developing and implementing new and emerging automotive technologies, safety compliance programs, and other business practices in connection with such technologies.

Reports from Federal Agencies

In April 2016 the GAO assessed vehicle cybersecurity and noted that the USDOT needs to define its role in responding to a real-world attack (GAO 2016). The GAO recommends some key practices to identify and mitigate vehicle cybersecurity vulnerabilities. See, e.g., Table 7.3 and Figure 7.3.



Source: GAO analysis of stakeholder information. | GAO-16-350

^aVehicle telematics systems—which include the dashboard, controls, and navigation systems—provide continuous connectivity to long- and short-range wireless connections.

Figure 7.3 Example of Vehicle’s Cybersecurity Mitigation Technologies Shown along an In-Vehicle Network (GAO 2016 p. 24)

Table 7.3 Key Practices to Identify and Mitigate Vehicle Cybersecurity Vulnerabilities Identified by Industry Stakeholders (GAO 2016 p. 21)

Key practice ^a	Description
Conduct risk assessments	Assess threats and vulnerabilities related to vehicles' electronic systems, including the potential impacts if known vulnerabilities are exploited, to inform and prioritize cybersecurity protections.
Incorporate security-by-design principles	Consider and build in cybersecurity protections starting in the early vehicle-design phases.
Create domain separation for in-vehicle networks	To the extent possible, locate safety-critical systems (i.e., steering, braking, etc.) and non-safety-critical systems on separate in-vehicle networks and limit communication between the safety-critical and non-safety-critical domains.
Implement a layered approach to security	Incorporate cybersecurity protections at multiple vehicle layers (e.g., at the electronic control unit level and the in-vehicle network level) to create multiple hurdles for cyber attackers and reduce the impact of a cyber breach.
Conduct penetration testing	Employ skilled assessors/evaluators who can simulate real-world vehicle cyberattacks in an attempt to identify ways to circumvent and defeat the vehicle's cybersecurity protections.
Conduct code reviews	Employ skilled assessors/evaluators to systematically examine the vehicle's software code so that any mistakes overlooked in the initial development phase can be addressed.
Develop over-the-air update capabilities	Establish mechanisms to remotely and securely update vehicle software and firmware ^b over the life of the vehicle in response to identified vulnerabilities.

Source: GAO analysis of stakeholder interviews. | GAO-16-350

^aThese key practices are organized based on the vehicle development process, beginning with the vehicle concept and design phases and ending with the vehicle operation and maintenance phase.

^b"Firmware" is the combination of a hardware device and computer instructions and data that reside as read-only software on that device.

Several individual states have also been very active in the oversight of C/AVs. Their legal regimes are discussed in the next section. As the end of 2017 at least 30 states had passed legislation to regulate C/AVs). One of the simplest proposals—in Connecticut—simply requires that “the general statutes be amended to allow the use of AVs for testing purposes, and direct[s] the Department of Motor Vehicles to promulgate regulations concerning the use of such vehicles” H.R. 6344, 2015 Gen. Assemb., Reg. Sess. (Conn. 2015).

7.4 Overview of State Laws Governing C/AVs

State regulations of C/AVs currently run the gamut from authorization to operate AVs on public roads in Nevada, to having regulations on testing but not public use in California, to having no regulation on C/AVs in some states. Initially, while the laws varied on important details, most of the states that were actively regulating C/AVs generally imposed some regulatory oversight of testing and/or deployment of C/AVs operating in the state (Kohler & Colbert-Taylor 2015). A few states also impose other restrictions, such as mandated technologies on C/AV vehicles sold in the states and disclosures for consumers regarding the OEM's collection of private information after sale of the vehicle.

Testing and Deployment of C/AVs on Public Roadways

As noted, NHTSA recommends states actually regulate the testing and operation of C/AVs on public highways (NHTSA 2013). At least 30 states explicitly allow C/AVs on at least some public roads only if they meet prescribed criteria. Several states go further and require the issuance of a license or permit as a precondition to operation (Cal. Regs. § 227.04(d); Nev. Regs. § 8.3). Not all states actively regulate testing or distinguish between operating a C/AV for testing versus operating a vehicle for regular deployment, however (e.g., D.C.

Code § 2352). Beyond direct oversight of testing, California and Nevada also required disclosure of accidents and near-misses occurring during testing (Cal. Regs. §§ 227.46, 227.48; Nev. Regs. § 10.4).

Nevada was the first state to enact legislation on C/AVs in 2011, after passing Assembly Bill (AB) 511, which defined “autonomous vehicle” and directed the state DMV to adopt rules for license endorsement and for operation, including insurance, safety standards, and testing (AB 511 2011). The regulations, first adopted in 2012 and later revised in 2013, require applicants show proof of 10,000 AV operational miles as well as a summary of statistics before being granted a license to test on public roads (Nevada DMV 2013). Nevada within its 2013 amendment to its AV law specified some Level 1, 2, and 3 technologies as not being “autonomous,” noting that autonomous technology means:

technology which is installed on a motor vehicle and which has the capability to drive the motor vehicle without the active control or monitoring of a human operator. The term does not include an active safety system or a system for driver assistance, including, without limitation, a system to provide electronic blind spot detection, crash avoidance, emergency braking, parking assistance, adaptive cruise control, lane keeping assistance, lane departure warning, or traffic jam and queuing assistance, unless any such system, alone or in combination with any other system, enables the vehicle on which the system is installed to be driven without the active control or monitoring of a human operator (Nev. SB 313, 2013).

Testing licenses in Nevada are predetermined and limited to specific geographic zones, although these may be enlarged (Nev. Rev. State. § 482A.120). General requirements that span across all AV testing in Nevada include having two persons physically in the vehicle while testing, including one person in the driver’s seat who is able to take control (Nevada DMV 2013). After testing is successful, the deployment of an AV is allowed in Nevada only after issuance of a “certificate of compliance,” issued by the manufacturer or a registered sales facility. The certificate can be issued only if the vehicle meets requirements set forth in Nevada regulations (Nev. Regs. § 16).

Florida adopted some of the provisions of Nevada law, but the State exerts considerably less control over manufacturers wishing to test AVs on public roadways and places no geographical restrictions on that testing. “In Florida, when a testing entity presents insurance to the Department and pays the title fees, the Department will brand the vehicle title ‘autonomous’ and ‘autonomous vehicle’ will print on the registration certificate” (Florida DHSMV 2014, p. 5). Thus, although there are certain standards required of AVs tested or deployed in the State, including a \$5 million proof of insurance and vehicle certification, “the Department does not require an application or otherwise regulate the testing entity.” The Department also does not have the authority to deny a request to test AVs in the State. Florida amended its legislation in July 2016.

California legislation and regulation provides similar types of oversight for AV testing. In contrast to Nevada, however, testing on AVs can occur on all roads in the state. Like Nevada, however, vehicle manufacturers must obtain a testing permit from the DMV and comply with permit requirements when testing AVs on California roads (California DMV 2012). California DMV requirements for manufacturer testing include registering the AV with the DMV, completing previous AV testing under controlled conditions, using qualified test drivers who sit in the driver’s seat with the ability to take control of the AV, and a \$5 million insurance or surety bond maintained by the manufacturer (CA Vehicle Code 38570(A)(5)). In order to deploy a vehicle in California after testing, the vehicle must be approved by the California DMV.

Michigan allows C/AV testing so long as the vehicle is operated by an authorized agent of the manufacturer, and an individual is present in the vehicle and able to take control immediately if necessary. But the State specifically bans operation of AVs for non-testing purposes (Mich. Comp. Laws §§ 257.663, 665). Tennessee legislation, by contrast, prohibits any political subdivision of the state from prohibiting the use of an AV so long as the vehicle complies with all safety regulations of the political subdivision (SB 598 2015).

Michigan amended its laws in late 2016 and driverless cars are now able to be driven for any of the following purposes: personal use; road testing; as part of a SAVE program or “on-demand automated vehicle network;” and as part of a platoon. For example, under SB 995-998, the list of eligible drivers will expand to include

people driving for personal use,⁴ university researchers who are conducting road-testing, and⁵ Michigan DOT employees who are conducting road-testing.⁶

This means HAVs, or driverless cars, will operate without a human driver or any human present in the car. Under existing law, even driverless cars that are being road-tested must have an “individual present” who “has the ability to monitor the vehicle’s performance and, if necessary, immediately take control of the vehicle’s movements.”⁷ However, under the changes described above to SB 995-998, an “automated motor vehicle” can be “operated without any control or monitoring by a human operator.”⁸ The artificial intelligence (AI) or computer will now be considered the “driver,” as specified in the following passage from that SB:⁹

When engaged, an automated driving system allowing for operation without a human operator shall be considered the driver or operator of a vehicle for purposes of determining conformance to any applicable traffic or motor vehicle laws and shall be deemed to satisfy electronically all physical acts required by a driver or operator of the vehicle.¹⁰

Michigan’s SB 995 defines an “on-demand automated motor vehicle network” as, “a digital network or software application used to connect passengers to automated motor vehicles for transportation between locations chosen by the passenger when the automated motor vehicle is operated without any control or monitoring by a human operator.”¹¹ This allows auto manufacturers to enter the app-based ridesharing world with HAVs. SB 995 defines a “platoon” as a “group of individual motor vehicles that are traveling in a unified manner at electronically coordinated speeds.”¹² To be able to operate AVs as part of a platoon, a plan for general platoon operations has to be filed for approval from the Michigan State Police and State DOT.¹³

Michigan’s SB 996 covers the SAVE Project,¹⁴ which is an “initiative that authorizes eligible motor vehicle manufacturers to make available to the public on-demand automated vehicle networks.”¹⁵ Vehicles in the SAVE fleet must have an “automated driving system,” “automatic crash notification technology” and a “data recording system” that keeps track of the AV’s “status” and the vehicle’s speed, direction, and location before a crash. Incident reports must be kept,¹⁶ and liability requires that, “For each SAVE project in which it participates, during the time that an automated driving system is in control of a vehicle in the participating fleet, a motor vehicle manufacturer shall assume liability for each incident in which the automated driving system is at fault.”¹⁷

It should be noted that SBs 995–997 do not follow the recommendations put forth in NHTSA’s 2016 AV guidance document in two crucial areas: setting minimum insurance coverage levels required for road-testing C/AVs/HAVs, and determining when manufacturers of driverless cars are liable for accidents caused by the C/AV/HAV they produced. For example, SB 996 provides that “a motor vehicle manufacturer shall assume liability for each incident in which the automated driving system is at fault,” subject to the state’s existing insurance code — but only for SAVE projects.¹⁸

SBs 995–997 also do not change current Michigan laws on liability for road-testing self-driving vehicles. All that a manufacturer must have in the way of insurance coverage is the same minimum liability that all

⁴ MICH. S.B. 995, page 10, lines 24-25, amendment to 257.665

⁵ Id., MICH. S.B. 955 at 10

⁶ Id. MICH. S.B. 955 at 10

⁷ MICH. COMP. LAWS 257.665(2)(b).

⁸ MICH. S.B. 995 at 10.

⁹ MICH. S.B. 995, at 10-11.

¹⁰ Id.

¹¹ Concurred MICH. S.B. 995, page 4, lines 13-19.

¹² MICH. S.B. 995 at?

¹³ MICH. S.B. 995, Sec. 40.c.

¹⁴ <http://www.legislature.mi.gov/documents/2015-2016/billintroduced/Senate/htm/2016-SIB-0996.htm>.

¹⁵ MICH. S.B. 995, at 5, ln.1-4.

¹⁶ MICH. S.B. 996

¹⁷ MICH. S.B. 996, pg. 4.

¹⁸ MICH. S.B. 996, sec. 665.B.4.

Michigan cars must have: \$20,000 in personal injury liability and \$10,000 in property damage liability.¹⁹ Legislators, potential victims, and manufacturers need to take notice of this oversight (Gurston, 2016). SB 995,996 and 997 all entered into law in November 2016.

Taking a slightly different approach, the District of Columbia enacted the Autonomous Vehicle Act of 2012, which expressly allows the operation of AVs on District roadways (D.C. Code §§ 50-2351 to -2354). The District requires only that a vehicle must have a manual override and a driver in the driver's seat ready to take over, and operate in compliance with the District regulations, D.C.'s other normal traffic laws and regulations (§50-2351). Rules to implement the law are being promulgated by the DMV, including procedures for registration and issuance of permits to operate AVs (Kohler & Colbert-Taylor 2015, p.117).

In 2015, both Arizona (EO 2015) and Virginia announced their decision to move forward with research and development of AV operations. In Arizona, Governor Doug Ducey signed Executive Order (EO) 2015-09 in August directing various agencies to "undertake any necessary steps to support the testing and operation of self-driving vehicles on public roads within Arizona" (Ducey 2015). The EO establishes the Self-Driving Vehicle Oversight Committee within the governor's office to develop regulations for enabling the development and operations of AV pilot programs at selected universities.

Utah in May 2016 authorized an autonomous motor vehicle study. HB 280 authorized that each agency of the state with regulatory authority impacting autonomous vehicle technology testing shall facilitate and encourage the responsible testing and operation of autonomous vehicle technology within the state. The bill authorizes that the departments of Public Safety, Motor vehicles, Transportation and Technology Services can contract and partner with groups for testing autonomous vehicles in the state. The Department of Public Safety, in consultation with other state agencies, including the Division of Motor Vehicles and the Department of Transportation, shall study, prepare a report, and make recommendations regarding the best practices for regulation of autonomous vehicle technology on Utah highways. The study shall include:

- 1) evaluation of standards and best practices suggested by the National Highway Traffic Safety Administration and the American Association of Motor Vehicle Administrators;
- 2) evaluation of appropriate safety features and standards for autonomous vehicles in the unique weather and traffic conditions of Utah;
- 3) evaluation of regulatory strategies and schemes implemented by other states to address autonomous vehicles, including various levels of vehicle automation;
- 4) evaluation of federal standards addressing autonomous vehicles; and
- 5) recommendations on how the state should address advances in autonomous vehicle technology through legislation and regulation.

A report was due in December 2016 to house and senate committees that included recommendations and findings.

Vehicle Requirements

NHTSA and the ULC both endorse several basic design features in AVs used for testing or deployment. These include a device that allows for quick disengagement from automated mode; a device that indicates to others whether the vehicle is operating in automated mode; and a system to warn the operator of malfunctions (ULC 2014, p.9). Several state laws include one or all of these requirements for AVs sold in the state. These states include California, Florida, D.C., and Nevada (ULC 2014 p. 9-10).

Individual states have also imposed other requirements. Nevada has required that EDRs capture data 30 seconds before a collision in AVs and preserve the data for 3 years (Nevada DMV 2014). Similarly, the District of Columbia's DMV issued guidelines in June 2014 that require that EDRs be completely separate from all other data systems, must provide data in a read-only format when requested, and must retain all data

¹⁹ MICH. COMP. LAWS 257.665(1); 500.3101; 500.3009(1). See also, Ch. 31 of the Michigan Insurance Code of 1956, 1956 PA 218, MICH. COMP. LAWS 500.3101 to 500.3179.

for at least 3 years following a collision (District of Columbia DMV 2014). California also requires a crash data recorder for AVs sold to the public and the State imposes detailed requirements governing the capabilities of the recorders (Cal. Vehicle code § 38750(c)(1)(G)).

Tennessee's SBN 1561, which was enacted in 2016 established certification program through its department of safety for manufacturers of AVs before such vehicles may be tested, operated, or sold. The law was enrolled and chaptered on April 27, 2016 at Pub.Ch 927. It also created a per mile tax structure for AVs (with a "use tax" that is in addition to the traditional gas tax). The Act distinguishes between a non-operator-required autonomous vehicle (NORAV) and an operator-required autonomous vehicle (ORAV).²⁰

Tennessee's SB 2333, which was enrolled and chaptered on March 22, 2016, allows a motor vehicle to be equipped with an integrated electronic display visible to the operator while the motor vehicle's autonomous technology is engaged.

Arkansas enacted HB 1754 on April 1, 2017 that regulates the testing of vehicles with autonomous technology and specifically added provisions regarding DATP systems and reduced the following distances of such systems.

The Act defines "driver-assistive truck platooning system" as technology that integrates sensor array, wireless communication, vehicle controls, and specialized software to synchronize acceleration and braking between two or more vehicles while leaving the designated vehicle's steering control and systems command in the control of its human operator. It additionally defines "autonomous technology" as technology installed on a motor vehicle that has the capability to drive the vehicle without the active physical control or monitoring by a human operator for any duration of time. "Autonomous vehicle" is defined as a vehicle equipped with autonomous technology that can drive the vehicle without the active physical control or monitoring of a human operator for any duration of time.

The Act amended Arkansas Code §27-51-305 regarding following too closely to not prevent overtaking and passing of vehicles equipped with DATP systems. Under the Act at Section 1 (c) vehicles equipped with DATP systems may follow other vehicles closer than allowed under subsection (a) and (b) (1).²¹ DATP is defined as technology that "integrates sensor array, wireless communication, vehicle controls, and specialized software to synchronize acceleration and braking between 2 or more vehicles while leaving a designated vehicle's steering control and systems monitoring in the control of its human operator."

Section 2 of the bill amends Arkansas Code Title 27, Chapter 51 at Subchapter 15, (§27-51-1408) to add an additional section that authorizes DATP truck platooning systems on a street or highway if a plan for general platoon operations is filed with the State Highway Commission. A person may operate a DATP system upon plan approval by the State Highway Commission, or after 45 days if the plan is not rejected by the State Highway Commission.

Operator Requirements

NHTSA recommends that an endorsement or separate driver's license should be issued for operators of C/AVs certifying that the operator has passed a test concerning safe operation of the C/AV or completed a certain number of hours operating the vehicle (NHTSA 2013).

²⁰ A NORAV is defined an autonomous vehicle that may have operational controls for a human operator, including a steering wheel, accelerator, or brake, but does not require a human operator to be present in the vehicle during vehicle operation. There are two special license requirements for operators of NORAVs appropriate to the class of vehicle based on weight rating or number of passengers. An ORAV is defined as an autonomous vehicle equipped with operational controls for a human operator, including steering wheel, accelerator, and brake, and requires a human operator to be present in the vehicle for vehicle operation.

²¹ These previously required a motor vehicle to follow not more closely than reasonably prudent having due regard for speed and trucks on a roadway outside of a business or residence district could not follow within 200 feet of another vehicle

Consistent with NHTSA’s recommendations, both Michigan and Nevada testing regulations for AVs require a special driver’s license certification and license plates (Nev. Admin. Code §§ 482A.040, .050, .110 (2014)). Nevada, the first state to enact AV legislation, has only briefly addressed private individuals as operators of AVs, stating that “[w]hen autonomous vehicles are eventually made available for public use, motorists will be required to obtain a special driver license endorsement and the DMV will issue green license plates for the vehicles.”

California lays out detailed requirements for an AV driver test: the manufacturer must identify the operator in writing to the DMV; the operator must have been licensed to drive a motor vehicle for at least 3 years immediately preceding application and can provide proof that during that time that the operator did not have more than one violation of specific sections of the vehicle code (Cal. Regs. §§ 227.18, 227.20). The AV operator must also have completed the manufacturer’s AV training program, which includes, but is not limited to, instructions on AV technology and defensive driver training (California DMV 2012).

Development of Definitions for Driver, Operating System and Dynamic Driving Tasks

Connecticut, in SB 260—which was enacted on June 27, 2017—defined the terms “fully autonomous vehicle,” “automated driving system,” and “operator.” The bill requires the development of a pilot program for up to four municipalities for the testing of fully autonomous vehicles on public roads in those municipalities. It specifies the requirements for testing, including having an operator seated in the driver’s seat and providing proof of insurance of at least \$5 million.

Colorado’s SB 213, effective on August 1, 2017, provides definitions for “automated driving system,” “dynamic driving task,” and “human operator.” The Act notes that the use of motor vehicles with Level 0 through 3 automations as defined by SAE J3016 is legal under Colorado law with a human driver in the vehicle and is not addressed in the Act.

“*Automated driving system*” is defined as hardware and software that are collectively capable, without intervention or supervision by a human operator, of performing all aspects of the dynamic driving tasks for a vehicle on a part-time or full-time basis, described under J3016 as Levels 4 and 5. “*Dynamic driving task*” is defined to include all of the following:

- Operational aspects, including steering, braking, accelerating, and monitoring the vehicle and the roadway;
- Tactical aspects, including responding to events, determining when to change lanes, turning, using signals, and other related actions.

Dynamic driving task does not include strategic aspects of driving, including determining destinations or way points.

The Act allows a person to use an automated driving system to drive or control a function of a motor vehicle if the system is capable of complying with every state and federal law that applies to the function that the system is operating. If the vehicle cannot comply with every relevant state and federal law, it must be submitted for approval via vehicle testing. The department must submit a report on the testing of the automated driving systems by September 1, 2018. The Act preempts state agencies and local jurisdictions from adopting or enforcing a policy, rule, or ordinance that sets standards for an automated driving system different from standards set for a human driver.

In the 85th Texas Legislature in 2017, two bills, both now in law, created the entrance of Texas into the realm of states with statutes regarding C/AVs/HAVs. SB 2205 does not authorize any of the state’s transportation

agencies, or law enforcement members with any rule making powers, but rather²² sets out a series of definitions²³.

“Automated driving system” is defined to mean hardware and software that, when installed on a motor vehicle and engaged, are collectively capable of performing the driving task without any intervention or supervision by a human operator. This includes all aspects of the entire dynamic driving task for the vehicle on a sustained basis and fallback maneuvers necessary to respond to a failure of the system.

- “Automated motor vehicle” is defined as a motor vehicle on which an automated driving system is installed.
- “Entire dynamic driving task” is defined as the operational aspects (steering, braking, accelerating, and monitoring the vehicle and the roadway) and tactical aspects (responding to events, determining when to change lanes, turning, using signals, and other related actions) of operating a vehicle. However, it does not include strategic aspects, including determining destinations or waypoints.
- “Human operator” is defined as a natural person in an automated motor vehicle who controls the entire dynamic driving task and “Owner” has the meaning assigned by current statute.

The subchapter and the department (DMV) govern exclusively unless otherwise indicated. The major items governed exclusively include AVs, with any commercial use or operation of AVs, and automated driving systems.²⁴

The act sets out duties for an operator when the automated driving system installed on a motor vehicle is engaged. Under this section, the owner of the automated driving system is considered to be the operator of this vehicle solely for the purpose of assessing compliance with applicable traffic or motor vehicle laws, regardless of whether the person is physically present in the vehicle while the vehicle is operating.

The automated driving system is considered to be licensed to operate the vehicle, when it is engaged. A licensed human operator, notwithstanding any other law, is not required to operate the motor vehicle if the installed automated driving system is engaged. The automated vehicle is authorized to operate in the state when it is engaged, without a human operator being physically present in the vehicle.

However, the automated vehicle, cannot operate on a highway in this state when it is engaged in automated mode unless the vehicle is:

- capable of operating in compliance with applicable traffic and motor vehicle laws of this state, subject to this subchapter;
- equipped with a recording device (as defined by current code) installed by the manufacturer of the automated motor vehicle or automated driving system;
- equipped with an automated driving system in compliance with applicable federal law and federal motor vehicle safety standards;
- registered and titled in accordance with the laws of this state; and
- covered by motor vehicle liability coverage or self-insurance in an amount equal to the amount of coverage that is required under the laws of this state.

The Act sets out that the duties required of the owner or operator after an incident involving the AV occurs shall comply with existing code.

For vehicle classification, the Act states that an owner *may* identify the vehicle to the DMV as having an automated driving system, or as an *automated motor vehicle*.²⁵ This section may also need amendment, as

²² SB, 2205, Sec. 545.452 (b).

²³ SB 2205, Sec 545.451

²⁴ SB2205, Sec 545.452 (a)

²⁵ SB 2205, Sec 545.456 Vehicle Classification for owner defined by Section 502.001 (31)

DMVs and state public safety providers may need to know the vehicle is automated for reasons of traffic safety regulations, if the licensing entity needs to provide data to law enforcement for purposes of determining the status of the vehicle after an incident, or if a criminal activity takes place.

Under the Act, after an incident occurs "a request to intervene" is defined as the notification by a vehicle to the human operator that the operator should promptly begin or resume performance of the entire dynamic driving task. This section is unclear, as the Act authorizes the movement of an AV without a human being present in the vehicle, so if the operator is not present, the terms "promptly begin or resume performance" will need to be defined for a vehicle without a human inside it. Finally, the Act concludes that:

- A motor vehicle equipped with hardware and software be capable of engaging in the entire dynamic driving task with the expectation that a human operator will respond appropriately to a request to intervene subject to the various sections of this Act; and
- Nothing as added by this Act, shall be construed to affect, alter, or amend the right to operate a motor vehicle equipped with hardware and software capable of performing the entire dynamic driving task with the expectation that a human operator will respond appropriately to a request to intervene.

Clarification of Liability Standards and Insurance Requirements

Several states impose special insurance requirements on C/AVs before they can be tested or deployed on public roads. Both California and Nevada, for example, impose a \$1–5 million insurance requirements before allowing testing of AVs on public roads (Cal. Vehicle Code § 3875(b)(3); Nev. Regs. § 8.4; Fla. Stat. § 316.86). Michigan, by contrast, does not impose additional insurance requirements on AVs for testing or deployment purposes (Mich. Comp. Laws § 257.665(1)).

Florida, Nevada, and the District of Columbia have liability protection for post-sale conversion of vehicles to AVs (Boske and Harrison 2014). Liability protection is given to OEMs whose vehicles are converted to C/AVs. California, however, has no explicit mention of such liability protection.

Following Distances and other Platooning Requirements

States have also begun to set up statutes regarding platooning and following distances. On May 9, 2017 Georgia enacted HB 472 which provides an exception for following requirements for vehicles following in a procession when speed of the non-leading, participating vehicles are coordinated automatically and it also repealed conflicting laws. HB 472 specifies that the law prohibiting following too closely does not apply to the non-leading vehicle in a coordinated platoon. It defines "coordinated platoon" as a group of motor vehicles traveling in the same lane utilizing vehicle-to-vehicle communication technology to automatically coordinate the movement of the vehicles.

South Carolina's HB 3289, enacted on May 31, 2017, relates to the distance that must be maintained between vehicles traveling along a highway, and provides that this section does not apply to the operator of any non-leading vehicle traveling in a procession of vehicles if the speed of each vehicle is automatically coordinated.

The Act revised the term "driver" to "operator" in regard to these vehicles. At section (b) it notes that "the operator of a truck or motor vehicle that is drawing another vehicle traveling upon a roadway outside of a business or residence district and which is following another truck or motor vehicle drawing another vehicle shall, whenever conditions permit, leave sufficient space so that an overtaking vehicle may enter and occupy such space without danger, except that this shall not prevent a truck or motor vehicle drawing another vehicle from overtaking and passing any vehicle or combination of vehicles."

For motor vehicles operated upon roadways outside a business or residence district in a caravan or motorcade—whether or not towing other vehicles—shall be operated as to allow sufficient space between each vehicle or combination of vehicles to enable any other vehicle to enter and occupy such space without danger. This Act does not apply to the operator of any non-leading commercial motor vehicle subject to federal motor carrier safety regulations and traveling in a series of commercial vehicles using cooperative adaptive cruise control or any other automated driving technology.

Section 2 of Arkansas' HB 1754 amends Arkansas Code Title 27, Chapter 51 at Subchapter 15, (§27-51-1408) to add an additional section that authorizes DATP truck platooning systems on a street or highway if a plan for general platoon operations is filed with the State Highway Commission. A person may operate a DATP system upon approval of the plan by the State Highway Commission, or if after 45 days the plan is not rejected by the State Highway Commission. The bill was enacted as at April 1, 2017.

The Act defines “*driver-assistive truck platooning system*” as technology that integrates sensor array, wireless communication, vehicle controls, and specialized software to synchronize acceleration and braking between two or more vehicles while leaving the designated vehicle’s steering control and systems command in the control of its human operator. It additionally defines “*autonomous technology*” as technology installed on a motor vehicle that has the capability to drive the vehicle without the active physical control or monitoring by a human operator for any duration of time. Finally, “*autonomous vehicle*” is defined as a vehicle equipped with autonomous technology that can drive the vehicle without the active physical control or monitoring of a human operator for any duration of time. The Act amended Arkansas Code §27-51-305 regarding following too closely to not prevent overtaking and passing of vehicles equipped with DATP systems. Under the Act at Section 1 (c) vehicles equipped with DATP systems may follow other vehicles closer than allowed under subsection (a) and (b) (1). These previously required a motor vehicle to follow not more closely than reasonable prudent having due regard for speed, and for a motor truck on a roadway outside of a business or residence district could not follow within 200 feet of another vehicle.

In April 2017, Tennessee enacted SB 676, which permits the operation of a platoon on streets and highways in the state after the person provides notification to the department of transportation and the department of safety. “*Platoon*” is defined as a group of individual motor vehicles that are traveling in a unified manner at electronically coordinated speeds.

Creation of Working Groups

In the United States, some states have resolved to study/research AVs, while some have prohibited any resolution for banning AVs, and others have attempted to make or amend legislation regarding liability in accidents.

Authorization for Studies/Research

Some states still seem to be in the watch and see type of role, and legislation and executive orders require the creation of a study group, or research product to be supplied. In Washington State, for example, the governor signed an executive order in June 2017 (Washington State Governor: EO 17-02, 2017) to set up an autonomous vehicle work group and to begin to address autonomous vehicle testing and enabling pilot programs within the state. The working group is to have at least one representative from the Governor’s office, and from other state agencies (that are listed). Pilot programs are authorized within the state in partnership with entities developing autonomous vehicle technology equipment. Pilot programs conducting testing and operation of autonomous vehicles with human operators physically present in the vehicle shall comply with these requirements:

- “Vehicles shall be operated or monitored only by a trained employee, contractor, or other person authorized by the entity developing autonomous technology.
- Vehicles shall be monitored, and an operator must have the ability to direct the vehicle’s movement if assistance is required.
- Individuals able to exercise operational control of an autonomous vehicle during operation shall possess a valid U.S. driver license.
- Vehicle owners shall attest to proof of financial responsibility as required by RCW 46.30.020.
- Developing entities shall self-certify to DOL that they are compliant with the above requirements before beginning a pilot program.”

In addition, the pilot programs that are conducting testing without a human operator present in the vehicle shall comply with these requirements:

- “Vehicles shall be equipped with an automated driving system that performs all aspects of the driving task on a part- or full-time basis within the vehicle’s operational design limits, and it must be capable of bringing the vehicle to a safe condition in the event of a system failure.
- Vehicles shall be capable of being operated in compliance with Washington State motor vehicle laws relevant to the vehicle’s operational design limits.
- Vehicle owners shall attest to proof of financial responsibility as required by RCW 46.30.020.
- Developing entities shall self-certify to DOL that they are compliant with the above requirements before beginning a pilot program.”

In Wisconsin, the Governor signed an executive order in May 2017 that will create a Steering Committee on Autonomous and Connected Vehicle Testing and Deployment (Wisconsin, 2017).

In North Dakota HB 1065²⁶, passed March 23, 2015, directed agencies to prepare a report – to be conducted in the 2015–2016 interim period – that could include research into the safety implications of C/AVs/HAVs and recommend any additional legislative or regulatory action. The legislative management team were directed to report findings and recommendations along with any legislation required to implement the recommendations to the 65th legislative assembly in January 2017. “Automated vehicle” was defined using the SAE Level 5 – Full Automation terms, where the unconditional, full-time performance of all aspects of the dynamic driving task is accomplished by an automated driving system.

In 2017, HB 1202²⁷ was passed which will require the North Dakota department of transportation to study the use of vehicles equipped with AVs and the data issues associated with those vehicles. In addition, the study will include a review of current laws dealing with licensing, registration, insurance, data ownership and use, and inspection and how they should apply to vehicles with automated driving systems. North Dakota’s DOT will report this study to the 66th legislative assembly of North Dakota.

Prohibitions on local jurisdictions creating any ordinances, zoning codes or resolution for banning AVs

Tennessee’s 2017 SB 151 prohibits political subdivisions, by ordinance, resolution, or any other means, from banning or regulating the use of an ADS-operated vehicle or SAVE project that is operating under the Act’s authority and otherwise complies with all laws of the political subdivision.

Texas SB 2205²⁸, which was enacted on September 1st, 2017 precludes political subdivisions or state agencies from imposing a franchise or other regulation related to the operation of an AV or automated driving system. The Act also does not authorize any of the state’s transportation agencies, or law enforcement members with any rule making powers, but rather ²⁹sets out a series of definitions³⁰.

Other Types of Provisions

Michigan’s SB 998, which was authorized in November 2016, protects mechanics from civil liability: the bill provides that “a motor vehicle mechanic or a motor vehicle repair facility that repairs an automated motor vehicle according to specifications from the manufacturer of the automated motor vehicle is not liable in a

²⁶ HB 2065. 2015. <http://www.legis.nd.gov/assembly/64-2015/documents/15-0167-03000.pdf>

²⁷ HB 1202. 2017. <http://www.legis.nd.gov/assembly/65-2017/documents/17-0711-04000.pdf>

²⁸ SB 2205. 2017. <http://www.capitol.state.tx.us/BillLookup/History.aspx?LegSess=85R&Bill=SB2205>

²⁹ SB, 2205, Sec. 545.452 (b).

³⁰ SB 2205, Sec 545.451

product liability action for damages resulting from the repairs.”³¹ SB 998 was presented to the Governor for signature on November 30, 2016.

California’s Proposed Regulation Amendments Drafted in 2017

After receiving feedback from manufacturers, organizations, consumers, local governments, insurance companies and other stakeholders, the California DMV has amended its approach and developed proposed regulations in March, October and November 2017. This new regulatory framework may help California’s reputation as an innovative state and promote the development of HAVs. California is currently the strictest of the states with regard to HAV regulations, so the regulatory framework it implements may be scrutinized as a possible model for various states hoping to regulate the future of HAVs in their states.³²

On March 10, 2017, the DMV proposed to amend Article 3.7³³ related to the testing of AVs (including those with no human driver) and adding Article 3.8 related to the public deployment of AVs. Senate Bill 1298 (Chapter 570; Statutes of 2012)³⁴ enacted Vehicle Code §38750 which requires the DMV to adopt regulations necessary to ensure the safe operation of AVs on public roads, with or without the presence of a driver inside the vehicle. In 2014, the DMV initially adopted regulations for the testing of AVs that required the presence of a driver inside the vehicle; however, HAV technology has improved since then, necessitating adjustments to existing policy.

AVs are now to be defined as SAE Levels 3–5³⁵ only in order to avoid confusion with vehicles that use advanced driver assistance systems (ADAS) but which are “not capable of, singularly or in combination, performing the dynamic driving task on a sustained basis without the constant control or active monitoring of a natural person.”³⁶ By limiting the HAV regulations to SAE Levels 3–5, California can also control any attempted application to SAE Level 0–2 vehicles already deployed on public roads (e.g., cars equipped with ADAS currently in use on the public roads).

In a big departure from previous 2014 testing regulations, the newly proposed regulations do not require the presence of a driver for testing and deployment purposes. In allowing testing of fully “driverless” vehicles, California is recognizing technological progress³⁷ and is poised to join Michigan³⁸ and possibly other states in accepting the presence of HAVs on the roadway, at least for testing purposes.

While the automotive industry still objects to California making NHTSA’s *voluntary* federal process mandatory,³⁹ the DMV has chosen to keep this provision in its newest, updated draft regulations. Under the

³¹ MICHIGAN S.B. 998. Sec. 3

³² <https://www.wired.com/2017/03/californias-finally-ready-truly-driverless-cars/>, (“The DMV’s rules are going to shift a big part of the conversation to the federal level,” says Bryant Walker Smith, who studies self-driving vehicles at the University of South Carolina. Federal regulators seem eager to advance autonomy (chiefly for the safety benefits), so what happens on California’s roads may well be replicated across US, and even internationally.)

³³ See Express Terms, Title 13, Division 1, Chapter 1, Article 3.7, Testing of Autonomous Vehicles; https://www.dmv.ca.gov/portal/wcm/connect/caa2f466-fe0f-454a-a461-f5d7a079de49/avexpressterms_31017.pdf?MOD=AJPERES

³⁴ SB 1298: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201120120SB1298

³⁵ Note: Under new CA Manufacturer Responsibility Regulations, level 3 is notably absent.

³⁶ See Art. 3.7, Testing of Autonomous Vehicles, Definitions, § 227.02 (b); also amended to use terminology of “automotive engineering”; see also pg. 4, Initial Statement of Reasons.

³⁷ See Initial Statement of Reasons (Initial Statement), supporting the revised Draft Regulations: the DMV notes that “since the adoption of the current testing regulations, the capabilities of autonomous technology have proceeded to the point where manufacturers have developed systems that are capable of operating without the presence of a driver inside the vehicle.” Therefore the revised draft regulations allow for the “testing of vehicles that do not require the presence of a driver inside the vehicle” and “ensure the testing of such vehicles is conducted on California roads in a safe manner.”

³⁸ See Michigan S.B. 996, 12/9/16, HAV legislation)

³⁹ https://cei.org/content/cei-comments-california-dmv-autonomous-vehicle-regulations#_ftn4, Due to the voluntary nature of the NHTSA Guidance, CEI stated in its comments to the DMV that the DMV should remove all references to the Safety Assessment Letter from its final testing and deployment rules.

proposed regulations, if a vehicle diverges from a “conventional vehicle design”⁴⁰ (e.g., exclusion of manual controls, etc.) and is not able to certify to current FMVSS, an approved exemption letter from NHTSA is requested by the California DMV.⁴¹ Unless granted an exception by NHTSA (or as allowed by Federal law), a vehicle cannot be sold with technology that makes inoperative any of the existing federal safety standards adopted by NHTSA (i.e., FMVSS).

According to page 2 of the DMV’s Reasons:

*“The proposed regulations require manufacturers to certify that their autonomous vehicles meet FMVSS. For vehicles that diverge from conventional vehicle designs, the department proposes that the manufacturer provide evidence of an approved exemption from NHTSA or an exemption authorized by Federal law. For testing without a driver and deployment of all levels of autonomous vehicles, the proposed regulations require the manufacturer to submit a copy of their 15-point safety assessment letter submitted to NHTSA pursuant to the “Vehicle Performance Guidance for Automated Vehicles” in NHTSA’s Federal Automated Vehicles Policy. The manufacturer’s participation in the safety assessment process provides further evidence to the department that the manufacturer has engaged in a robust design, development, and testing process and is collaborating with NHTSA at the federal level on vehicle safety topics.”*⁴²

In claiming that the copy of the NHTSA letter is “evidence” that the manufacturer has engaged in a “robust design...process,” the California DMV has elevated the letter beyond its voluntary submission to NHTSA (NHTSA, 2016e at page 15). Manufacturers and consumer groups alike are unhappy with the uncertainty about the letter’s requirements and have submitted comments on the lack of Federal standards for HAVs. When the Senate Commerce Committee was working on a bipartisan HAV deployment bill in February, it took testimony from GM, Volvo, Toyota, Lyft and the RAND Center about the lack of traditional rulemaking on the federal government’s part.⁴³

California requires AV developers to submit to the DMV the same “safety assessment” letter they are required to provide to NHTSA. Some groups, such as Consumer Watchdog, have called this practice “irresponsible” (FixedOpsBusiness, 2017) because then the developer then essentially controls HAV safety determinations. Consumer Watchdog has stated that the DMV’s proposed regulations are fundamentally flawed because they rely on the federal government to set enforceable safety standards for AVs. According to Consumer Watchdog,

“...as the DMV’s Initial Statement of Reasons notes, NHTSA has not adopted any regulations governing the testing or operation of automated, or self-driving, vehicles on public roads, streets, and highways. So, there is no federal safety standard specifically governing autonomous technology and NHTSA’s policy amounts to asking automakers voluntarily to please drop a letter in the mail that says, ‘yes, we thought about these issues’” (FixedOpsBusiness, 2017).

Consumer Watchdog argues that anchoring California’s AV policy to federal policies and not actual standards cannot possibly provide adequate protection for the public. Without FMVSS that apply to AVs, California must enact its own safety standards. The DMV’s original AV regulations put safety first, while still allowing responsible innovation. According to Consumer Watchdog, “It is imperative that the Department maintain those high standards, continuing to put public safety first, as it proposes new regulations” (FixedOpsBusiness, 2017).

Previous draft regulations would have required third-party certification and the prerequisite of a testing permit. Under the recent proposed regulations, the state relaxed these requirements. Manufacturers would be allowed to self-certify⁴⁴ and to sell AVs regardless of whether a manufacturer had previously held a state testing permit.

⁴⁰ See p. 2, Initial Statement of Reasons, CA DMV.

⁴¹ See p.2 of Reasons, CA DMV.

⁴² See Initial Statement of Reasons, CA DMV.

⁴³ <https://www.recode.net/2017/2/14/14612280/self-driving-car-regulations-house-commerce-hearing>, Feb. 14, 2017.

⁴⁴ See Initial Statement, p. 3: The DMV rejected the idea of “requiring manufacturers to have a vehicle demonstration test conducted by an independent third party to assess the vehicles’ capability to perform driving tasks and the

The DMV concluded that this former third-party idea would not “uniformly determine”⁴⁵ the safe operation of all vehicles, and thus the current self-certification permit model has many detailed requirements.⁴⁶

The California DMV will require that vehicles meet FMVSS⁴⁷ or have an exemption from NHTSA. California will rely on the federal AV policy guidelines issued last September. Compliance with federal law is still required, so any future requirements added at the federal level (by NHTSA) would apply.

Article 3.7 Testing – sets new rules that require evidence of ability of insurance to cover up to \$5 million,⁴⁸ and certify that for truly driverless HAVs, the manufacturer wanting a testing permit must certify that “to the extent that the autonomous vehicle is at-fault in any collision, the manufacturer shall assume any and all responsibility for liability associated with the operation of the vehicles on public roads.”⁴⁹ Passengers that are not involved in the operation of the HAV when technology is engaged, cannot be charged a fee or receive compensation.⁵⁰

Under the new “Manufacturer’s Testing Permit,” §227.18 (a) has been amended to clarify that manufacturers testing AVs without human drivers (“Driverless” in the regulations) must also apply for AV testing permits.⁵¹ The use of terminology now has Operational Design Domain in which the manufacturer intends to operate,⁵² and the phrase “each ODD” has been added. These changes were necessary because the DMV has added the concept of ODD to the regulations.⁵³

For all test vehicles, the manufacturer shall not test an AV on public roads “unless the manufacturer has tested the autonomous vehicles under controlled conditions that simulate as closely as practicable each ODD in which the manufacturer intends the vehicles to operate on public roads and the manufacturer has reasonably determined that it is safe to operate the vehicles in each ODD.” For HAVs without human drivers, the manufacturer must also inform the DMV “of the intended ODDs of the autonomous vehicle” and agree to provide updates if the ODD’s change.⁵⁴

For HAVs without a human driver, the manufacturer wishing to obtain a testing permit must certify that “the local authorities within the jurisdiction where the vehicle will be tested have been notified of the ODD of the vehicles to be tested and the testing has been coordinated with those local authorities.”⁵⁵ The manufacturer must send to the DMV a copy of the written notifications provided to each local jurisdiction of testing.⁵⁶

submission of a demonstration test report certifying that the vehicles performed as necessary to operate safely on public streets.”

⁴⁵ Id. P. 3.

⁴⁶ See § 228.06 (a) (10) Application for a Permit for Post-Testing Deployment of Autonomous Vehicles on Public Roads ; https://www.dmv.ca.gov/portal/wcm/connect/caa2f466-fe0f-454a-a461-f5d7a079de49/avexpressterms_31017.pdf?MOD=AJPERES

⁴⁷ See § 228.06 (a)(7) “the manufacturer shall certify that the autonomous technology meets (FMVSS)”

⁴⁸ See Requirements for a Manufacturer’s Testing Permit, § 227.04 (c) ; https://www.dmv.ca.gov/portal/wcm/connect/caa2f466-fe0f-454a-a461-f5d7a079de49/avexpressterms_31017.pdf?MOD=AJPERES

⁴⁹ See Express Terms, § 227.38(b), (specifically for driverless HAVs, testing permits).

⁵⁰ See § 227.02 (j) Definitions.

⁵¹ See p. 6, Statement, “Manufacturer’s Testing Permit”, §227.18. (a)

⁵² See p. 7, Express Terms, § 227.18(b) “manufacturer shall not test [an AV] on public roads unless the manufacturer has tested the autonomous vehicles under controlled conditions that simulate as closely as practicable each Operational Design Domain in which the manufacturer intends the vehicles to operate on public roads and the manufacturer has reasonably determined that it is safe to operate the vehicles in each Operational Design Domain.”; https://www.dmv.ca.gov/portal/wcm/connect/caa2f466-fe0f-454a-a461-f5d7a079de49/avexpressterms_31017.pdf?MOD=AJPERES; See also § 38750 Vehicle Code.

⁵³ See p. 7, Express Terms, “Manufacturer’s Testing Permit”, §227.18. (a); https://www.dmv.ca.gov/portal/wcm/connect/caa2f466-fe0f-454a-a461-f5d7a079de49/avexpressterms_31017.pdf?MOD=AJPERES

⁵⁴ See Express Terms, § 227.38(d), (specifically for driverless HAVs).

⁵⁵ See Express Terms, § 227.38(a), (specifically for driverless HAVs, testing permits).

⁵⁶ See Express Terms, § 227.38(a), (specifically for driverless HAVs, testing permits).

California is the only state that requires companies to publicly report accidents and “disengagements”; i.e., when a human intervenes with autonomous mode in unsafe situations. The data has shown an impressive HAV safety record in its annual reports. The proposed regulations added reporting requirements for truly “unmanned” vehicles.⁵⁷ Under the new proposed regulations, manufacturers with test permits for both types of AVs (with or without human driver) must retain “data related to the disengagement of the autonomous mode” and must submit an annual report to the DMV by January 1st of each year.

The annual report must summarize disengagements for each month,⁵⁸ including: (A) whether the vehicle is capable of operating without a driver;⁵⁹ (B) the total number of autonomous mode disengagements⁶⁰; (C) the total number of miles each AV was tested in autonomous mode on public roads; and ⁶¹(D) if a human driver had to take over, the period of time elapsed before the driver assumed manual control (i.e. handoff period).⁶²

For truly driverless AVs, the manufacturer must certify that “there is a communication link between the vehicle and the remote operator to provide information on the vehicle’s location and status and allow two-way communication between the remote operator and any passengers”⁶³ and that the manufacturer will “continuously monitor the status of the vehicle and the two-way communication link while the vehicle is being operated without a driver.”⁶⁴

Public Deployment of AVs

Deployment of AVs is defined in the draft regulations to mean “the operation of an autonomous vehicle on public roads by members of the public who are not employees, contractors or designees or a manufacturer or other testing entity.”⁶⁵ Deployment also includes when a manufacturer “sells, leases or otherwise makes autonomous vehicles available for use outside of a testing program”⁶⁶ and the operation of AVs “outside of a testing program.” California also proposed a change to the state’s current regulations in that the state would no longer require driverless AVs to have conventional manual controls such as steering wheels and pedals, if the vehicle complies with all applicable FMVSS, or the manufacturer provides evidence of an exemption that has been approved by [NHTSA].⁶⁷

In its application for a public deployment permit, manufacturers “shall identify in the application the ODD in which the subject autonomous vehicles are designed to operate and certify that the vehicles are designed to be incapable of operating in the autonomous mode in areas outside of the disclosed ODD.”⁶⁸ The manufacturer shall also identify any commonly occurring or restricted conditions including but not limited to: snow, fog, black ice, wet road surfaces, construction zones, and geofencing by location or road type, under which the vehicles are either designed to be incapable of operating or unable to operate reliably in the autonomous mode and certify that the vehicles are designed to be incapable of operating in autonomous mode under those conditions.⁶⁹ Under the new proposed regulations, manufacturers must certify in the public deployment permit application that the AVs are equipped with an autonomous technology data recorder that captures and stores autonomous technology sensor data for all vehicle functions that are controlled by the autonomous technology at least 30 seconds before and at least 5 seconds after, or until the vehicle comes to a complete stop after a

⁵⁷ See Reporting Disengagement of Autonomous Mode, § 227.50(a).

⁵⁸ See Express Terms, § 227.50 (b)(3).

⁵⁹ See Express Terms, § 227.50(b) (3) (A).

⁶⁰ See other required details, § 227.50(b)(3)(B) (i-vi): (the circumstances, testing conditions, location/type of street, driver presence, facts causing the disengagement - such as weather, road surface, construction, emergency or collision, who/what initiated the disengagement, and the type of incident preempted by the transfer of control to the test driver.

⁶¹ See Express Terms, § 227.50(b) (3) (C).

⁶² See Express Terms, § 227.50(b) (3) (D).

⁶³ See Express Terms, Application for a Permit for Post-Testing Deployment of Autonomous Vehicles on Public Roads, § 228.06 (b)(1)

⁶⁴ See Express Terms, Application for a Permit for Post-Testing Deployment of Autonomous Vehicles on Public Roads, § 228.06 (c) (1) (A).

⁶⁵ See Express Terms, Definitions, § 228.02 (c).

⁶⁶ See Express Terms, Definitions, § 228.02 (c) (1).

⁶⁷ See Express Terms, § 228.06(b) (3).

⁶⁸ See Express Terms, § 228.06(a) (1). (How will this be enforced?)

⁶⁹ See Express Terms, § 228.06 (a) (2).

collision, whichever is later, with another vehicle, person or other object while the vehicle is operating in autonomous mode.⁷⁰

This stored data must be “in a read only format” and “capable of being accessed and retrieved by a commercially available tool.”⁷¹ It is possible that the privacy concerns regarding this regulation will be similar to those raised for EDRs.

The manufacturer seeking an AV’s public deployment must certify that it “has conducted test and validation methods and is satisfied, based on the results of the tests and validations, that the vehicles are safe for deployment on public roads in California.”⁷² The manufacturer must also certify the AV technology “is designed to detect and respond to roadway situations in compliance with all provisions of the California Vehicle Code and local regulation applicable to the operation of motor vehicles, except when necessary for the safety of the vehicle’s occupants and/or other road users.”⁷³ The manufacturer shall also certify “that, when necessary, it will make available updates pertaining to the autonomous technology at least annually or by the effective date of any changes in the California Vehicle Code and local regulation” as applicable to the performance of the dynamic driving task in the vehicle’s ODD.⁷⁴

The manufacturer shall also certify “it will make available updates pertaining to location and mapping information utilized or referenced for the purpose of vehicle location and operation on a continual basis consistent with changes to the physical environment captured by the maps.”⁷⁵ The manufacturer must also provide a “certification that the vehicles have self-diagnostic capabilities that meet current industry best practices⁷⁶ for detecting and responding to cyber-attacks, unauthorized intrusions, and false or spurious messages or vehicle control commands.”⁷⁷ Questions may arise as to whether manufacturer self-certification and mention of best practices are enough to protect HAVs from hacking once they are deployed.

With its deployment permit application, a manufacturer must submit the “test data demonstrating that the manufacturer’s autonomous technology has been tested in the ODD in which the subject autonomous vehicles are designed to operate.”⁷⁸ This data shall include “all locations where the vehicle has been tested,”⁷⁹ and the total number of vehicle test miles driven on public roads in autonomous mode, separately reported for each [ODD] and breaking out California testing from *non*-California testing.⁸⁰ The manufacturer must also provide a description of “the testing methods used to validate the performance of the subject autonomous vehicles”⁸¹ and “the general types of safety-critical incidents encountered during testing and the measures taken to remediate the causes of these incidents.”⁸² Further, the “data shall also include the number of collisions that resulted in damage of property or bodily injury or death and a full description of the causes of collisions and measures taken to remediate the causes.”⁸³

⁷⁰ See Express Terms, § 228.06(a) (5).

⁷¹ Id.; how does this compare to regular vehicle EDR rules?

⁷² See Express Terms, § 228.06(a) (10).

⁷³ See Express Terms, § 228.06(a) (8).

⁷⁴ See Express Terms, § 228.06(a) (8) (A).

⁷⁵ See Express Terms, § 228.06(a) (8) (B).

⁷⁶ Industry best practices for cyber-safety have been published by the NHTSA (National Highway Transportation Safety Administration), <https://www.nhtsa.gov/press-releases/us-dot-issues-federal-guidance-automotive-industry-improving-motor-vehicle>, and Auto-ISAC (Automotive Information Sharing and Analysis Center), <https://www.automotiveisac.com/best-practices/>

⁷⁷ See Express Terms, § 228.06(a)(9), https://www.dmv.ca.gov/portal/wcm/connect/caa2f466-fe0f-454a-a461-f5d7a079de49/avexpressterms_31017.pdf?MOD=AJPERES

⁷⁸ Express Terms, § 228.06(a)(7).

⁷⁹ Express Terms, § 228.06(a)(7).

⁸⁰ Express Terms, § 228.06(a)(7)(A).

⁸¹ Express Terms, § 228.06(a)(7)(B).

⁸² Express Terms, § 228.06(a)(7)(C).

⁸³ Express Terms, § 228.06(a)(7)(D).

Local Jurisdiction Activities

Cities have also attempted to regulate C/AVs/HAVs, through amendments to their city ordinances. It should be noted that some cities are allowing pilot tests to occur without any formal legal changes. For example, Pittsburgh has not amended its ordinances, but has a single agreement with Uber whereby the city allows them to permit under existing state law with a licensed human driver in the vehicle.

In 2014, the city of Coeur d’Alene, in Kootenai County, Idaho, amended its municipal code to add a section that defined *robot*, authorized use of robots on public property and the use of autonomously operated vehicles on city streets. The ordinance provided for repeal of conflicting ordinances (City of Coeur d’Alene, 2014).

<p>SECTION 1. That Coeur d’Alene Municipal Code Section 4.05.030(B) is amended to read as follows: 4.05.030: DEFINITIONS: ROBOT: A self-powered, programmable, mechanical device capable of operating autonomously or via remote control. This definition does not include autonomously-operated motor vehicles defined under Chapter 1, Title 49, Idaho Code</p> <p>SECTION 4. That a new section 10.02.040, entitled Autonomous Vehicles, is added to the Coeur d’Alene Municipal Code as follows:</p> <p>10.02.040: Autonomous Vehicles: The safe operation of autonomously-operated motor vehicles is permitted upon city streets, provided such operation complies with all applicable city, state and federal laws.</p>
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Figure 7.4 Coeur d’Alene Amendment (Sterling Codifiers).

The City of Boston announced, in September 14, 2016, that it would launch a program to explore HAV technologies that would focus on creating policy recommendations and supporting on-street testing of HAVs (City of Boston, 2016). However, on the same day as the Boston mayor’s announcement, Chicago Aldermen Ed Burke and Anthony Beale threw down a gauntlet when they proposed an ordinance that would ban AVs (Graham, 2016) in the City of Chicago. The proposed ordinance would amend Municipal Code Chapter 9-76, inserting a new section 9-76-240 - Autonomous Vehicles Prohibited. The ordinance states that

no person shall operate an autonomous vehicle upon any roadway. Autonomous vehicle is defined as any vehicle equipped with autonomous technology that has been integrated into the vehicle. An autonomous vehicle does not include a vehicle that is equipped with one or more collision avoidance systems, including, but not limited to, electronic blind spot assistance, automated emergency braking systems, park assist, adaptive cruise control, lane keep assist, lane departure warning, traffic jam and queuing assist, or other similar systems that enhance safety or provide driver assistance, but are not capable, collectively or singularly, of driving the vehicle without the active control or monitoring of a human operator (City of Chicago, 2016a).

As noted in the state review section some states have crafted legislation that preempts local governments from enacting zoning or other ordinances in the area of AVs.

7.5 International Developments

There has been considerable interest in regulating and encouraging C/AV technology abroad. In Europe, much of the push for research and development of autonomous driving technologies comes from a desire for competitiveness and to reap the benefits of the technology in European transportation systems. CVs are also very much a point of interest for transportation technology developers and policy makers on the continent. In the European Union there are currently no laws regarding AVs. Some national governments have delved into the idea of autonomous driving by funding studies, and individual states have also passed legislation since 2016.

Many proponents for autonomous driving in Europe claim that the Vienna Convention on Road Traffic was the greatest obstacle preventing a more robust approach to the development and adoption of these technologies. In Article 8, the Convention used language that incidentally prevented the development and

testing of AVs by requiring that “*Every driver shall at all times be able to control his vehicle*” (Economic Commission on Europe 1968).

As greater concern mounted about Europe’s lack of contribution to the progression of autonomous driving, EU member states began to consider how they could move past the challenges they were facing. As more conversations were facilitated, it became clear that the primary catalysts for the development of AVs in Europe were competitiveness, sustainability, efficiency and harmonization between national borders, low carbon levels, and, to a lesser degree, safety (Schreus et al. 2015). Finally, after the governments of Germany, Italy, France, Belgium, and Austria submitted an amendment in 2014, the United Nations amended the Convention on Road traffic to allow drivers to take their hands off the wheel of self-driving cars (SafeCarNews 2014). This is a significant development for autonomous driving and autonomous technological development, because arguably the greatest obstacle was removed and development of beneficial policies regarding AVs can now be explored more aggressively.

EU Initiatives

Within Europe, many states have begun to investigate the integration of C/AVs/HAVs into their interconnected transportation networks through research and study groups. There have not been any specific laws or policies out of the EU on C/AVs/HAVs yet, but this is expected to be forthcoming in 2018, as there are concerns (much as there are in the US) that member states will create a patchwork of regulations that will impede the movements of people and goods within the EU. Under the EU governing treaties, there is latitude to create legislation on this front, as it falls within the four main pillars that underlie the EU: freedom of the movement of people, goods, services and capital. In addition, current EU laws provide some insight into how C/AVs/HAVs can be operated across EU transportation networks. Directive 2007/46/EC regulates how new vehicles should be designed and operated. The purpose of this Directive is to set up a fully harmonized EU-wide framework for the approval of motor vehicles, thus creating an internal market within the European Community and ensuring a high level of road safety, health protection, environmental protection, energy efficiency, and protection against unauthorized use. EU Roadworthiness Directive 2014/45/EU provides a basis for checking that vehicles throughout the EU are in a roadworthy condition and meet the same safety standards as when they were first registered.⁸⁴

A number of initiatives are under development to support a harmonized approach by amending international regulations and preventing fragmentation. In the most noteworthy of these, put in place by the United Nations (UN) Economic Commission for Europe (UNECE), the World Forum for the Harmonization of Vehicle Regulations (WP 29) is assessing proposals covering semi-automated driving functions (autopilot systems to be used in traffic jams, self-parking functions and highway autopilots), which will ultimately pave the way for more highly automated vehicles. An example of the challenges faced is given by the ongoing work to amend UN R79 on steering equipment that currently only allows automatically commanded steering functions up to 10 kph, while beyond 10 kph only “corrective steering function” is allowed. As such, some SAE Level 2, 3, 4 and 5 systems are not allowed with current requirements and an amendment is needed to accompany the development of automated systems. Discussions are ongoing at UNECE also to examine UN R13 on braking systems, which does cater for “automatically commanded braking,” but may require some examination to confirm its suitability. UNECE work in this area is fundamental to prevent legislative barriers that also limit the introduction into the market of lower levels of automation, which are ready to be deployed in the short term, as well as to pave the way for the place of higher levels of automation into the market. (European Parliament, 2016 p. 52-53)

As concern continued to mount in Europe about its lack of contribution to the progression of C/AVs/HAVs, EU member states began to consider how to rectify this. Within member states’ conversations at national levels, the catalyst for faster development of C/AVs/HAVs in Europe was felt to sit within competitiveness, sustainability, efficiency, and harmonization across the states; climate change issues; and, to a lesser degree, safety (Schreus et al., 2015). In 2014, the UN Working Party on Road Traffic Safety (WP.1) proposed amendments to Article 8 and Article 39 of the 1968 Vienna Convention, aimed at ensuring that safety rules do not hamper the advancement of new technologies aimed at improving road safety. According to the

⁸⁴ Research for European Parliament Tran Committee: Self-Piloted Cars: the future of road transport, 2016 at [http://www.europarl.europa.eu/RegData/etudes/STUD/2016/573434/IPOL_STU\(2016\)573434_EN.pdf](http://www.europarl.europa.eu/RegData/etudes/STUD/2016/573434/IPOL_STU(2016)573434_EN.pdf)

amendment, “systems which influence the way vehicles are driven,” as well as other systems which can be overridden or switched off by the driver, are deemed to be in accordance with Article 8 of the Vienna Convention. The amendment was adopted by the UN on September 23, 2015, and became effective on March 23, 2016. However, the European Parliament noted in the 2016 report that SAE levels 3 and above would still be incompatible with the Vienna Convention and that a further amendment process would be necessary to permit these fully driverless vehicles (European Parliament, 2016 p. 55).⁸⁵

Current EU initiatives include research under the 7th Framework Program for Research and Technological Development. The EU Commission developed several projects under this framework, including AdaptIVE, which is a 42-month project on challenges in addressing automated driving. The project was expected, by December 2016, to have reviewed and defined the legal aspects of automation on EU public roadways; project results are expected in 2017. Project goals under AdaptIVE are to define and validate new methodologies for safety evaluation, demonstrate the feasibility of automated driving, and provide guidelines for cooperative controls (AdaptIVE, 2016).

The largest and most publicized EU foray into autonomous vehicles was the CityMobile2 project, which began in 2012. CityMobile2 is an AV project providing public transit that is funded by the EU’s Seventh Framework Programme for Research and Development of Various Technologies (CityMobile2 2015). The project has operated demonstrations in a handful of EU member states with La Rachele, France receiving most of the attention. The technology is still in the early stages of development and policy and legal questions seem to have kept the project from being implemented more quickly. The conversations and feedback from both parties resulted in the Transport Minister authorizing CityMobile2 (CityMobile2 2015).

The EU is also providing funding for research on autonomous driving, most notably through European Commission projects aimed at keeping the Union competitive from a market perspective. The European Commission Directorate General for Communications Networks, Content & Technology, also known as DG Connect, is an organization within the European Commission that researches ITS and also supports research in the area of automated mobility. DG Connect is also associated with the autonomous driving forum called iMobility and forwards readers to the forum’s website when searching for automated driving. Moreover, the EU now provides a platform called FUTURIUM for debating the future and trajectory of autonomous driving on the continent (Schreus et al. 2015). Although none of these initiatives are explicitly for the purpose of developing autonomous driving policies or regulations, they are worth noting if only for the sake of acknowledging the EU’s recognition of potentially serious changes coming to the transportation field.

A number of individual EU countries are seeking to enable research and develop within their borders. Below are examples of the most prominent initiatives.

France

France, under its “New Industrial France” program, proposed that self-driving cars could be allowed on public roads in 2015. In August 2016, the Council of Ministers ratified an amendment to the Vienna Convention under the rubric of this national program. The amendment allows cars to drive autonomously if the driver can override or switch the systems off at any time (Government of France at Elysee France/conseils des Ministries, 2016). While the council of ministers stressed that the amendment is an experimental phase, the goal was to give automakers a competitive edge to prepare for the mobility of tomorrow. It should be noted that the

⁸⁵ Another impediment to the slow uptake of C/AVs/HAVs in the EU is Economic Commission for Europe (ECE) Regulation 79, which contains requirements for a specific steering configuration (Lutz, 2016). An advanced driver assistance steering system is only allowed to control steering as long as the driver remains in primary control of the vehicle at all times (paragraph 2.3.4). Paragraph 5.1.6 also requires that such systems shall be designed such that the driver may, at any time and by deliberate action, override the function. Paragraph 23.4 does distinguish between two types of assistance systems. The “Automatically commanded steering function” (paragraph 2.3.4.1), which generates continuous control action assisting the driver in following a particular path, in low speed maneuvering or parking operations, is limited to 12 km/h (10 km/h + 20% tolerance), paragraph 5.1.6.1. The “corrective steering function” (paragraph 2.3.4.2.) such as ESP (Electronic Stability Program) or lane assist is not subject to speed limitations. This function can change the steering angle to maintain the desired direction for the vehicle or influence its movement. Since this function may only operate for a limited duration, the driver must keep his hands on the steering wheel at all times.

ratification of the amendment did not draft any explicit rules or regulations on the management of these vehicles on the road. It is expected that manufacturers will be asked to register with the French government before testing on public roads. Since 2015, the PSA group (a multinational manufacturer of vehicles) has held permission from the French government to test its four self-driving cars.

Finland

Finland's road traffic legislation permits AV trials (Trafi Finnish Transportation Safety Agency website, April 2016). The statutory basis for this is The Vehicle Act, Section 66f (1090/2002); Government Decree on Vehicle Registration, Section 32 (893/2007); and the Vehicle Tax Act, Section 35(1)8 (1482/1994). The agency tasked with implementing the AV trials is "Trafi" the Finnish Transportation Safety Agency. Trafi's model was developed to be clear and make the process as simple as possible; in many ways, it mirrors Michigan's approach to testing HAVs.

An enterprise or agency can apply to get a test plate certificate. The certificate is valid for one year. The holder of the test plate can operate a vehicle in road traffic on a temporary basis without being liable for car and vehicle tax on the AV. The application process is on-line. The test plate certificate costs 300 Euros (€) and the test plate is €9. An appendix to the application requires that the applicant enclose a trial plan that includes...

- a general description of the trials,
- technical specifications of the test vehicles,
- information on the road area where the trials are intended to be conducted,
- proof of insurance coverage for third party liability,
- and a description of how road safety will be ensured.

The first test plates were issued in July to the Metropolia University of Applied Sciences and VTT Technical Research Center of Finland. Testing was to occur in Helsinki in July and August of 2016, and Tampere in September 2016. The tests would involve electric buses in Helsinki and passenger vehicles in other cities/regions. Traffic arrangements on the test routes were to be planned individually between the authorities in charge of the road and those performing the trial. Trafi was also to draw up separate safety plans for each trial as well.

Germany

Germany passed legislation on December 13, 2016 (Act to Amend Articles 8 and 39 of the Convention on Road Traffic of November 8, 1968), which was similar to France's in that it implemented an amendment to the Vienna Convention on Road Traffic. The amendment allows the transfer of driving tasks to the vehicle, provided that the technologies are in conformity with UN vehicle regulations or can be switched off or overridden by the driver (German Federal Law Gazette, 2016). In September 2016, the German Minister of Transport, Alexander Dobrindt, announced that draft traffic laws were being developed that will require that the vehicle have a steering wheel and that a human must sit behind the steering wheel. Minister Dobrindt also announced a basis for future legal guidelines for C/AV/HAVs that would echo Isaac Asimov's three laws of robotics. Manufacturers are expected to work towards this prior to formal legislation being passed. Minister Dobrindt has also created an ethics commission to work upon the specific legislative language for robotics (Wirtschafts, 2016).

AutoNOMOS

AutoNOMOS Labs is a project at the Freie Universität Berlin that researches and develops autonomous and driver-assistance technologies (Autonomos Labs, not dated). The Stadtpilot is another research project that seeks to develop autonomous technologies and test them in real city traffic (Technische Universität Braunschweig, 2010). From a policy perspective, the German Transport Ministry is pushing the conversations about autonomous driving at the national level. They hold round table meetings with members from various transportation stakeholder groups twice a year to address the issues, in addition to assembling working groups

to look at policy and legal questions (Schreus et al. 2015). The hope is that they will reach a much better understanding of the features that both benefit and hinder the eventual adoption of AVs. Germany seeks to be a leader in developing policy for AVs and the country hopes to provide an environment for its many automakers to capitalize on this potential market.

The Netherlands

In June 2014, the Dutch government announced its intention to allow large-scale testing of C/AVs/HAVs on Dutch roads. The government acknowledged that, in order to make this possible, existing legislation needed to be amended. The Dutch had been involved in some trials on the main road network at a smaller scale, such as the Dutch Integrated Site on Cooperative Mobility in Helmond. In January 2015, the government proposed an exemption to rules allowing the larger scale testing, which would be approved once legislation was changed. The Ministry of Transportation published an exemption process for large-scale testing on public roads. In July 2015, the Netherlands Vehicle Authority (RDW) and the Minister of Infrastructure and the Environment, prepared regulations that make this legally feasible. The new legislation for automated driving on the public roads came into force on July 1, 2015. The system for application is online through the RDW website.⁸⁶

There are three stages in how the RDW evaluates test applicants:

- 1) written evaluation, roughly comprising an overview of changes to the vehicle, and the impact these have on safety, and counter measures;
- 2) functionality testing (at a closed facility) of aspects the applicant seeks to test on public roads: the ‘happy flow test’;
- 3) a stress test at a closed facility. This tests system robustness, both in technical and functional terms.

If this final phase is completed successfully, consideration will be given—in consultation with the road manager(s)—as to suitable locations to be opened up and what circumstances will apply. This may involve recommendations from knowledge institutes like the Road Safety Research Institute (SWOV) or cybersecurity experts. The exemption lists all relevant circumstances together with the licensed drivers, the duration of the exemption, and the vehicles (EUTruckplatooning.com website, not dated). The Netherlands’ approach is somewhat similar to California’s approach to testing of C/AV/HAVs.

Sweden

In April 2016, the Swedish Minister for Infrastructure announced her goals for proposed legislation for C/AV/HAV trials (DriveSweden.net, 2016). This is expected to be drafted and passed into law by mid-year 2017 and followed later on in 2017 with draft legislation for full commercializing of C/AVs/HAVs. The minister noted that she did not believe international conventions prevented trials on roads, and she also noted that EU law did not prevent such trials either.

The minister outlined that the Swedish Transport Agency would be responsible for issuing permits to carry out trials, which would be based on some conditions, including limitations to time and geographic areas. The agency would supervise the performance of trials and would be able to revoke permits. The agency would also be able to impose requirements for marking of vehicles. Data collection and storage should ensure consistency with national/international regulations and the tests’ organization should indicate how road safety will be ensured under trial conditions. The testing agency should also provide reports on incidents. Liability should be tested in trials where an HAV handles all driving functions, including safety, and the driving system would be regarded as the vehicle driver. When the vehicle is in self-driving mode, criminal liability shall be borne by whoever applied for the permit. An HAV (i.e., SAE levels 3 and above) could be driven by a physical driver on certain routes, and under these circumstances the physical driver would bear criminal liability (i.e., SAE levels 0–2). Compensation for traffic crashes would continue to be applied under the current regulatory framework to all levels of C/AV/HAVs. The minister did not believe that a constitutional amendment was

⁸⁶<https://www.rdw.nl/english/information/Paginas/Method-admittance-procedure-ITS.aspx?path=Portal/Information%20in%20English/Intelligent%20Transport%20Systems>.

required. Data from the vehicle would be used for crash investigation, and whoever was granted the permit for trials would be responsible, on request, for submitting to the policyholder of the C/AV/HAV, data available from the vehicle's sensors to investigate the insurance case. Insurance companies, the minister noted, could obtain access to data through a civil law agreement with the insured. One interesting item to note was camera surveillance, which would require new regulations and need to be incorporated into the trial legislation. According to the minister:

“Visual data obtained from the outside of the vehicle shall be permanently and irrevocably anonymized before storage. Against this background I consider that the camera surveillance that takes place in trials of self-driving vehicles, in places to which the public has access, can be exempted from the permit and disclosure requirements. The interception of communications or audio recording must not be carried out using microphones outside the vehicle. Camera surveillance of a place to which the public does not have access shall be exempted from the requirement for consent in relation to people who are outside the vehicle. This may, for example, cover the performance of a trial in a car park where only self-driving vehicles may park. Consent shall be required in respect of surveillance which takes place inside a vehicle. The Swedish Data Protection Authority shall supervise the camera surveillance carried out by self-driving vehicles” (DriveSweden.net, 2016).

The minister did not believe that it was possible to lay down specific infrastructure requirements in the trial legislation for the various trials. Depending upon the trials, a test organization may choose, however, to ask for infrastructure adaptations. The minister's starting point was that the test organization would discuss this with the road authority, on finding suitable routes for testing. Finally, on the work environment, the minister noted that trials using vehicles would still fall under the employer's responsibility to ensure that the driver has knowledge and skills required to carry out the trial and that the work environment is safe.⁸⁷ In many ways, Sweden's proposed approach is similar to California's approach, and to the 2016 NHTSA's policy guidelines on state roles/responsibilities.

“Drive Me”—Self-Driving Cars for Sustainable Mobility is the first large-scale autonomous driving project being undertaken in Gothenburg, Sweden. The collaborative project between Volvo, the Swedish Transport Administration, the Swedish Transport Agency, Lindholmen Science Park, and the City of Gothenburg will have 100 vehicles driving autonomously on the city's public roads (Swedish Transport Administration 2015). This is a solid breakthrough as much of the testing of self-driving vehicles in Europe has been done on private roads. Sweden has also been at the forefront of studying CVs with its SARTRE Project. The Safe Road Trains for the Environment project is funded by the European Commission under the Framework 7 program and aims to develop strategies and technologies to have platooning vehicles on public highways (SARTRE 2015). Government and industry are excited about greater transport efficiency and safety to be gained from platooning.

United Kingdom

In 2013 the UK's government pledged, as part of its National Infrastructure Plan, to review its legislative and regulatory framework to enable trials of C/AVs/HAVs on the UK's roads (ANWB, 2015). The government announced the driverless cars competition on July 30, 2014, and encouraged individual municipalities to work with technology developers to test their vehicles in their cities. This was followed up with a December 2014 announcement that four cities (Greenwich, Bristol, Milton Keynes and Coventry) were awarded up to £10 million to test driverless cars (ANWB, 2015). In February 2015, the Department of Transport UK released a summary report and action plan for how to handle autonomous driving by creating a Code of Practice. The proposed idea of the Code of Practice is intended to promote safety and set clear guidelines for responsible testing (Department of Transport UK, 2015). The Department of Transport, in a detailed review of regulations in February 2015, reported the following:

⁸⁷ (Adapted from: <http://www.drivesweden.net/en/news/sweden-proposes-very-progressive-legislation-self-driving-vehicle-trials>)

- Driverless vehicles can legally be tested on public roads in the UK today, providing a test driver is present and takes responsibility for the safe operation of the vehicle and that the vehicle can be used compatibly with the road law;
- A Code of Practice will be published in this spring for those wishing to test driverless vehicles on UK roads;
- Domestic regulations will be reviewed and amended by the summer of 2017 to accommodate driverless vehicle technology;
- Officials will liaise at an international level with an aim to amend international regulations by the end of 2018. (Government UK, 2015a)

In July 2015, the government issued guidance and a code of practice on C/AV/HAV technology testing (Government UK, 2015b). This Code of Practice provides guidance for anyone wishing to conduct testing of HAV technologies on public roads or in other public places in the UK. It details recommendations which the government believes should be followed to maintain safety and minimize potential risks.

The test driver under the guidance must be licensed and trained and supervise the vehicle at all times and be ready and able to over-ride automated operation. Test drivers and operators supervising public road testing of C/AVs/HAVs will need skills over and above those of drivers of conventional vehicles. For example, it will be important to ensure they have an excellent understanding of the capabilities, and potential limitations of the technologies under test, and to already be familiar with the characteristics of the vehicle, preferably through extensive experience of tests conducted on closed roads or test tracks. Testing organizations should have robust risk management, process and training procedures in place for test drivers and operators and should ensure they hold the appropriate UK driving license, or recognized equivalent (Government UK, 2015b).

The vehicles must be roadworthy and must, if used on a public road, meet the relevant national in-service requirements. A test vehicle that is over 3 years old (or 4 years old in Northern Ireland) must also have a valid inspection certificate (called a MOT). An electronic data recorder is also required in the vehicle, and should record:

- whether the vehicle is operating in manual or automated mode,
- vehicle speed,
- steering command and activation,
- braking command and activation,
- operation of the vehicle's lights and indicators,
- use of the vehicle's audible warning system (horn),
- sensor data concerning the presence of other road users or objects in the vicinity,
- remote commands which may influence the vehicle's movement (if applicable).

The code also details guides for cybersecurity, software levels, process for transition between automated and manual modes, and failure warning requirements.

In February 2017, the UK introduced the Vehicle Technology and Aviation Bill, which set out how liability for accidents involving HAVs will be apportioned.⁸⁸ Under the bill, the UK government would be responsible for keeping a list of all HAVs in the UK.⁸⁹ Insurance liability is listed in Section 2 and under subsection 2 (1) where (a) an accident is caused by an automated vehicle when driving itself, (b) the vehicle is insured at the time of the accident, and (c) an insured person or any other person suffers damage because of the accident.

⁸⁸ Vehicle Technology and Aviation Bill (HC Bill 143). , https://www.publications.parliament.uk/pa/bills/cbill/2016-2017/0143/cbill_2016-20170143_en_2.htm

⁸⁹ HC Bill 143, part 1, Automated Vehicles; liability of Insurers Etc., Section 1.

Under these circumstances, the insurer would be liable for that damage. Damage is defined as death or personal injury, and any damage to property other than the automated vehicle,

- 1) goods carried for hire or reward in or on that vehicle or in or on any trailer (whether or not coupled) drawn by it, or
- 2) property in the custody, or under the control, of:
- 3) the insured person (where subsection (1) applies), or
- 4) the person in charge of the automated vehicle at the time of the accident (where subsection (2) applies).

If damage is caused or arises, insurance liability limits will follow those detailed in the Road Traffic Act 1988 and cannot be limited or excluded by a term of any insurance policy. The Act also provides details on contributory negligence under section 3 where an insurer or vehicle owner is liable under section 2 to a person (“the injured party”) in respect of an accident, and (b) the accident, or the damage resulting from it, was to any extent caused by the injured party.

Section 4 covers a crash resulting from unauthorized alterations or a failure to update software. An insurance policy under subsection 4 (1) can limit or exclude insurance liability for damage suffered by an insured person in an incident where the accident occurs because of:

- alterations to the vehicle’s operating system made by the insured person, or with the insured person’s knowledge, that are prohibited under the policy, or
- a failure to install software updates to the vehicle’s operating system that the insured person is required under the policy to install or to have installed.

However, under subsection 4 (2) any liability exceptions are restricted such that any exclusion or limitation for damage by an insured person who is not the policy holder will apply only if

- alterations made to the operating system at the time of the accident were known by the person to be prohibited under the policy; or
- a failure to install software updates is known by the person is required under the policy to either install themselves or have them installed.

The amount paid by the insurer is recoverable from the person to the extent that the policy provides for this. This right of recovery in subsection (5) is further limited from the insured person who is not the holder of the policy. It will apply only in relation to

- alterations to the vehicle’s operating system which, at the time of the accident, the person knew were prohibited under the policy, or
- a failure to install software updates which at that time the person knew he or she was required under the policy to install or to have installed.

However, as the UK introduced a general election in early 2017, this bill did not become law and a new bill the Autonomous and Electric Vehicle Bill was introduced into the House of Commons in June 2017 after the election. The UK’s Department for Transport also issued principles for cybersecurity of smart and connected vehicles in August 2017 (get citation). The principles are similar to NHTSA’s 2016 policy components.

Singapore

Singapore began authorizing limited AV permits in 2015. In February 2017, Singapore saw a bill to amend its Road Traffic Act⁹⁰ introduced into the Singapore Parliament. This would authorize HAVs to be tested on

⁹⁰ Singapore Statutes online at <http://statutes.agc.gov.sg/aol/search/display/view.w3p?page=0;query=DocId%3Aba3acbbe-2ce4-4b3f-8011-5bfae19cfbbc%20%20Status%3Ainforce%20Depth%3A0;rec=0>

all public roads. Testing is authorized currently only on small segments of roads around two tech hubs in the city.⁹¹ The Land Transport Authority (LTA), in a factsheet regarding the bill noted that this would provide a more responsible regulatory framework to support AV trials, and provide flexibility to create and amend rules to facilitate trials when needed. AV technology would be defined as:

Any particular technology that relates to the design, construction or use of autonomous motor vehicles or relates to advances in the design or construction of autonomous motor vehicles. Autonomous motor vehicle is defined as a motor vehicle equipped wholly or substantially with an autonomous system (driverless vehicle) and includes a trailer drawn by such a vehicle. Autonomous system for a motor vehicle is a system that enables the operation of the motor vehicle without the active physical control of, or monitoring by, a human operator.

The bill adds new Sections C, D and E to the principal Act regarding trials and use of AVs, and authorized the minister to make rules to regulate trials of AVs. Any person authorized to undertake a trial would need liability insurance. The bill also required that for any trial, a notice of the trial's elements to denote areas where the trial will take place and the name of every participant who will be conducting the trial, along with the period of time and other limitations such as weather would be necessary. The LTA could proscribe construction design or use of technology, equipment, or devices in relation to the AV used in the trial, including sensor data, video footage and messages from a failure alert system that can take immediate manual control.⁹² The bill did not pass out of Parliament.

Japan

In 1996, Japan began its progression to the utilization of AVs with the Advanced Cruise-Assist Highway System (AHS) Research Association demonstrating the convoying of vehicles. Since then, a number of companies have sought to bring greater autonomy to the country's roads. A number of government ministries are now working together to effectuate AVs on Japanese roads and the government has defined four levels of vehicle autonomy in much the same way that NHTSA has (Japan Ministry of Economy 2014), in an effort to help catalyze greater conversation about autonomous driving and begin to frame the self-driving conversation.

Work has been done to make provisions for AV technologies, although there is still no classification of driver's license for these vehicles. However, in 2013, Nissan's AV Leaf was given an AV license plate and allowed to operate on Japanese roads (Motherboard, 2013). This is in line with the company's desire to have multiple vehicles operating autonomously on Japanese roads by 2020. This vehicle is not completely autonomous but utilizes autonomous driving features. The Cross-Ministerial Strategic Innovation Promotion Program is another Japanese government project that is researching autonomous driving (JCSTI 2014).

In the future, Japanese authorities intend to implement multimodal transportation systems centered on pedestrian utility. Policymakers believe AVs will be a supplement to these networks and create safer and more time-efficient transport options (JCSTI 2014). However, Japanese legislation is still fairly prohibitive of vehicle autonomy, save for the authorized exceptions (i.e., Nissan Autonomous Leaf). The Road Traffic Act requires drivers to ensure safety at all times while the car is being driven (Nikkei 2015). It's clear how this requirement can be problematic for the potential of self-driving cars and it's fairly similar to the pre-amended Vienna Convention. Time will tell if Japan seeks to amend its regulations in the same way the EU member states lobbied for the new Convention on Road Traffic.

The Ministry of Economy, Trade and Industry's (METI) fiscal year 2017 Budget Request requested funds to encourage private sector investment in key focus areas. This included a requested 270-million-dollar investment to realize the "fourth industrial revolution" that would develop innovations in Artificial Intelligence and other advanced technologies, including autonomous vehicles (METI, 2016).

⁹¹ Land Transport Authority of the Singapore government. 7 February 2017 accessed at: <https://www.lta.gov.sg/apps/news/page.aspx?c=2&id=cb1d0f2e-a254-45e2-acd7-bf96b843b017>

⁹²Parliament of Singapore website at [https://www.parliament.gov.sg/sites/default/files/Road%20Traffic%20\(Amendment\)%20Bill%205-2017.pdf](https://www.parliament.gov.sg/sites/default/files/Road%20Traffic%20(Amendment)%20Bill%205-2017.pdf)

Canada

In Canada, no federal laws have yet been passed regarding C/AVs/HAVs as of the drafting of this chapter. The Government of Ontario launched a pilot program for testing vehicles on Ontario's roads in 2015 allowing the testing of C/AVs/HAVs and related technology on their roads to begin in January 2016. According to the Ministry of Transportation in Ontario (MTO), this step will promote research and development by the 100 companies and institutions involved in the C/AV/HAV industry (MTO, 2015). The proposed pilot framework set conditions to facilitate testing of C/AVs/HAVs for the next 10 years. While in autonomous mode, vehicles are subject to these rules:

- Restricted use for testing purposes only;
- A driver must be present in the vehicle at all times and have a valid G class driver's license;
- Driver must be trained to safely operate an autonomously equipped vehicle;
- Driver must remain seated in the driver's seat at all times monitoring the safe operation of the AV, and be capable of taking over immediate manual control;
- May only be operated by those drivers approved by the ministry (i.e., employed by the manufacturers, software developers, etc.) and for testing purposes only.
- A copy of the signed application form must be kept in the motor vehicle at all times;
- Eligible participants must have insurance of at least \$5,000,000;
- All current Highway Traffic Act rules of the road and penalties will apply to the driver/vehicle owner; and,
- Vehicles must comply with SAE Standard J3016 and any requirements of the Motor Vehicle Safety Act (Canada) that apply to automated driving systems for the vehicle's year of manufacture.

For the purposes of Ontario's testing pilot, "*automated vehicle*" means: a motor vehicle, commercial motor vehicle, or a street car, with an automated driving system that operates at the Society of Automotive Engineers (SAE) International driving automation Level 3, 4 or 5.

As of July 2017, Ontario has approved seven entities to participate in the pilot: The University of Waterloo, The Erwin Hymer Group, QNX, Continental, X-Matik Inc., Magna and Uber (Ontario Ministry of Transportation, Automated Vehicles Website, not dated.)

Australia

The federal government of Australia has not introduced any legislation regarding C/AVs/HAVs. So, similar to the US and Canada the states are leading the way. In November 2016, the National Transport Commission of Australia (NTC) announced that while current regulations do not adequately support C/AVs/HAVs, the ministers had agreed to phase reform so that conditionally C/AVs can operate safely and legally on roads before 2020, and HAVs from 2020 onward. To provide certainty on the use of existing technology, the ministry reaffirmed its existing policy position that the human driver remains in full legal control of a vehicle that is partially or conditionally automated, unless or until a new position is developed and agreed upon (NTC, n.d.). A policy paper set out the NTC's recommendations and policy positions and was released in November 2016 (NTC, 2016a). It outlined the near, medium and long-term reforms that will be required. One area that the policy paper discusses was the need for clarification of control and proper control, as well as driver and driving. The policy paper also looks at vehicle designs and standards, including modification and in-service compliance, liability, and safety assurances for vehicles that do not require a human driver (NTC, 2016a).

This was accompanied by NTC releasing in November 2016 the National Guidelines for Automated Vehicle Trials: Discussion Paper (NTC, 2016b). The report discusses management of trials, safety management plans, insurance, data and information, cross border trials, heavy vehicle trials, and next steps. The NTC asked for feedback on a series of questions relating to the application of guidelines, the management of trials, the safety management plan, insurance, and data and information.

The Government of South Australia introduced legislation for on-road testing of AVs in September 2015 (Government of South Australia: Attorney General's Office 2015). The Motor Vehicles (Trials of Automotive Technologies) Amendment Bill will provide for exemptions from existing laws to allow trials of AVs on public roads. Amendments included a change in the definition of *uninsured motor vehicle*; an insertion of a new section for trials of automotive technologies; authorization for the Minister of Transport to issue, publish, and adopt guidelines; and authorization for the Minister of Transport to authorize trials of automotive technologies.

The bill requires the Minister to report to Parliament within 6 months of the completion of an authorized trial and to prepare a report in relation to the authorized trial (HA GP 334-B OPC 12 September 23, 2015 (Government of South Australia: DPTI 2015)).

The New South Wales Government set up a website (www.future.transport.nsw.gov.au) in 2016 as a portal to improve the future of transport over the next 15 years: the website includes review of HAVs. The Future Transport Technology Roadmap is currently receiving comments and was to be published at the end of January 2017. The Roadmap includes transforming the transportation agency itself to adopt practices from technology leaders in other sectors. As part of the Future Transport Technology policy process, the Ministry created technology strategies including “enable[ing] connected, automated vehicle platforms.”

7.6 Summary

In this chapter, the legal environment around self-driving vehicles with CAVs has been discussed. Currently, the testing of C/AVs is underway and there is enthusiasm about further integration of the benefits and capabilities of automated transportation. Policymakers are eager to learn more about this new technology and how it will work with, and change, existing legal infrastructure. There are still questions about the most useful role of local governments in overseeing CAV technology that will need to be addressed in the future.

CHAPTER 8 TEXAS LEGAL ENVIRONMENT FOR SELF-DRIVING VEHICLES

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8.1 Background

The law has been cited as one of the primary obstacles to the effective and efficient integration of connected and/or autonomous vehicles (C/AV) onto public roadways (Davidson and Spinoulas 2015). Without well-defined liability, privacy, and licensing structures, some observers worry that automobile manufacturers may be reluctant to conduct research or install new technologies in vehicles (GAO 2013, p.28).

For states like Texas, where testing of C/AVs is underway, and a bill passed that authorizes deployment in 2017, there is enthusiasm, as well as some caution, about further integration of the benefits and capabilities of automated transportation onto state highways and policymakers are eager to learn more about the intersection of this new wave of technology with the existing legal infrastructure. Specifically, policymakers are interested in whether the existing law prohibits or impedes testing or deployment of the technology or, conversely, whether greater legal oversight may be desirable. Moreover, in light of the limited federal regulation of C/AV transportation, there are questions about the most useful role of states and local governments in overseeing this new technology.

This chapter takes a first cut at mapping out the larger legal terrain governing C/AVs in the State of Texas. Specifically, it considered whether the testing and deployment of C/AVs on Texas highways is legal and

explores the scope of regulatory oversight - as at November 2016 - with respect to ensuring a safe transition to driverless cars. The chapter also considers whether litigation over crashes involving C/AVs may alter existing liability rules, including the liability of regional transportation agencies like TxDOT; what the advent of C/AVs means for consumer privacy; and whether C/AVs also present added security risks for Texas citizens. As a mapping exercise, the review provides an initial overview of these many important pieces and how they connect and relate within the current state and federal legal system. A number of topics—e.g., the Fourth Amendment treatment of various types of data in C/AVs—will require additional and perhaps continuous research as the technologies evolve and their capabilities become clearer.

The chapter provides a matrix of recommendations across all topic areas, including highlighted issue-areas that are likely to be of particular interest to state DOTs and other regional transportation stakeholders. This section makes clear that a “no action” approach in Texas—essentially making no changes to the existing legal system—will allow for the eventual integration of C/AVs onto State highways. It recommends a series of more targeted, anticipatory legislative and regulatory adjustments that should make the integration of C/AVs both more predictable for the industry and increase public confidence by managing a number of foreseeable public risks associated with this emergent technology.

The chapter follows Chapter 7 which describes existing federal, state, and international law governing C/AVs in 7.2 and as a general introduction provides decision-makers with an orientation to the larger legal landscape. Sections 8.2 through 8.5 within this chapter consider the challenges presented by C/AVs with respect to legality, liability, and privacy in the State of Texas. Section 8.2 begins with an analysis of the current legality of autonomous vehicles (AVs) on Texas highways. Although in general C/AVs appear to be legal under existing law as at November 2016, a number of discrete issues are likely to arise at this intersection that would benefit from resolution in advance. Section 8.3 highlights some of the likely liability questions as C/AVs become more prevalent in the State. This section considers not only changes in the nature of crash litigation in general but also some of the ways that the regional transportation agencies’ liability may be altered. Section 8.4 provides an analysis of both privacy and security issues associated with C/AVs. The analysis again identifies several more specific privacy and security challenges that could be addressed within Texas and proposes several reforms to address these challenges.

Factual Assumptions that Serve as the Backdrop for the Legal Analysis

To conduct a rigorous legal analysis, a lawyer must first identify the relevant “facts” underlying the issue under investigation; yet the emergent nature of C/AV technologies makes specifying these “facts” a slippery exercise. Since the facts are continuing to evolve, we began our analysis by developing a working understanding of the most likely scenarios, illustrated in Figure 8.1. These scenarios, drawn heavily from the Organization for Economic Co-operation and Development (OECD) (OECD 2015) and Anderson et al. (Anderson et al. 2014), served as the factual backdrop upon which our legal analysis is based.⁹³ If very different technological circumstances ultimately emerge in the future, analysis and recommendations should be adjusted accordingly.

⁹³ For an elaborate description of the distinctive features of purely driverless technologies for autonomous and connected vehicles, see Glancy et al. 2015.

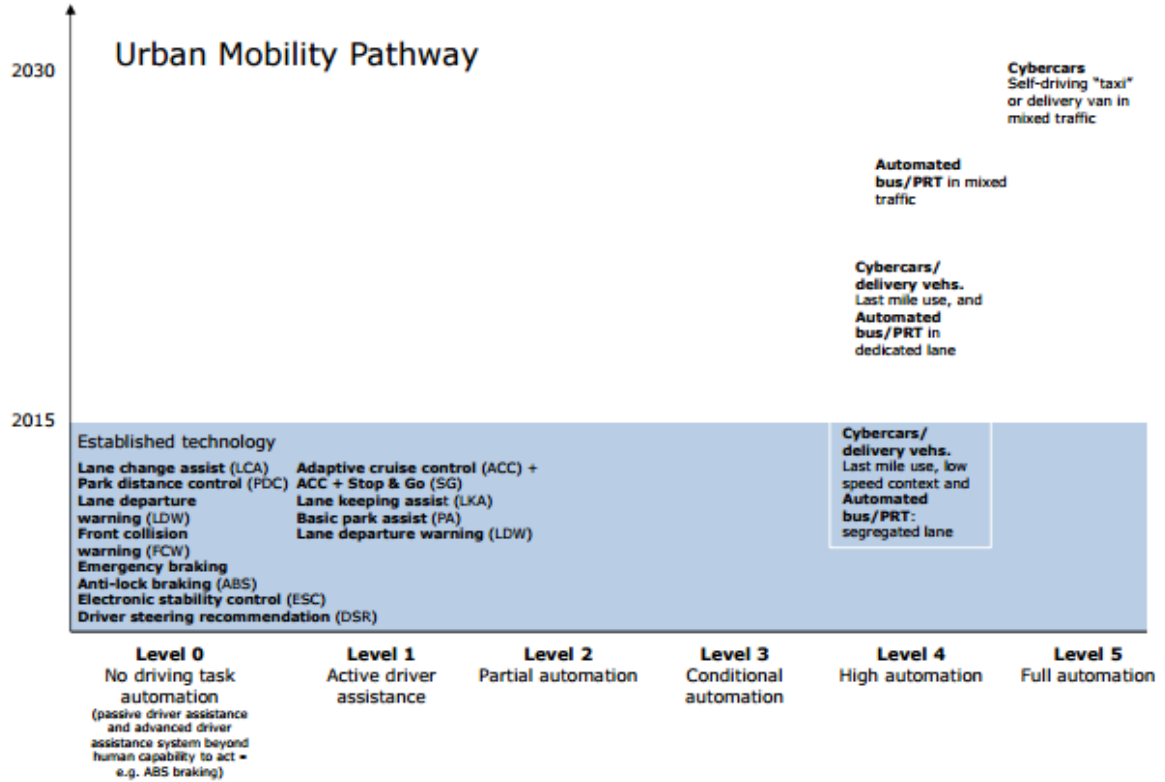


Figure 8.1 Automated Private Vehicle Pathway (OECD 2015 p. 21)

In the near term (e.g., by 2020), we assumed the following:

- Low levels of automation will be incorporated into an increasing number of new vehicles. Some of this automation will involve handoff technology, for example when the automated mode of a C/AV encounters a situation (e.g., emergency) that requires relatively immediate manual control. Some of the automation may also be retrofitted through personal devices that can be used to make driving smarter, albeit we expect retrofitting to be a small part of the progress towards C/AVs.
- There will be considerable testing of C/AVs on public roads, including connected, driverless cars with an operator in the front seat.
- The infrastructure needed for connected vehicles (CV) (that is, those with vehicle-to-vehicle (V2V) and vehicle-to-infrastructure [V2I] capabilities) will include roadside devices transferring signals in localities that choose to invest in the technology.
- Crash rates may begin to decline, but the combined reality of mixed vehicles (partial automation and non-automation) with the trial-and-error phase inevitable in perfecting handoffs and gauging operator automation preferences in automated cars will, in the short term, counteract some of the longer-term safety benefits of C/AVs.
- Individual vehicles will collect some private information on driver habits/preferences that will be transmitted to original equipment manufacturers (OEMs) and possibly other businesses.

In the longer term (e.g., 2025 to 2030) we assume the following:

- Automation will become increasingly common on the roadways, and handoffs in those vehicles will perform much better in minimizing user error. The reliance on automation will be standard at least in traffic jams, highway driving, and parking assistance.

- Driverless cars without operators will be used in low-speed designated areas (e.g., government or college campuses and on highways, perhaps through truck platoons).
- Infrastructure that the government will need to provide will depend on whether V2I technologies become an important facet of C/AV transportation. It is difficult to predict whether this will occur, although there is some skepticism given the costs.
- C/AV crashes will occur primarily as result of vehicle updates and maintenance issues, user errors during handoffs, and users taking control and crashing.
- C/AVs will have the potential to generate a considerable amount of information on operators and occupants that will be collected by OEMs and perhaps others.

8.2 The Legality of Licensing C/AVs: A Texas Example

At the time of analysis during 2016, Texas had not yet passed laws or regulations that regulate C/AV use directly. This section thus considers the existing law—all of it developed without C/AVs in mind—that nevertheless will serve to regulate this new technology as it is assimilated into the State, used in this work as a case study.

The operation of C/AVs on Texas roadways is likely to intersect with existing Texas law in two overlapping ways. The first is governed by legislation that identifies who can operate vehicles in Texas and the responsibility of these owners for violations. The second involves rules of the road and other practical constraints on the operation of vehicles.⁹⁴

Operation of Motor Vehicles in Texas

While there are ambiguities, the most plausible reading of the Texas Motor Vehicle Code with respect to C/AVs is that to be operated legally on Texas roadways, each vehicle must have an identified and legally responsible human operator with a valid driver's license. Specifically, the general structure of the Texas Motor Vehicle Code places full responsibility on "operators" of vehicles to comply with all Code requirements, rules of the road, and other laws. While "operators" are defined as "persons" who need not be humans by definition (Texas Transportation Code § 541.001(4)), these "persons" must nevertheless obtain a drivers' license in order to operate a vehicle on a highway in the state (§ 521.021). Existing driver's license requirements, moreover, include a number of requirements (e.g., thumbprint; photo; signature; residence) (§ 521.121) that can only be satisfied, as currently designed, by humans.

Although this licensed "operator" need not be actively driving the vehicle, the most plausible interpretation of the statute does demand the "operator" to at least be present in the vehicle while it is moving in order to be in compliance with the law. Violations of the Code, moreover, fall on the licensed "operator" of the vehicle, although they can be imposed jointly on other operators as well.

Despite a relatively clear structure that seems to tolerate the operation of C/AVs on Texas roadways, there are nevertheless gaps and ambiguities in the law regarding the legality of

- vehicles without a designated operator;
- the operator's physical role in operating the vehicle;
- non-human "operators"; and
- the ultimate legal responsibility for violations. Each is discussed in turn.

⁹⁴ As noted earlier, the technologies themselves are not so clearly distinct that the differences between Autonomous Vehicle and Connected Vehicle have legal relevance. Rather than an artificial parsing of CV vs. AV – which simply can't be done at present in most areas of the analysis – we take a broad view of the technologies to ensure a more comprehensive assessment of the emerging law/policy. Where there are meaningful distinctions to be drawn with regard to the law and CVs vs. AVs, these are drawn out within sections 3 through 5.

Vehicles without a Designated Operator

Numerous responsibilities and requirements attach to the “operator” of a motor vehicle, but there does not appear to be the critical legal link in Texas Law that prohibits vehicles from “moving” on Texas roadways unless they are being moved by an “operator” (“persons” cannot “operate” a vehicle without a driver’s license [§ 521.021], but presumably vehicles can move without being controlled by persons). One could argue, then, that driverless cars are legal without a designated “operator” aboard the vehicle or even remotely controlling the vehicle.

Such a literal interpretation of the Texas Motor Vehicle Code is likely to be unpersuasive, however. First, the bulk of the Motor Vehicle Code and drivers’ handbook prescribes requirements, rules of the road, and other operational requirements for “operators” (see, e.g., §§ 545.151, 542.4045, 544.008, 544.010, 545.051, 545.052, 545.062). The interpretation that some vehicles can operate without “operators” would thus exempt those vehicles from virtually all of the applicable rules of the road and related operational requirements. Vehicles with operators, in other words, would be subject to hundreds of specific requirements; driverless cars, by contrast, would need only ensure that they are not driven in ways that are “unsafe” (§ 547.004(a)). Additionally, the prohibition that an “operator” may not leave a car “unattended” without first stopping the vehicle completely would make little sense if other vehicles could move freely without operators (§ 545.404). Finally, in criminal interpretations of the Texas Code, the courts have held persons liable for “operating” cars if they are started, even if they are idling.⁹⁵

A much more plausible interpretation of the Motor Vehicle Code as applied to C/AVs, then, is that each vehicle that moves on the roadways must be controlled by an identified “operator,” and that under current law to be “authorized, this “operator” must have a driver’s license. The licensed “operator,” in turn, is responsible for compliance with the Motor Code and other rules of the road. This obligation falls on the operator and not on the vehicle. Moreover, if there is no identifiable “operator” present in a vehicle (authorized or unauthorized per the criminal code), the vehicle could presumably be confiscated (e.g., § 545.305).

Designated Operator’s Role in Physical Operators

Even if each vehicle moving on State highways must be operated by a licensed “operator,” there is still the open question of whether that operator actually needs to be steering or controlling the vehicle at all times, as well as whether the operator needs to be physically present in the vehicle. Both issues remain somewhat ambiguous under current law, although our reading of the law and associated case law suggests that current law allows operators to be at least partly inattentive, provided they are in control in the vehicle. By contrast, Texas law can be read to preclude driverless cars controlled remotely by licensed operators, although greater legal clarity would help reinforce this or the opposite interpretation.

The Inattentive Operator: Texas law defines the “operator” of a vehicle to be that person “who drives or has physical control of a vehicle” (§ 541.001(a)). The definition of “operator” seems to allow for the possibility that this person may not be operating the vehicle per se but has ultimate “physical control” (e.g., “hand-off” to human operator) of the vehicle.

Texas law thus currently seems to allow an operator to be present in the vehicle, but not necessarily in constant control of the vehicle. The Motor Vehicle Code imposes visibility requirements on that operator—they must be able to see the road (§ 545.417), and have a view of approaching traffic at intersections (§ 544.010(c)). But presumably one can comply with these requirements and still allow the “operator” to turn the actual operation over to an automated process.

The Remote Operator: Current law seems to require that “operators” must be present in the vehicle while it is moving, although this requirement is somewhat ambiguous. Speaking most directly to this point is the Texas

⁹⁵ See *Denton v. State*, 911 S.W.2d 388,389 (Tex.Crim.App. 1995) (finding that starting the ignition and revving the accelerator was sufficient to find that defendant “operated” the vehicle as an element in “Unauthorized Use” charge required) but see *Texas Dept. of Public Safety v. Allocca*, 301 S.W.3d 364 (Tex.App.-Austin) (sleeping defendant in driver’s seat parked legally on private property does not provide “probable cause” to believe that the vehicle had been previously operated).

Transportation Code requirement that operators cannot leave vehicles “unattended” unless they come to a complete stop, with keys removed, etc. (§ 545.404). The common sense meaning of this provision (see Tx. Gvt. Code § 311.011) is that vehicles are not allowed to move unless an operator is present in the vehicle. While it is possible that the term “unattended” could be interpreted to exclude remote operators of AVs or perhaps even to allow AVs to also count as “operators” (§ 545.002) so that the vehicle is in fact not unattended, such interpretations strain the common sense thrust of § 545.404 and at the very least would benefit from some clarifying regulatory guidance or regulatory interpretation.

In addition, at least one other section also places responsibilities on “operators” in ways that appear to require that the “operator” be present in the vehicle; see, e.g., § 550.021 (operator requirements in emergencies), § 550.023 (duty to render aid), and § 550.024 (duty on striking unattended vehicle to find and notify the vehicle’s operator or leave note). This section may also be interpreted to allow the “vehicle” to be designated as a supplemental “operator” capable of fulfilling the emergency operations through software and related technological capabilities, but this again strains common sense.

Non-human Operators: The Texas Motor Vehicle Code explicitly lists “operators” as “persons” (§ 541.001(1)), which in turn means “an individual, firm, partnership, association, or corporation” (id. at §541.001)(4)).⁹⁶ At first blush, then, Texas law would seem to allow OEMs and other commercial entities to be “operated;” humans are not required.

However, this broad interpretation of the legality of a non-human operator is undermined by the Code’s prohibition of a “person” operating “a motor vehicle on a highway in this state unless the person holds a driver’s license issued under this chapter” (§521.021). Thus, while it would seem that non-humans can be operators in the State, the license requirements as currently drafted exclude that possibility by requiring a license and then conditioning these license requirements on a variety of “human” demands (e.g., photos, thumbprints, etc.) (§ 521.121).

It is possible that Texas’s reciprocity with regard to the licensing requirements of other states would allow non-human operators to operate vehicles in the State (§ 521.030). For example, if Nevada provides drivers’ licenses to non-human operators of driverless vehicles, then provided there is a person associated with that license, this vehicle would presumably be legal on Texas roads.

Legal Responsibility for Violation

Although it seems most likely that all vehicles in operation in the State will have a licensed “operator” present in the vehicle, there remains the possibility that in cases of violations—e.g., speeding, crashes involving the violation of rules of the road, etc.—the licensed “operator” can argue the manufacturer is a second operator who should be held responsible for the violation. Enforcement personnel will inevitably confront the possibility of facing two “operators”—one a licensed human present in the car and the other a manufacturer (also a “person” exerting some “physical control” of the vehicle)—both of which point the finger at the other with respect to responsibility for violations (e.g., Glancy et al. 2015 p.52).

Texas law provides for the possibility that multiple parties can be jointly responsible for violations of the Code, but it does not appear to allow the responsibility of the licensed operator to be avoided by shifting responsibility to other supplemental operators. Section 542.302, for example, holds owners or others directing the operation of the vehicle liable for violations of law; however, this section does not suggest that these

⁹⁶ The Texas Code also “include[s]” within the “operator” category the vehicle itself in certain situations (§ 545.002). This could be read to imply that a “vehicle” can be the official “operator” and that the license requirements are not always applicable. A careful reading of the text, however, signals that this added entity is supplemental “operator” and not a substitute “operator.” Specifically the section states that “a reference to an operator includes a reference to the vehicle operated by the operator if the reference imposes a duty or provides a limitation.” By its explicit terms, then, vehicles or other nonhumans do not supplant the “licensed person” as “operator;” the vehicles are only “included” within the “operator” definition in certain circumstances.

owners' responsibility supplant the responsibility of the primary, licensed operator (e.g., § 547.004—"a person commits an offense that is a misdemeanor if the person operates or moves or, as an owner, knowingly permits another to operate or move, a vehicle that: 1) is unsafe so as to endanger a person"). Rather, a common-sense interpretation suggests that both owners and operators can simultaneously be responsible for violations.⁹⁷ However, Texas law does appear to place responsibility only on those operators performing an act; thus, there remains the possibility that an operator can escape liability this way (e.g., §542.302 (assigns owners or employers with violations if they knew of or directed the violation)).

Rules of the Road and Related Requirements on C/AVs

Rules of the road present some relatively minor legal impediments to the smooth deployment of C/AVs in the state.

Rules of the Road

There are a few rules of the road that may restrict the operation of C/AVs, although the C/AV technology may ultimately be capable of meeting these requirements. For example, special requirements apply to operators in the presence of "emergency vehicles" (§ 545.156(a) and when following "school buses" that stop (§ 545.066)). The safety signals to stop or pass can include auditory and hand signals (id). Moreover, the appropriate operator response—e.g., yielding or pulling over to the side of the road until the vehicle has passed—may require some operator control. C/AVs will need to ensure compliance with these rules of the road to avoid violations and accidents, either through handoffs or other automated capabilities.

In several other settings, Texas law permits the use of auditory signals and temporary speed signs and traffic signals (e.g., for worker zones). See, e.g., Texas Driver Handbook, Sept. 2014, p.38 (governing temporary signals); p.35 (governing railroad crossings). C/AVs again would need to be equipped to either hand off control in settings with these temporary or auditory signals or be prepared to navigate in automated mode despite these alternate types of signals.

Texas law also assigns considerable driver discretion at right-of-way intersections (id., TDH, p.22). C/AVs may again require careful programming to ensure not only that the right-of-way is gauged correctly given the rules of the road, but also to do so defensively given the likely driver errors that may arise with vehicles that are not automated (e.g., mis-gauging one's proper place in the queue).

Safety Inspections Required for Registration: Texas law requires that steering systems be inspected in all vehicles. The Texas Department of Public Safety's criteria require the inspector to have the capability to turn any motor vehicle's wheel to pass inspection (Tx Department of Public Safety, Vehicle Inspection Chapter 4). As long as C/AVs operate with steering wheels, this requirement will not be an impediment. But for vehicles without steering wheels, the Code requirements may need to be amended to permit vehicles without traditional steering wheels.

Legal Operation of Truck Platoons

There are several ways that truck platoons may violate existing Texas law. These include not providing adequate following distance; moving without an operator in each vehicle; and operating in the passing lane. Texas A&M Transportation Institute (TTI) conducted a study specifically addressing the broader legal impediments to the use of truck platoons in Texas, including added legal restraints imposed by Federal Motor Vehicle Safety Standards (FMVSS) and FMCSA; readers are referred to that project (authored by Jason Wagner in August 2015) for a more focused analysis.⁹⁸

⁹⁷ Reinforcing this interpretation is a provision that includes in the definition of "operator" the "vehicle" in certain settings. § 545.002. The section broadens the definition of "operator" but does so in a way that implies not that only one party can ultimately be held responsible but the reverse.

⁹⁸ Since the instant project consists of a larger mapping project, potential obstacles and conflicts are highlighted at a general level. Fortunately, with respect to the very important topic of truck platoons, TxDOT has already commissioned a more focused study of the intersection between truck platoons and Texas law. Our analysis provides only a

Many and perhaps most of these legal conflicts can be ameliorated if truck platoons are equated to “tow” trucks, with each truck in the sequence treated as a vehicle in the tow line. In the case of towing, “an operator of a truck or of a motor vehicle drawing another vehicle who is on a roadway outside a business or residential district” can be treated as a single unit (§ 545.062). Treating platoons as a towing operation with multiple vehicles allows for the following legal accommodations:

- *Licensed Operators on a Vehicle*: If truck platoons consist of a first, operator-controlled vehicle that is connected to “towed” vehicles, then a licensed operator need only be present in the first truck that is doing the towing. Subsequent vehicles in the platoon without operators would not technically be in violation of Texas law; since they are towed, they are presumably not “unattended” under Section § 545.404.
- *Following Distance*: The requirement of a following distance that allows for sufficient space between vehicles to allow passing (see § 545.062(c)) will not apply if the vehicles in the platoon are being towed by the lead truck.

However, even if truck platoons are treated as towing operations, some legal ambiguities and impediments may remain that need to be addressed:

- *Trucks (often) prohibited in passing lane*: Under Texas rules of the road, trucks are generally not allowed in the passing lanes. This prohibition would thus need to be amended to allow for a third, restricted lane for platoons (Benning 2013). Restrictions imposed by localities (e.g., prohibiting towing trucks from driving in passing lanes) may also need to be amended.
- *Multiple vehicles in a “tow”*: Since the Transportation Code refers only to a single “vehicle” being drawn behind the first, a clarification may be needed to allow for the towing of multiple vehicles (e.g., truck platoon).
- *Merging*: Any existing restrictions on merging by towing vehicles or other oversized trucks may also need to be revisited to allow for truck platoons, although we were not able to locate any specific restrictions in place at the statewide level.

8.3 Tort Liability

There is a general consensus that the common law liability rules developed through tort law are well-suited to assimilate C/AV technology in apportioning legal liability for crashes (Anderson et al. 2014; Brookings 2014; and Kalra et al. 2009). After providing a brief orientation to liability law in Texas, we discuss a few potential complications and ambiguities that might impact transportation agencies and other litigants as C/AVs are assimilated onto Texas highways. As with the licensing discussion, these complications are relatively minor.

Background on Liability Rules

Legal responsibility for crashes in Texas is governed largely by tort law—a body of judge-made, case-by-case law that determines liability according to principles of fault. Although there have been some shifts in features of these liability rules in the case of vehicular crashes, for the most part the rules governing crashes have proven both consistent and adaptable to changes in technology. Adjusting general liability rules to new technologies, including and particularly in transportation, is thus a familiar and well-known exercise for the legal system.

Under the tort law of Texas, operators of vehicles must behave “reasonably” while driving. When they fail to act reasonably and their negligent act causes harm, they can be held liable for the damages they cause. Private victims, working through the tort system, provide incentives for operators to be “reasonable” and hold them accountable when their deviations cause harm. In the court’s assessment of this reasonableness, the actor’s

reconnaissance-level identification of the relevant issues arising with the testing and deployment of truck platoons in Texas; the TTI report should provide readers with in depth treatment of these issues.

conduct is compared to that of an abstract reasonable person, with no special allowances for age, mental ability, or intoxication.

Somewhat similarly, when issues arise regarding the safe design of a vehicle by manufacturers, manufacturers are similarly held to “reasonable” standards of design. Manufacturers must ensure that the benefits of their design choices outweigh the risks and other social costs, particularly when compared against alternative design options. These product liability standards incorporate a flexible, “reasonable-like” expectation into the design choice and hold manufacturers financially liable for crashes only when the risks of a design outweigh its value.

The flexible test of “reasonableness” built into the common law liability system thus provides a versatile standard for assessing liability when crashes occur. Nevertheless, there are several ways that C/AVs raise challenges for the well-settled common law liability system that may warrant targeted intervention.

More Complicated Crash Litigation

In the world before autonomous cars, when a car is operating in ways that violate rules of the road or are otherwise “unreasonable,” the operator is generally both the obvious and exclusive liable party. Crash litigation—at least with respect to identifying the “liable” party in these crashes—is relatively simple. While there can be complicated disputes about whether a party actually did operate the car in an unreasonable way, whether the plaintiff’s damages claimed resulted from the crash, whether the plaintiff was also at fault, etc., the fact that the driver is the primary and generally exclusive defendant is generally straightforward.

This is not always the case of course; in crashes that are the result of design defects of a vehicle, the plaintiff can sue and recover against the manufacturer of the defectively designed vehicle as well as the operator if the latter was also negligent. (See, e.g., *General Motors Corp. v. Grizzle*, 642 S.W.2d 837 (Tx. Ct. App. 1982)). In these more infrequent cases, car crash litigation can include complicated product liability claims.

In the new world of AVs, however, product liability claims against manufacturers will become the rule rather than the exception. If a C/AV is a potential cause of a crash and the C/AV was operating in automated mode, the manufacturer will be joined as a defendant in the litigation and the primary claims brought against the manufacturer will be complex product liability causes of action. For example, the identification of a defect in a C/AV (e.g., proving an erroneous algorithm or other error in the vehicle software), the assignment of potential driver error in heeding a warning, evidence required to establish a defect will complicate discovery and raise the costs of suit for the plaintiff and/or the insurer bringing the claim. While these increased complexities might be offset by the possibility of fewer crashes, at least during the transition period involving more complicated handoffs and mixed use of C/AVs with non-automated vehicles (see below), it is possible that litigation will actually rise, at least for a brief period. Indeed, some posit that this initial mixed-use, experimental period may chill development of the technology over the long term (Kalra et al. 2009; Glancy et al. 2015)

To avoid costly product liability claims, victims in car crashes may be able to allege that the manufacturer of a C/AV operating in autonomous mode violated Section 547.004(a) of the Texas Code. That section holds that “A person commits an offense that is a misdemeanor if the person operates or moves or, as an owner, knowingly permits another to operate or move, a vehicle that: (1) is unsafe so as to endanger a person.” A successful negligence per se claim filed in tort law could help circumvent some of the complexities of products liability evidence by flipping the burden of proof to the manufacturer. But only actual experimentation will reveal whether this statutory violation might streamline litigation involving C/AV manufacturers.

Added Challenges in Determining Fault or Defect in Crashes Involving C/AVs

The open-ended and adaptable test for defect and fault applies similarly to C/AVs. Under tort law, C/AVs must be designed “reasonably,” with “reasonable” warnings, and in ways in which the “risks outweigh the benefits.” Yet applying these flexible tests will still entail considerable fact-intensive assessments, generally made by juries in case-specific crashes. As a result, manufacturers will face some unpredictability with regard to both how their design choices will fare in practice and with regard to how juries will assess those choices in hindsight, often years after the accident occurred. The areas where C/AV-related liability is likely to be

most unpredictable with respect to their reception in the tort system include 1) handoffs for mid-levels of automation and connectivity and 2) proof of a defect in C/AVs.

Handoffs for Mid-levels of Automation and Connectivity

Commentators spotlight the “handoff” within each C/AV (the quick transition from automated to manually controlled) as an area where liability is likely to be both unpredictable and an important disciplining force for the technology’s development (Kalra et al. 2009). Fact-intensive questions will arise with respect to both the manufacturers and the operators: How alert and attentive should drivers be in various situations? What is expected of “reasonable drivers”? Should vehicle designers foresee the possibility that some owners will fall asleep or be slow to take over operation? What types of alert systems are needed to lead owners to use the automation, and thus prevent accidents? If operators turn off the automated feature to avoid annoying vibrations or noises, could manufacturers be liable in part for the foreseeable use of their technology?

In the short term, because consumers will be unfamiliar with AV and CV technology, manufacturers could even have a duty to safely instruct consumers on how to use the vehicles. This duty could conceivably be discharged by having users read an instruction manual, undergo a tutorial in the vehicle or at the dealership, or be certified in some way (Guerny et al. 2013)

In resolving litigation in this area, courts and juries will need to determine what constitutes an adequate warning for purposes of a handoff.⁹⁹ Courts will also need to decide whether and how to allow comparisons among automated and non-automated vehicles. If a handoff is designed in a way that presents some foreseeable risks of driver error, will the C/AV be compared against cars that have no automation at all (and hence pose no risk), against cars with similar levels of automation, or against an even narrower class of cars struggling with the same difficult design challenge (Marchant et al. 2012).

Proof of a Defect in C/AVs

Crashes that involve some apparent failure of automated technology in C/AVs will inevitably raise product liability claims, and plaintiffs—whether third parties or the occupant—will need to pinpoint a defect as part of their case. As just discussed, amassing this evidence and even identifying a theory for the defect may be challenging.

Because of these difficulties, it has been suggested that plaintiffs will focus initially on locating design defects associated with more tangible aspects of the car, such as when a car is designed with one laser sensor on the front of the vehicle instead of two (Guerny et al. 2013). In these settings, plaintiffs will still need to establish that other vehicles used two sensors and that the utility of double-sensors outweighed the risks,¹⁰⁰ but in cases involving improvements, these dual showings may not be difficult. If this type of litigation is successful, it could encourage defensive manufacturing practices (a sort of “arms race” in adding sensors, etc.) to ensure that vehicles maximize the use of obvious features on the vehicle but also minimize the risks of errors or crashes.

Plaintiffs will encounter particularly significant difficulties bringing claims against manufacturers in cases of inexplicable crashes involving automation (e.g., C/AVs careening into poles) since there may be no theory or explanation for the product failure. To date, Texas has not adopted the malfunction test, which would allow for lightened burdens for injured plaintiffs.¹⁰¹ The parallel negligence claim of *res ipsa loquitur*—which provides the plaintiff with an inference of negligence if the accident itself suggests negligence—may provide a lightened burden,¹⁰² but in a product liability case concerning C/AVs, both the “exclusive control”/no fault

⁹⁹ See, e.g., *DaimlerChrysler Corp. v. Hillhouse*, 161 S.W.3d 541, 550 (Tex.App—San Antonio, 2004) (imposing liability for a confusing warning).

¹⁰⁰ See, e.g., *Genie Indus., Inc. v. Matak*, LEXIS 437, *19-26 (May 8 2015) (applying the risk utility factors even with a safer alternative design); *Timpte Indus. v. Gish*, 286 S.W.3d 306, 311 (Tex.2009); Tex. Civ. Prac. & Rem. Code Ann. § 82.005(a) (1)-(2) (West 2015)

¹⁰¹ *Ford Motor Co. v. Ridgway*, 135 S.W.3d 598, 601-602 (Tex. 2004).

¹⁰² *Porterfield v. Brinegar*, 719 S.W.2d 558, 559 (Tex. 1986).

of plaintiff elements may be difficult for a driver to establish. Professor David Vladeck has suggested that courts apply strict liability principles to these cases (Vladeck 2014). Professors Sophia Duffy and Jamie Patrick Hopkins have also suggested that, in these cases, owners of AVs and CVs be held strictly liable and forced to maintain larger insurance policies (Duffy et al. 2013). They suggest that given the potentially low rate of accidents involving AVs and CVs and the low rate of inexplicable accidents in general, greater insurance requirements will neither deter implementation by manufacturers nor use by consumers (Duffy et al. 2013). Conversely, such crashes may be rare enough that common law adjustments to defects law or *res ipsa* can accommodate difficult cases.

Litigants and courts may also struggle with identifying the appropriate comparators for different levels of automation or technological capabilities in product liability claims. In the abstract, courts typically consider risks and utilities of a product in relation to competitors. Yet all Level 3 automation in V2V consumer vehicles may not necessarily be similar; different C/AV vehicles may involve significant apples/oranges comparisons even within the same level of automation (Karla et al. 2009). As C/AV technologies improve and prices drop, moreover, CAVs that are older and have lower levels of automation may begin to be compared to price-equivalent but much more capable, newer vehicles. Rapid changes in the safety and price over time, in other words, could make the identification of comparison products even more difficult and may lead to a de facto incentive for rapid turnover and high market demand for new vehicles.

Software Errors, Particularly Those Occurring after Manufacture

Crashes that are the result of software errors or malfunctions may also present complications in determining and allocating liability. Courts across the country have generally refused to subject software defects to strict liability in products liability law (Polin 2015). Since it is nearly impossible to design software without errors, plaintiffs are likely to face considerable difficulty in proving that software was negligently coded/created (Polin 2015). Alternatively, software could also be viewed as a component part of the product, which would not affect the products liability analysis. Even updates, which are effectively updates of the software built into the initial vehicle, would be considered part of the finished product. While the latter view will likely prevail, the important role of software in vehicle design and in preventing crashes may raise some new questions in the product liability analysis.

Further issues could arise if software updates are not automatic. For example, at least one current company, Nissan, offers its CARWINGS software on a subscription basis (Svarcas 2012), and it is plausible that other manufacturers will do the same, especially in the short term. If the software update reveals a defect in the original software, even if it is not automatic, this feature could be used by plaintiffs to argue that the update meets Texas’s “substantial degree of control” requirement such that these manufacturers would have a continuing obligation to warn of product defects and issues. Additionally, because offering updates to consumers is similar to the defendant’s blade replacement program in *Bell Helicopter Co. v. Bradshaw*, 594 S.W.2d 519 (Tex.App—Corpus Christi, 1979), doing so would also likely constitute a manufacturer’s voluntary assumption of a post-sale duty to warn. Manufacturers could potentially discharge this duty by alerting the driver via the car that an update was needed or by using more traditional means, i.e., the use of regular mail or telephone. Several commentators predict, however, that these types of post-sale duty cases will raise important and complicated liability questions as a result of the rapid pace of technological innovation (see, e.g., Walker-Smith 2014).

Federal Safety Standards

Although federal safety standards do not yet exist with respect to C/AVs, if and when they are promulgated they will likely exert a substantial influence on Texas liability law. Section 82.008 of the Texas Civil Practice and Remedies Code allows a defendant in a products liability action to establish a rebuttable presumption that they are not liable if their product conforms to mandatory safety standards or regulations or to pre-market licensing requirements promulgated by the federal government or a federal agency (Tex. Civ. Prac. & Rem. Code Ann. § 82.008 (West 2015)). NHTSA standards that satisfy this provision thus offer manufacturers added protection from tort liability in the State of Texas. This presumption can be rebutted by a showing that the standards, regulations, or pre-market licensing requirements were inadequate to protect the public from unreasonable risks or damage or by showing that the defendant withheld material information from the federal government or agencies (*id.*). This is likely to be a difficult showing for a plaintiff, however.

Depending on the nature of federal involvement, it is also possible that the federal standards will expressly or implicitly preempt state common law claims, including claims of inadequate warning. While this preemption is disfavored and appears to be precluded under current law (49 U.S.C. § 30103(e)), it remains a future possibility if the U.S. Congress passes legislation with express preemptive effect.

Evidence: EDRs, when present in a vehicle, ensure that a great deal of information about the vehicle and occupant are available shortly before the crash. Although the use of EDRs predates and is separate from C/AV technology, the two technologies overlap. Indeed, in some states EDRs are required for all C/AVs.

Although the privacy and related concerns about protecting this data are currently being addressed at the federal level, the EDR data is well-positioned to be central to tort litigation. Texas law does allow retrieval of data from EDRs by “court order” (§ 547.615(c)(1)). Presumably in cases where the EDR data will prove probative in determining the cause of an accident, the court will acquiesce. In crashes in which both or all cars involved in the accident have an EDR and/or other additional data recording devices, this added evidence should prove invaluable in sorting out responsibility.

Due to the vital role EDRs are likely to play as evidence in tort litigation, however, it will also be important to ensure that the data cannot be manipulated. Until the integrity of EDRs and other recording devices can be protected, such data may need to play a more qualified role in C/AV litigation in the State.

Modifications to C/AVs by Third Parties: Several states and NHTSA have shown interest in the liability issues that arise when owners retrofit cars with C/AV technology (ULC 2014). The added safety hazards that seem likely to arise in this area, coupled with the complications in a traditional liability analysis with respect to fault and cause, may lead to significant complications in liability cases and insufficient deterrence for those engaged in the modifications. Indeed, the ULC Subcommittee identified this issue as one that might be worthy of legislative attention, while recommending that state legislators otherwise leave tort liability alone.

Under Texas common law, manufacturers are already well-positioned to defeat claims arising from third party modifications to C/AVs since the plaintiff has the burden of proving that a defect introduced by the manufacturer was a “producing cause of plaintiff’s injuries” (Ford Motor Co. v. Ridgway 135 SW3d 598, 600 (Tex. 2004)). The Texas Supreme Court has also refused to adopt and apply the 3rd Restatement of Torts (§ 3), which provides plaintiffs with an inference that harm was caused by defect and that it existed at time of sale/distribution (when certain conditions are met), even when the product is not new/nearly new and has been previously modified or repaired (id). Additionally, § 82.002 of the Texas Civil Practice and Remedies Code does not require manufacturers to indemnify sellers (which appears to include any commercial entity performing the modification) in cases where the harm was the result of the seller “negligently modifying or altering the product for which the seller is independently liable.” While this latter provision does not immunize the manufacturer from liability, it suggests that primary liability will not necessarily lie with the manufacturer in cases of their party modifications.

New Issues Affecting Governmental Liability

Texas agencies, including TxDOT, the DMV, and municipalities, generally enjoy immunity for planning and governmental functions. This includes road design and also the dissemination of information. The integration of C/AVs onto Texas highways is not expected to dramatically alter the government’s liability, even with the heightened technological complexity of connected infrastructure. Nevertheless, there are several features of the future C/AV world that do create ambiguities with regard to governmental liability.

Malfunctioning Road and Traffic Signals and Related Equipment

In Texas, the installation and operation of traffic-control devices, signs, warnings, and other signals installed by governmental entities (both State and municipal) are partially protected by governmental immunity (§ 101.060 (see also § 101.0215(a)(21) and (31))). Roadside unit (RSU) and related infrastructure needed to provide connected roadways also appears to fall within the terms of this partial immunity for road and traffic signals. (It is assumed in this analysis that connected infrastructure will fit neatly within the general concept of traffic and road control devices of § 101.060; if this is not the case, however, then additional analyses must be undertaken as to whether they are personal or real property under the Act).

While the decision to place a sign or control device is discretionary (§ 101.060(a)(1); *City of Grapevine v. Sipes*, 195 S.W.3d 689, 693 (Tex.2006)), once that signal is in place, the government can be liable for malfunctions, stolen or missing signals, or defects in these devices, with some exceptions (*id.* at § 101.060(a)(2)). This liability is imposed, however, only if the government received notice and did not make repairs within a reasonable time.¹⁰³

With respect to malfunctions of digital or “connected” signals, it is not clear how “notice” under subsection (a)(2) will be triggered for purposes of the Act. Connected roadway devices will presumably involve real time communications not only between the device and vehicles, but also as between the device and the government operating the signal. In theory then, the government may receive instantaneous “data” revealing a problem with a signal; this immediate message is not available for non-digital signs and signals.¹⁰⁴ The courts could thus determine that notice occur immediately—when the malfunctioning signal is sent. Or notice could be triggered once an employee has reason to discover the defect from the incoming data. As a result of the future legal uncertainty, which presumably could discourage the government from utilizing connected or digital technologies for fear of greater liability, legislative clarification of the notice requirement would be beneficial.

It is also possible, however, that since connected infrastructure malfunctions occur with respect to the transmittal of “data or information,” the courts might exempt malfunctions in connected infrastructure from liability altogether. This exemption would occur if the digital infrastructure is categorized in this context as “data” devices rather than “personal” or “real property” (§ 101.021). (See, e.g., *Univ. of Tex. Med. Branch v. York*, 871 S.W.2d 175, 178-179 (Tex. 1994) (holding that information is an “abstract concept, lacking corporeal, physical or palpable qualities,” and thus intangible)).¹⁰⁵

Roadway Maintenance

C/AVs may also present additional liability risks to transportation agencies and municipalities with respect to their road maintenance responsibilities. Some of the ways that C/AVs could alter the current liability landscape include:

- **Special defects on the roadways, such as excavations and roadway obstructions:** These obstructions can lead to potential liability of governmental entities if these defects are not addressed in a reasonable way—e.g., with signage, fencing, etc. (§ 101.060(c)).¹⁰⁶ The capabilities of C/AVs

¹⁰³ In the case of destruction of the signal or device by third parties, the government must receive “actual” notice; this “actual notice” includes a “subjective awareness of fault” that goes well beyond the collection of data or even the results of a safety inspection. *TxDOT v. Anderson*, WL 186868, at *4 (Tex.App—Tyler, 2008).

¹⁰⁴ See, e.g., *Alvarado v. Lubbock*, 685 S.W.2d 646, 649 (Tex. 1985) (several pieces of evidence from other police citations revealing that the city knew of the discrepancy between the posted speed limit, and the speed limit authorized by ordinance was enough to cause an issue of material fact.); *State v. Gonzalez*, 82 S.W.3d 322, 329-330 (Tex. 2002) (city did not have actual notice that stop sign disappeared, because even though it knew the stop sign was prone to being stolen the city had just replaced the sign); *City of Midland v. Sullivan*, 33 S.W.3d 1, 12 (Tex. App.—El Paso 2000 pet. dismissed) (city had notice of defective traffic condition by way of faded pavement markings).

¹⁰⁵ See also:

- *Univ. of Tex. Health Sci. Ctr. v. Dickerson*, 2014 Tex. App. LEXIS 1889, *19 (Tex. App.—Houston [14th Dist.] 2014, no pet.) (“[T]he use of computers, telephones or records to collect and communicate information is not a use of tangible personal property under [the Tort Claims Act,]” and “cannot provide the basis for a waiver of immunity under the [Act].”)
- *Dear v. City of Irving*, 902 S.W.2d 731 (Tex. App.—Austin, 1995 writ denied) (“The Supreme Court has specifically held that the Tort Claims Act does not eliminate governmental immunity for injuries resulting from the misuse of information.”)
- *Axtell v. Univ. of Tex. at Austin*, 69 S.W.3d 261, 263 (Tex. App.—Austin, 2002 no pet.) (“The tangible personal property exception of the Act does not encompass an injury resulting from the disclosure of confidential information, however that information is transmitted.”)

¹⁰⁶ “A special defect” under § 101.060(c) is “an excavation or roadway obstruction [that is a] present ‘[] unexpected and unusual danger to ordinary users of roadways.’” *State v. Rodriguez*, 985 S.W.2d 83, 85 (Tex. 1999). See also *Morse v. State*, 905 S.W.2d 470, 475 (Tex. App.—Beaumont 1995, writ denied) (holding that ten-inch drop-off along shoulder that prevented car’s left wheels from reentering the roadway once they had slipped off was a special defect); see, e.g., *State*

to detect these defects may differ from non-automated vehicles, leading to a different set of required signals for C/AVs. Transportation agencies and other governmental entities responsible for these special defects may need to develop best practices for meeting their obligation of reasonable care with respect to AVs that rely on sensors.

- **Differing vulnerabilities with regard to road repair:** C/AVs may have the capacity to learn of and avoid certain types of road defects, such as potholes, using digital information on landforms that far exceed the abilities of human drivers. Conversely, there are some roadway hazards that may stump C/AVs but are easy to avoid for human operators. Blowing debris (paper bags) or perhaps other visual obstructions that in fact are not real impediments, for example, could lead to considerable delays and inconveniences for C/AVs but not for non-automated vehicles.

Cumulatively, regional transportation agencies like TxDOT may face twice the maintenance burden, or at least a more extensive maintenance challenge, in a world of mixed vehicles where hazards are perceived differently. Moreover, the standards for reasonableness may become more of a moving target, particularly for hazards that are unique to C/AVs.

Implications of Liability Challenges for Insurance

At least some insurance companies predict that the effects of C/AVs on their net payouts and profits may ultimately be a wash. Insureds who drive C/AVs may face fewer crashes, but the cost of this vehicle—when there is a crash—may offset the reduced crash rate since the vehicle’s replacement/repair value is likely to be greater than the cost of an average non-automated vehicle (Swiss Re Centre for Global Dialogue 2015; see also Glancy et al. 2015 p.65). At best, the insurance industry seems to believe that the financial gains from insuring C/AVs is currently uncertain (Insurance Information Institute 2015).

Insurance companies are also reportedly wary of the increased costs of crash litigation that are likely to arise as C/AVs become more integrated on roadways. As discussed above, these increased litigation costs result from novel product liability claims against the manufacturers that may become commonplace in crashes caused in part by a C/AV (id.). Insurance companies may seek to circumvent these transaction costs by altering the contractual arrangements or by devising other methods to limit the costs of crash litigation in the future (ITS International 2015).

Finally, insurance companies are likely to take advantage of the ability of C/AVs to store and share data (Scism 2013). “Because connected vehicles provide rich sources of information about both vehicles and drivers, automobile insurance companies have taken a [particularly] keen interest in connected vehicles and the data they generate” (Glancy 2014, p.1647). This data will not only be central in resolving responsibility in crashes, but it may also be available to insurers in setting premiums for individual drivers.

8.4 Privacy and Security

One of the most significant policy challenges facing C/AVs is ensuring the appropriate level of privacy and security for consumers. The information-intensive feature of C/AVs raises unresolved issues of how much data will be collected and/or recorded within the vehicle, who will “own” or have access to the data, and the resulting implications for personal privacy of users (Anderson et al. 2014, p.94). At the same time and in contrast to tort liability, because privacy and security are relatively new social issues, there is not yet a coherent legal infrastructure in place to manage them. The combination of technological uncertainties and legal instability presents challenges that are particularly acute for states at the cutting edge of integrating this new technology.

This section provides a very brief summary of the factual backdrop and then considers how the privacy and security issues are being treated under current law in Texas and nationally.

Dep't of Highways v. Kitchen, 867 S.W.2d 784, 786 (Tex. 1993) (holding that ice on bridge during winter was not a special defect because it is not unexpected or unusual).

Privacy Concerns

There is widespread consensus that C/AVs will pose threats to traditional understandings of individual privacy. While there are risks to the disclosure of personal identifying information, like a driver's license, the bulk of concerns are related to risks posed by having personal information collected and used—generally to the consumer's detriment—by manufacturers, insurers, and others. A great deal of data on the location, movement, habits, and other features of drivers will become available in a connected system and will even be recorded and potentially accessed in C/AVs that are self-contained (Woodyard and O'Donnell 2013; Markus 2013; Glancy 2012). One set of authors conclude that “[e]ven if this data is scrubbed of unique individual identifying markers, for instance VIN-numbers, or IP- or MAC- addresses, data-mining techniques will almost certainly be able to reconstruct personal identifying information about particular vehicles and by extension their regulator occupants” (Kohler & Colbert-Taylor 2015, p.120-121).

CVs that rely on infrastructure or vehicle communications will present the greatest risk of loss of private information (Glancy 2014), particularly if they cannot be turned “off” by the user so that information continues to be shared with third parties. The operating mechanism of these vehicles is premised on sharing information with other vehicles and/infrastructure in a type of data cloud. Moreover, information on the movement and operation of vehicles, particularly in connected systems, may also need to be stored and analyzed to improve the system. “A new car may have more than 145 actuators and 75 sensors, which produce more than 25GB of data per hour. The data is analyzed by more than 70 onboard computers to ensure safe and comfortable travel” (Glaskin 2014, p.40). In one of the most rigorous analyses of privacy and security risks associated with connected systems, Prof. Glancy identifies at least five distinct features of CVs that present particular risks to privacy (p. 1635; and p.2639-40). Figure 8.2 illustrates the various data components in V2V technology.

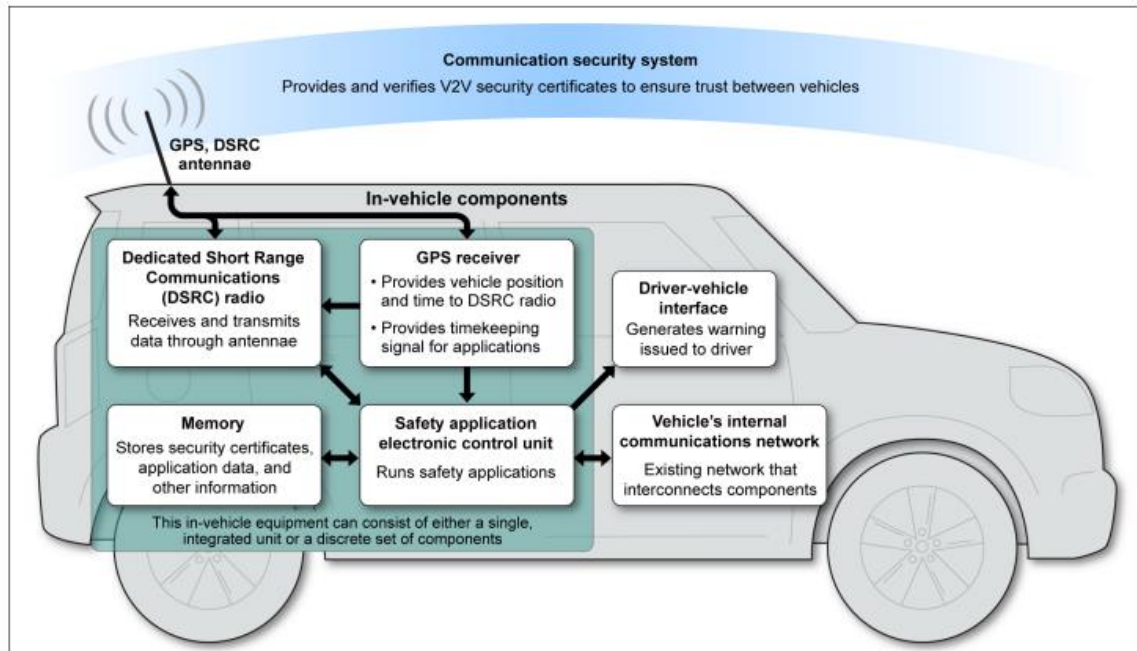


Figure 8.2 Data Components in V2V Technology (GAO 2013, p. 12)

Even for self-contained C/AVs, privacy will be compromised in potentially significant ways. One of the simplest and most common technologies in place to record information about occupants and vehicle patterns are EDRs. EDRs, like flight recorders, are programmed to collect data on the vehicle and occupant information

shortly before an impact or crash. EDRs are voluntarily installed in the majority of vehicles under production.¹⁰⁷

A still greater imposition on personal privacy will likely arise from the development of various information-intensive devices built into or used by the vehicle, including entertainment systems, onboard computers, and other infrastructure (Woodyard and O'Donnell 2013). Manufacturers have already obtained patents for in-car advertising, and the potential for targeted advertising of individuals using this data is generating widespread attention (Kohler & Colbert-Taylor 2015, p.122). Route planning may also be affected by manufacturers and others using this personal data. For example, individuals may be capable of being re-routed past specific physical locations based on a history of the owner's impulse buying and unplanned stops.

Personal data on AV drivers can be collected in a variety of ways. Some of these devices will collect information on the vehicle occupants, including their location, near misses, entertainment preferences, etc., and transfer that information to manufacturers and possibly others in real time. Other information may be stored and retrieved in the vehicle itself.

Regardless of the methods of collection, manufacturers have signaled their intent to collect this data. A telematics services subscription agreement by Tesla, for example, reserves the right to obtain information about the vehicle and its operation, accidents, and the operators' use of the vehicle and services (Walker-Smith 2014). While the Tesla agreement (and a similar one by Nissan) makes clear that data will be collected, users may not fully appreciate the extent that their privacy might be compromised. The agreement allows the company to collect the following:

“(x) information about the vehicle and its operation, including without limitation, vehicle identification number, location information, speed and distance information, battery use management information, battery charging history, battery deterioration information, electrical system functions, software version information, and other data to assist in identifying and analyzing the performance of your Tesla EV; (y) information about your use of the Services; and (z) data about accidents involving your Tesla EV (for example, the deployment of air bags)” (Id. quoting Tesla agreement, at 1789).

Walker-Smith also notes that under the agreement,

“the customer ‘owns’ these data but ‘grant[s] to Tesla a worldwide, royalty free, fully paid, transferable, assignable, sublicensable (through multiple tiers), perpetual license to collect, analyze and use’ them. These data may help the company to check, maintain, analyze the performance of, and help in the maintenance of the vehicle; ‘research, evaluate and improve’ its technology; ‘comply with the law and any and all legal requirements,’ including valid enforcement requests and orders; ‘protect the rights, property, or safety of’ the company, the customer, or others; and ‘perform market research for Tesla’s own purposes,’ a list that ‘is not meant to be exhaustive’” (Id., at 1790, footnotes omitted).

Governmental entities can also collect personal information on operators driving on Texas highways, even without a connected infrastructure and V2I communications. In the State of Texas, for example, governmental entities have collected drivers' information with Bluetooth readers and other easily available tools (Examiner 2015). But in the future, with V2V and V2I possibilities just on the horizon, the data will not only become more readily available, in some cases extensive data collection will be necessary to enable the connected infrastructure to direct traffic. While it is possible that the connectivity equipment can use the data only in real time, without storing it, this less intrusive option may prove inadequate for purposes of accident reports, technological capabilities, etc. Thus, transportation agencies and other entities may find themselves faced with databases on consumer travel habits that contain some private information, regardless of their best efforts to avoid this scenario.

¹⁰⁷ To ensure the usefulness of EDRs in litigation and related matters, NHTSA requires standardized minimum features for these voluntarily installed EDRs in all vehicles built on or after Sept. 1, 2010 (49 CFR Part 563).

Alongside more immediate privacy concerns associated with data storage and use is the government's own routing decisions that may be viewed as "infring[ing] on the individual right to privacy, including the right to physical autonomy" (Kohler & Colbert-Taylor 2015). The government could use routing to bypass protests or provide some drivers with more rapid routes than others. The latter possibility is particularly worrisome if faster routes are reserved for drivers with a higher status or a willingness to pay for the privilege.

The seemingly inevitable future for C/AV technologies is thus one in which the traditional concept of privacy and the infringement on individual autonomy by both the private and public sector will be more limited. Yet the point at which privacy and/or security interest are being breached or the appropriate state reaction to unrestricted consumer data collection, particularly by private businesses, is open to debate. The law governing this area, moreover, is still developing, offering little guidance in the interim.

The Law Addressing Privacy Concerns Involving C/AVs

Current Texas law unevenly places restrictions on the ability of governments or private entities to collect, tabulate, or even share (or sell) data on individual driving habits. Meanwhile, the collection and use of remaining information that nevertheless charts the location, use, accidents, etc., of a vehicle and its operator appears largely unprotected under Texas law.

Protection of Sensitive Information

The laws in the State of Texas provide citizens with strong protection from third-party access to sensitive information and information contained in EDRs. EDRs provide a particularly good reference point since much of the data collected in EDRs may not be terribly different from the types of data that can be collected through other devices installed in a C/AV as just discussed. In Texas, any governmental or private access to EDR data is generally off-limits except in one of the following four narrow categories:

- 1) On court order;
- 2) With the consent of the owner for any purpose, including for the purpose of diagnosing, servicing, or repairing the motor vehicle;
- 3) For the purpose of improving motor vehicle safety, including for medical research on the human body's reaction to motor vehicle accidents, if the identity of the owner or driver of the vehicle is not disclosed in connection with the retrieved information; or
- 4) For the purpose of determining the need for or facilitating emergency medical response in the event of a motor vehicle accident. (§ 547.615(c))

These protections of privacy in Texas are reinforced by other laws that protect other sensitive information. Under Texas Transportation Code §§ 371.001 & 371.051, license plate data collected on toll roads are not allowed to be collected or shared except for very limited official purposes. Motor vehicle records also cannot be subject to the State's Open Records Act, thus providing some privacy protection for the release of driver's license and registration information or other personal identification information (§ 552.130(a)). The federal Driver Privacy Protection Act reinforces Texas's law. It prohibits state motor vehicle offices from disclosing photos, name, address, telephone number, and medical or disability information, with narrow exceptions (18 U.S.C. § 2721).¹⁰⁸ Several federal statutes also protect consumer privacy in ways that would seem to at least preclude unauthorized interceptions of signals from C/AVs (Glancy et al. 2015, p.81-83). Private businesses are also prohibited from allowing "sensitive personal information" of individuals to be accessed by third parties without consent of the owner (§ 521.052). "Sensitive information" for purposes of the Act includes specifically enumerated information that consists of medical information, Social Security or drivers' license

¹⁰⁸ Note that the Act "prevents private actions against states." *Travis v. Reno*, 163 F.3d 1000, 1006-1007 (7th Cir. 1998); *Downing v. Globe Direct LLC*, 806 F. Supp. 2d 461 (D. Mass. 2011), *aff'd*, 682 F.3d 18 (1st Cir. 2012) ("Congress, moreover, has not abrogated the States' sovereign immunity with respect to private DPPA lawsuits.").

information, or credit card information. In cases of a breach or disclosure, the businesses are also required to notify individuals that their sensitive personal information has been accessed illegally (§ 521.053).

Limitations in Current Laws with Respect to Privacy and C/AVs

While it is conceivable that the data collected by manufacturers, the government, and others in a C/AV system would include some “sensitive” information under Texas law, personal information in the C/AV context likely includes a wealth of other personal information that does not fall into this “sensitive information” list but is nonetheless considered private (§ 521.002(2)). The statute does not appear to reach this information. Accordingly, if OEMs, software companies, or insurers install data chips, road cameras, or other mechanisms to collect information on individual drivers outside of the EDR, there appear to be no explicit legal prohibitions, restraints, or even requirements of disclosures for these various avenues of information access under Texas law. While consumers may have claims under contract law or tort law, even these prophylactic private remedies are likely to be incomplete at best.

Additionally, even with respect to “sensitive information,” there appears to be no prohibitions for private businesses in legal possession of the data to use it for internal commercial purposes (e.g., targeted marketing strategies); the law precludes “unlawful” use and “disclosure” to third parties, but it does not appear to prohibit commercial use of data for purposes of product development, advertising, or pricing and sales (§§ 521.051-.053 (in 521.051(a) consent appears required only when the sensitive information is used to acquire goods in the person’s name)). Federal legislation does not fill in these gaps in state protection (GAO 2012).

Insurance companies may also be able to gain access to this non-sensitive information under current law, perhaps through sales arrangements with the OEMs or others. Through a much more fine-grained understanding of the drivers’ habits (e.g., speeding, nighttime driving; handoffs; etc.), insurance companies can develop much more accurate policies governing insureds or avoid some drivers altogether. In fact, insurance companies are currently recruiting volunteer policy-holders to use devices to track their habits, thereby reducing their premiums (Glancy 2014; Scism 2013). While this activity is voluntary, it signals the insurers’ great interest and use for this personal information that falls outside of the narrower radius of “sensitive information.”

In contrast to private parties, the Fourth Amendment does impose constraints on governmental entities’ ability to collect private information on drivers (Glancy 2014). It is not clear at what point at which those protections might be triggered in cases where individualized personal data is collected or analyzed by the government beyond the infrastructure needs of V2I and V2V (Kohler & Colbert-Taylor 2015). It seems likely that the routine management and oversight of a C/AV system would not trigger these constitutional protections since they do not have surveillance or the “search” of individuals as their purpose and may not provide identifying information (Glancy 2014). Even in cases in which the data is used by the government in investigating the conduct of an individual driver, however, some have argued that the government may be allowed to access this data outside of the Fourth Amendment through a rigorous licensing program that provides the government with a type of implied consent to the information (Roseman 2014, p.32). The scope of the government’s access to the information, however, deserves considerably more analysis, which in turn will depend on a better understanding of the types of information and access that will be available in C/AVs in the future (Glancy 2014; Palodichuk 2015).

On the other hand, municipalities and state agencies—outside of constitutional violations—are immune from private tort claims from those whose information was shared, even in cases where sensitive information is disclosed in violation of Texas law. As discussed earlier, state agencies and municipalities may be immune from suit with respect to negligent acts that involve the disclosure of information, including presumably confidential information. In the State of Texas, as contrasted with several other states, there also appear to be no requirements that the State notify persons if or when their data has been breached, even as a result of the State’s negligence (Fromkin 2009).

Texas law not only immunizes the government, but it may actively require agencies to disclose all unprotected information, even if it identifies citizens, through the Open Records Act. Protected information includes that information expressly prohibited from disclosure under § 552.130(a) and federal law; only “information

considered to be confidential by law, either constitutional, statutory, or by judicial decision” is exempt from disclosure (§ 552.101). Thus, to the extent that the State collects, processes, stores, or otherwise is in possession of additional information on individual vehicles (e.g., make, model, speed, location and time), it may be required to share this information upon request.)¹⁰⁹

At the state level, at this point only one state appears to have passed a law to address the consumer privacy related to C/AVs—the State of California. California requires that a “manufacturer of the autonomous technology installed on a vehicle shall provide a written disclosure to the purchaser of an AV that describes what information is collected by an autonomous technology equipped on the vehicle” (Chapter 570, DIVISION 16.6. § 38750(h)). Since the law is only 3 years old, it is too early to predict its implications for manufacturers of C/AVs sold in the State or even sold outside the state. The California law has also been criticized by consumer groups as taking too soft a stance on the ability of OEMs and others to collect private information (Lenth 2013, p.796).

Finally, with respect to government-related disclosures or breaches of confidential information with respect to its citizens, roughly half the States require by legislation that a governmental entity notify persons of the breach of confidentiality in cases where the government was the cause of the breach (Froomkin 2009). Out of these states, only a few allow suit to be brought by an individual against the state if it does not report the breach in a timely manner. In Louisiana, for example, the fine is not to exceed \$5,000 for each violation, while in New Hampshire the plaintiff receives such damages as “the court deems necessary and proper.” Agencies in states that do not allow individuals to bring suit can still face fines or suits from the state’s Attorney General or other centralized authority.

In these various laws, there appear to be two general approaches to the privacy challenges arising with respect to C/AVs. One approach limits or even prohibits the use of certain technological mechanisms for data collection. The second approach requires manufacturers and software developers to disclose the nature of the information they can gather on consumers in an accessible way. Despite their different institutional mechanisms of oversight, running through both approaches is the premise that without some early legal oversight of the privacy-related features of the technology, the “genie will be out of the bottle.” OEMs, software developers, and perhaps even insurers that become accustomed to and develop financial plans premised on access to private data will both resist and face high costs in altering their plans if that easy data access is constrained later down the road.

Security Concerns and the Existing Law

A related but very different risk from the data-intensive operations of C/AVs is the potential for security breaches that endanger life as well as financial and other private information through criminal hacking of the data and infrastructure. Some of the more frightening scenarios include a terrorist who is able to hack into a CV system and direct all cars to drive off bridges into the water or crash into one another (Douma and Palodichuck 2012).

Engineers and others familiar with the technological systems concede that the hacking risks are not trivial and that C/AV systems cannot be designed in ways that are completely free of hacking risks. Stop buttons may have the potential to electronically disengage vehicles, allowing some operator control over the worst types of data-hacking. Yet short of this ability to stop some terrorist manipulation of complete transportation systems, the other types of risks of hacking into data systems remain a continuing concern.

Another set of scenarios involve using self-driving cars remotely as bomb-depositors or drug-traffickers. In this security breach, the larger system is not hacked (Douma and Palodichuck 2012); rather, a single car itself or series of cars are remotely controlled for criminal purposes. Since anonymity is difficult to achieve, criminal commentators are more sanguine about the ability of the criminal system to sanction these types of uses (id).

¹⁰⁹ The courts impose privacy exceptions in some cases, for example, if the information sought to be disclosed is highly embarrassing and has no public value. See, e.g., *Indus. Found. of S. v. Tex. Indus. Accident Bd.*, 540 S.W.2d 668, 685 (Tex. 1976).

Still, the remote use of C/AVs provides a new tool in the arsenal for mass attacks that will need to be factored into the larger criminal justice equation.

While not specifically tailored to the hacking of C/AVs, there are several federal laws that appear to penalize these attempts, including the Computer Fraud and Abuse Act, the Digital Millennium Copyright Act, the Wiretap Act, and the USA Patriot Act (Kohler & Colbert-Taylor 2015). Texas Penal Code (Title 7, Chapter 33) also provides anticipatory deterrence against hacking. “A person commits an offense if the person knowingly accesses a computer, computer network, or computer system without the effective consent of the owner” (Tex. Penal Code Ann. § 33.02(a)). The penalty is dependent upon the aggregate amount of money involved (id. at § 33.02(b-2)). The aggregate amount consists of the “benefits obtained and the losses incurred because of the fraud, harm, or alteration” (id. at § 33.02(c)). A violation of this statute ranges from a Class B misdemeanor to a felony of the first degree (id. at § 33.02(b-2)). If the hacker obtains the identifying information of another, the violation is upgraded to either a second degree or first-degree felony regardless of the amount in question (id.).

8.5 Conclusions and Recommendations

There are numerous public and private benefits associated with C/AVs, but these technologies also present risks and challenges to our transportation systems. In this chapter we investigated the legal status and near-term legal issues associated with the liability, licensing, and privacy of C/AVs in the State of Texas. Although this reconnaissance work considers the law from numerous vantage points, we are particularly attentive to how the introduction of C/AVs in the State of Texas may affect the priorities, liability, and responsibilities of a regional transportation agency like TxDOT.

This bird’s eye view of the intersection of the law and the use of C/AVs in Texas reveals several areas that deserve legislative and regulatory attention (as well as additional research) in the near term. First and perhaps most immediate is the need for policymakers to consider whether the testing and deployment of C/AVs in the State will benefit from more formal, legal oversight. A second, near-term issue at the intersection of C/AVs and Texas law is the need for some adjustments to current liability laws, including with regard to TxDOT’s responsibilities, in order to provide greater predictability as these new vehicles are tested and deployed on Texas roadways. Finally, C/AVs present a number of important public conflicts arising at the intersection of driver privacy, autonomy, and security. While NHTSA and the FTC appear to be taking primary responsibility for the development of national standards and directives, several State-specific reforms may also be beneficial to minimize the risks of C/AVs to the privacy and autonomy of Texas citizens.

A number of other, less immediate legislative guidelines identified in this chapter should further streamline the integration of C/AVs, providing both predictability to the industry and raising the trust and safety of the vehicles as they become prevalent on Texas highways. By identifying the “low-hanging-fruit” in need of some attention within the State, the chapter identifies a number of issues that are not only well-positioned for State legislative guidance, but for which the lack of legal action itself constitutes a choice.

The Need for Immediate and Long-term Planning

The transition from HVs to C/AVs will not just bring benefits to the state of Texas but also present challenges that will need to be addressed. Several U.S. states have already taken steps in preparing for this paradigm change, and Texas will need to do the same. Strategies that are of importance to ushering in C/AV use are organized into three flexible time periods: short term (next 5 years), medium term (5–15 years), and long term (15+ years). The associated descriptions should begin a discussion of the steps that Texas can take to best prepare the state transportation system for the onset of C/AVs.

Today’s vehicles operate under human control, relying on human senses and reflexes. Level 2 C/AV technologies are being installed in both the vehicles themselves and within the transportation infrastructure that seek to augment human senses and reflexes for enhancing safe operations. Level 4 vehicles are building on the current work, with the likelihood of extensive street and highway operations within 5 years. There are challenging legal liability issues arising in these developments for FHWA and the state DOTs, state Departments of Motor Vehicles and local governments. One of the most important of these issues will be at

the interface of these agencies as C/AV Standard Setting Organizations (SSOs) and the bounds of their sovereign immunity.

A near term example can be found in the lane markings—paint stripes and road “buttons”—whose standards are incorporated in the Manual of Uniform Traffic Control Devices (MUTCD). A number of different trials have shown that certain conditions (rain, snow, etc.) seriously degrade C/AV sensors’ ability to correctly recognize lane markings. Work is already underway at the Texas A&M Transportation Institute to determine standards that seek to increase correct identification by the various sensor types available for C/AVs. DOT or municipal transportation departments must show that they regularly maintain the effectiveness of lane markings to avoid liability. It will take some years in actual use to determine the length of time the new C/AV compatible lane markings remain effective, allowing public agencies to set up defensible maintenance schedules.

Mid-term examples will be the RSU devices and other transportation system infrastructure whose technical standards and operations/maintenance standards are currently in development. These technologies are essentially wholly new in highway transportation operations. The RSU that identifies a wrong-way driver must tie in to warning devices in suitably equipped C/AVs as well as provide an appropriate warning to “dumb” vehicles. And, in addition to the vagaries of weather and any limits imposed by basic design, the RSUs will need to be secure against cyber-attack and unintended cyber interference. Whatever standards are set must stand up to liability claims based on possible public agency failures in designing or maintaining them with due technical and practical diligence.

In the long term, the standards set by the public transportation agencies for C/AV operations will be focused on maintaining adequate levels of transportation capacity and minimizing congestion. TxDOT will be inextricably linked into the process and infrastructure for using “platooning,” continuous flow intersections, and other traffic management systematic approaches for increasing roadway capacity safely. Continuous flow intersections in “urban canyons,” for instance, will undoubtedly need extremely accurate survey “benchmarks” and cyber protected operations algorithms to be effective and safe. In these circumstances, it is likely that regional transportation agencies will need to completely redo their design, operation and maintenance manuals to reflect the complete change in system dynamics driven by C/AV technology. And, again, all these changes and additions will need to be demonstrably appropriate and diligent, with continuing likelihood of maintaining suitable and safe operations.

Getting from Here to There

In short, although the future is uncertain with regard to *how* C/AVs will assimilate into the existing Texas transportation system, there appears to be little doubt that some assimilation will occur over the next few decades. The literature suggests that policymakers will follow one of two general paths:

- 1) legislators will pass a holistic program to guide assimilation of the new technology into the state; or
- 2) policymakers will develop incremental regulations or legislation to address specific impediments or public concerns as they arise (OECD 2015).

The choice between a holistic or incremental approach, however, takes the policymaker only so far; he or she still must select the topics, issues, and alternatives that deserve legal attention. In the recommendation section offered here, we present the options as a smorgasbord or matrix of possibilities organized by policy topic. The matrix in Table 8.1 provides a mix-match set of options and issues, leaving it to policymakers to determine the approach, as well as the priorities and preferences, with regard to pursuing each and every issue. To provide some ease of use, the issues of concern within each column are ordered roughly by their immediacy. Presumably passing legislation to allow for vehicles without a human operator present is of lower priority than ensuring the legality of truck platoons. Also included in the menu are issues that do not yet appear ready for legal action, but nevertheless warrant attention (indicated with italics); for example, TxDOT or the Texas Legislature could request and develop focused information-collection and periodic reports to stay abreast of these potential issues that will benefit from legal attention down the line.

All of the items in Table 8.1 deserve careful consideration as regional policymakers build a legal regime to facilitate the integration of C/AVs, with the State of Texas used as an example here. The items in the shaded cells, however, are those that are likely to be of particular interest to local transportation stakeholder TxDOT. Even for shaded items that ultimately require legislative attention, TxDOT seems to be the best entity to frame and engage the legislature in addressing the issues.

Before describing the various options and issues, it is important to note that another plausible legal alternative, albeit one that entails greater public risk, is for Texas policymakers to take little to no legal action at all. As discussed in the analysis above, liability rules and even most of the licensing and rules of the road requirements will allow for the legal integration of C/AVs onto state highways without added legislation. While this “no action” alternative is not recommended by either NHTSA, the ULC Subcommittee, or in the considerable body of scholarly commentary (particularly regarding the testing and operation of C/AVs), it remains a legally plausible option for the State of Texas. We first list a series of adjustments that are recommended to existing laws and programs, and then offer more targeted suggestions for TxDOT’s oversight of C/AVs.

Table 8.1 Matrix of Topic Areas for C/AV Policies in Texas

Safety on the Highway: Section 2.3	Legality: Section 2.3	Liability: Section 2.4	State Responsibilities/Liability: Section 2.4	Privacy and Security: Section 2.5	Advance Broader Public Goals in C/AV Innovation: Section 2.6
Testing & development	Clarify the identity of ‘Operator’	Streamline crash claims;	Clarify what constitutes ‘notice’ for malfunction in digital traffic	Improve consumer information	Collect reports on C/AVs
Vehicle registration/certification	Clarify whether operator needs to be on board	Address other difficult liability issues	Exempt license plates & other identifiable information from disclosure under the State Open Records Act	Restrict sharing consumer to third parties	Encourage greater innovation
Added operator requirements	Adjustments for truck platoons		Require State Agencies to alert individuals when their privacy is breached	Criminalize hacking	
License plate tags or other markers	Legalize texting and other bad behavior			Encourage innovation in cyber security	
Rules for intensive uses					

Ensuring the Safety of C/AV Testing and Deployment on Public Highways

Although C/AVs promise to provide heightened safety, the newness of the technology, combined with some public concern, has prompted several states to engage in the oversight of basic safety features of the emerging technology as it enters public roadways. At the same time there is pressure on state policymakers to provide some modicum of legal oversight on the use of C/AVs; both NHTSA and European leaders are cautioning against too much state intervention for fear it will chill the technology.

The consensus emerging from commentators is that states still play an important role in overseeing the testing and use of C/AVs driven within their states (ULC 2014). States are cautioned to resist the temptation to prescribe acceptable types of technology or impose requirements on vehicle manufacture and design; instead they play the leading role in overseeing the early use of the technology to prevent accidents on public highways. In the recommendations below, primary emphasis is thus placed on locating some least common denominator solutions—where the state can provide the greatest safety oversight with the least imposition on the development of this new technology.

Testing and Deployment of C/AVs on Texas Highways

As discussed, because of the risk of accidents early in the use of the technology, coupled with public concern about the new technology, there is a growing consensus that states should actively regulate the use of C/AVs at both the testing and the full deployment stage. The ULC Subcommittee recommended a uniform state act that “expressly prohibit[s] any use (including testing) of autonomous vehicles on public roads except as expressly permitted by the uniform act” (ULC 2014, p.5). Several states have required agency approval for testing and deployment of C/AVs. In order to test a C/AV in Nevada, for example, the state requires added insurance; proof that one or more of the vehicles has been driven a combined minimum of 10,000 miles in autonomous mode; a demonstration of the technology to the DMV; and a demonstration that its technology can be driven in the geographic locations designated for testing (Nev. Reg. § 8.3). California requires identifying information to be provided to the DMV for each vehicle that is being tested (Cal. Regs. §227.16). Both Nevada and California require a license or permit for testing as well (Cal. Regs. § 227.04(d) and Nev. Regs. § 8.3).

By contrast, Texas currently has not passed laws or regulations to formally oversee the testing or deployment of C/AVs. As discussed, under current law C/AVs appear to be legal on Texas highways, at least if an operator is present. As a result, driverless vehicles with operators aboard may enter the public highways without notification to TxDOT or the Texas DMV, and without added government regulation or mandated reporting of their crashes or activities.

One option available to Texas is to prohibit the use of C/AVs for testing or deployment without prior authorization from TxDOT. Because of the changes that are likely over the next decade or so in use of C/AVs, the Legislature may also wish to place a 10-year sunset on the law.

If Texas chooses to engage in formal oversight of the testing and deployment of C/AVs, it will need to define what a C/AV is, identify the nature of the oversight for testing, and may need to identify the point at which a “tested” vehicle is authorized for full deployment and/or restricted deployment on Texas roads. In regulating the testing of C/AVs in particular, the State could require (among various possibilities arising in the states) that tested vehicles have operators aboard during all testing; require some driver qualifications for AV operation; require insurance; limit testing with respect to certain areas; provide reports of crashes and near misses; and require crash data records be deployed and shared with the State. As a less onerous approach, the Legislature (or perhaps even TxDOT) would require all testing to be reported to the State before it is conducted.¹¹⁰ This will allow the State to at least monitor the testing activity.

¹¹⁰ States like Florida take an even more limited approach. Florida sets standards and require registration of C/AVs, but then allow them on roadways once registered. (To date, no applications for registration of AVs have been submitted). While this light-handed approach does not appear to be endorsed by model state law committees or academic commentators (see in particular UWash Tech, undated, in App. G), Florida’s

The more difficult decision in such an oversight law is identifying the appropriate point at which C/AVs pass “testing” and can be deployed on public highways. Several states (such as Nevada and California) require the statewide certification and approval of C/AV models before they can be driven on public roadways. An alternate approach is to require a minimum of test miles on public roads free of concerning accidents, with reporting of all driving tests to the State. The State might even allow use of C/AVs provided they meet one of several requirements that include not only some testing but take full legal responsibility for any crashes occurring in the state (Risen 2015).

As noted below, if testing involves the operation of cars without operators present in the vehicle, this testing would likely be in violation of § 545.404. If the State wishes to encourage the testing of C/AVs on Texas roadways without an operator aboard the vehicle, it will need to exempt testing of unoccupied, driverless vehicles from § 545.404 and may need to institute other controls to ensure safe testing conditions. Such added testing requirements could be included in a testing/oversight law.

Vehicle Registration of C/AVs

Under existing Texas law, *C/AVs appear to be legal as long as the vehicle is registered and a licensed operator is present*. The DMV safety inspection required for vehicle registrations does not appear to take into account the possibility that a vehicle has automated features.

The State of Texas could add additional safety requirements for C/AVs at the registration stage to ensure they meet minimum requirements. There are several safety features that both the ULC Subcommittee and NHTSA, as well as some states, believe are essential for a C/AV either tested or in use in the State:

- 1) Device to disengage the automated system.
- 2) Device to indicate whether the vehicle is operating in autonomous mode.
- 3) System to warn operator of failure.

For C/AVs, annual checks or on-line certifications of regular updating of the vehicle may also be valuable. Particularly in the early stages of automation, it is likely that the software and recall of vehicles may be an active area (OECD 2015, p.29). Owners will need to take responsibility for ensuring this is completed. Texas may insist on evidence that owners are fulfilling these responsibilities on an annual basis.

If the State chooses not to restrict or oversee the deployment of C/AVs on public highways, it also could use the vehicle registration requirement as a way to at least develop a reporting system for the number and types of C/AVs in use on highways. C/AVs might also be assigned special numbers or designations on the license plates, see Section 6.2.4.

Added Operator Requirements

Under Texas law, there are also no additional licensing requirements imposed on operators of AVs. Some states require added endorsements or training for those wishing to operate an AV (ULC 2014, p.12). The State of California requires that the driver has undergone training by the manufacturer (Cal Regs. § 227.20). Restrictions on C/AV operators could also be instituted in Texas.

License Plate Tags or Other Indicators of C/AVs

Several states have enacted, and the ULC recommends, some public marker for C/AVs, such as a special license plate (ULC 2014, p.11). This recommendation may be particularly well-placed for the operation of truck platoons on highways. Since the requirement is imposed on owners and occurs during the licensing of the vehicle, this type of requirement would seem to have little to no negative impact on technological

approach offers yet another option for C/AV oversight that focusses on standards rather than state oversight during testing and deployment.

innovation or sales of C/AVs. Indeed, these demarcations could serve as a way to build public confidence and trust and may even boost the market for C/AVs as they become more commonplace.

Targeted Requirements for Intensive Uses of C/AVs like Truck Platoons

Even without statewide legislation that restricts and regulates the use of C/AVs on Texas roadways, some more intensive uses of C/AVs will require greater governmental oversight. Truck platoons are a particularly discrete type of C/AV that demands added government oversight during both testing and operation. Among the many regulatory decisions to be made are the following:

- whether to identify a designated lane and/or roadway pre-approved by TxDOT; platoons could be prohibited on other public highways in the State without advanced permission;
- size and length requirements, presumably promulgated by TxDOT, that restrict platoon length and the maximum number of units per platoons;
- a cap on the number of platoons allowed on a public road at any given time;
- passing requirements and restrictions;
- time of day rules, minimum speeds, and similar operational requirements.

The more intensive the use of highways by truck platoons, the more necessary it will be for TxDOT to revisit its pavement and bridge design standards. In revising these large-scale road features, there will need to be close interaction between TxDOT, the legislature, DMV, Department of Public Safety, and local jurisdictions along platoon routes. Finally, platoons will need to assemble/disassemble (or form and dissolve as directed while en-route to their destination), and the locations for this work ideally should be designated in advance, in locations that are appropriate, safe, and in keeping with the planning done by local governments.

State agencies like TxDOT are well-positioned to anticipate these and other challenges that arise from the use of truck platoons, but many of these challenges fall outside the four corners of the current legal and transportation system and thus require future legal directives. With respect to resources at least, Congress appears aware of some of these future challenges. Federal funding may be available in the future to support some of this work by TxDOT and other state agencies (e.g., S. 1647, 114th Cong., 1st Sess. 2015—not passed by proposing targeted funding for smart transportation).

Legality: Regardless of whether the State regulates testing and deployment of C/AVs on Texas highways, some legal clarifications will be helpful in providing greater predictability for the legal requirements governing C/AVs. Indeed, these clarifications are more important if the State decides not to restrict the use of C/AVs.

Clarification

Clarification is needed in order for the law to properly address C/AVs. This includes better defining the identity of an operator, specifying whether operators must be aboard a moving vehicle, and stating whether the law permits truck platoons.

Clarifying the Identification of an Operator

As discussed previously, the Texas Motor Vehicle Code places responsibility for complying with all licensing requirements and traffic requirements on the “operator” of a vehicle. While “operator” is a broad term that appears to encompass sleeping occupants, there is nevertheless the possibility that the Code could be interpreted to allow (because it does not prohibit) the use of vehicles that are “operator-less.” Unlike vehicles with operators, moreover, these vehicles without occupants and without designated operators would be free of most of the licensing and rules of the road requirements since the Transportation Code places responsibility for compliance on the “operator” of the vehicle (rather than the vehicle itself).

In the short term, to avoid confusion, the State could clarify that each vehicle on the Texas highway must be controlled by a designated “operator” that meets the requirements of § 521.021 (“A person...may not operate a motor vehicle on a highway in this state unless the person holds a driver’s license issued under this chapter”).

Clarifying whether Operators Must Be Aboard a Moving Vehicle

The Texas legislature should also clarify whether an operator must be aboard a vehicle during its operation since current law is ambiguous on that point. (Note that for at least testing, NHTSA “strongly recommends” that “states require that a properly licensed driver be seated in the driver’s seat and ready to take control of the vehicle while the vehicle is operating self-driving mode” (NHTSA 2013, p.12)). Section 545.404 does prohibit operators from leaving vehicles “unattended,” and the best reading of this Section is that the legislature intended to preclude the operation of vehicles without a human operator aboard the vehicle. Yet because of residual ambiguity, perhaps “unattended” could be amended to explicitly prohibit vehicles that are being remotely controlled.

Alternatively, if it is the case that Texas wishes to allow vehicles on public highways that do not have operators present, then the law should be amended to legalize these operator-less vehicles. Presumably, some safety requirements and limitations will also need to be included in this exception.

Legal Clarifications to Permit Truck Platoons

If the State of Texas determines that truck platoons are a beneficial activity, then several relatively minor adjustments to existing law will be needed to streamline their operations in Texas. As mentioned earlier, there are several rules of the road and motor vehicle requirements that conflict with the use of truck platoons (e.g., following distance; licensed operator in vehicle). Most of these conflicts could be cured by a regulatory determination that truck platoons are the legal equivalent of a single “tow” truck for purposes of the law. Such an interpretation then allows for a closer following distance and operation without an operator.

Yet identifying truck platoons as “tow trucks” under the law still may be considered insufficient to ensure that this new technology is monitored and operating safely on Texas highways, at least during its first few years of introduction. For example, TxDOT or some other entity will also need to identify the appropriate lanes and routes for platoons, which in turn could require adjustments to the “no trucks in left passing lane” ban in place in some areas. Some accommodation may also be needed for merging on and off highways and for fueling and other necessities. Finally, legal clarification is needed to allow the “towing” of trucks in platoons to include multiple vehicles.

Thus, in terms of legal and policy attention, truck platoons seem to demand focused legislation or regulatory oversight. TxDOT or another agency should engage in this oversight or work with the legislature to ensure the proper requirements and preparations are in place to ensure a smooth integration of truck platoons onto State highways.

Adjustments to Current Driving Laws

Adjustments to current driving laws must be made in order to accommodate the presence of C/AVs. Law forbidding “bad” driving behaviors should be relaxed, tort and private injury law should be revisited, and simple crash claims in C/AV litigation needs to be streamlined, and many more.

Legalization of Texting and Other “Bad” Behaviors in Some Driving Settings

If driverless vehicles are deployed in ways that are believed by policymakers to be safe, then Texas may reward owners of these vehicles by lifting certain prohibitions for operators while driving in automated mode (OECD 2015 p.29). Texting while driving is illegal in some localities in Texas (TxDOT, Cell Phone Ordinances, undated). If texting bans become more prevalent, the State could allow texting in identified driverless vehicles while in automated mode. Florida and Michigan have already passed laws permitting texting while operating an AV in autonomous mode (Fla. Stat. § 316.305(b)7, Mich Comp. Laws § 257.602b(4)(e); see also ULC 2014, p.13 with similar recommendations).

Other “bad” habits may also be exempted from civil and criminal liability in the State in narrowly tailored settings. For example, if driverless vehicles are able to operate safely without a competent operator, perhaps even alcohol consumption (including in the vehicle) might be allowed (see §§ 49.031, 49.04 for current prohibitions).

Adjustments to Tort and Private Injury Law

The strong consensus among commentators is that tort liability laws should be left undisturbed to the extent possible to allow the flexibility of the common law to adapt to the technological changes presented by C/AVs (UWash Tech, undated, p.20). Nevertheless, there are several modest adjustments that may deserve consideration to alleviate some of the most substantial concerns about the integration of C/AVs into existing tort liability law.

Streamlining Simple Crash Claims in C/AV Litigation

As C/AVs become more commonplace on highways and are implicated as the cause of crashes, what used to be “simple” crash litigation will necessarily include more complicated product liability claims against manufacturers. There are several approaches that could anticipate and alleviate some of this potential future uncertainty. The approaches could be used in all crashes or only crashes that involve a limited amount of damage (perhaps less than \$75,000), since it is the smaller cases that will be most impacted by these more complicated and expensive claims.

First, in deciding cases that involve allegations that the automated features of the vehicle in part caused the crash (thereby implicating the vehicle manufacturer), the Texas courts deciding common law claims could impose a non-delegable duty on the owner/operator consistent with the insurance coverage. Non-delegable duties can be imposed under the common law by courts deciding tort cases.¹¹¹ With a non-delegable duty, the owner/operator would be the presumptive responsible parties. While the owner/operator of the AV could engage the vehicle manufacturer and others in a third-party suit for indemnification, a case brought by an outside party could recover all damages against only the owner/operator. If greater legal certainty is desired, the Texas legislature could also codify this type of legal responsibility on owners. The overriding goal of this legislative directive is to save accident victims, including TxDOT, from the expense and delay associated with unraveling responsibility among the manufacturer, driver, owner, and software developer, as well as others.

Alternatively, with respect to claims by third party victims harmed by a C/AV in automated mode (or perhaps all persons, including owners), the legislature could place the burden of proof on the manufacturer of the C/AV to establish that the crash was not caused by a defect in the vehicle. (There is some indication that the OEMs themselves may already be accepting this responsibility, although it is not clear if these commitments are legally binding [Volvo Car Group 2015]). For example, the law could direct that in crashes involving C/AVs as a possible cause, the OEM will be considered jointly responsible with the operator unless the OEM can establish that there was no defect in the vehicle, consistent with the rules of fault and product liability in

¹¹¹ See *Maloney v. Rath*, 445 P.2d 513, 516 (Cal. 1968) (providing examples of non-delegable duties in common law: “the duty of a condemning agent to protect a severed parcel from damage...the duty of landowners to maintain their property in a reasonably safe condition...to comply with applicable safety ordinances...the duty of employers and suppliers to comply with the safety provisions of the Labor Code....”). A non-delegable duty could be placed on C/AV operators for the for the criminal misuse of their vehicle, for example, federal courts have placed non-delegable duties on the purchasers of guns for their criminal misuse. See, e.g., *City of Phila. v. Beretta U.S.A. Corp.*, 277 F.3d 415, 426 (3d Cir. 2002) (“Accordingly, we will dismiss plaintiffs’ claims that tort liability should be assessed against gun manufacturers when their legally sold, non-defective products are criminally used to injure others.”). See *First Commercial Tr. Co. v. Lorcin Eng’g*, 900 S.W.2d 202, 205 (Ark. 1995) (holding that a firearm manufacturer is not responsible for the criminal misuse of its product); see also *Riordan v. Int’l Armament Corp.*, 477 N.E.2d 1293, 1295 (Ill. App. 1985) (“[T]he distribution of handguns by the defendants-manufacturers was intended for the general public, who presumably can recognize the dangerous consequences in the use of handguns and can assume responsibility for their actions.”).

the State of Texas.¹¹² Given the loss-spreading and low crash rate of C/AVs, placing this responsibility on the manufacturers may be beneficial not only in streamlining liability but could even create greater trust in the market. Owners will appreciate the implicit “guarantee” that crashes will be rare and will have incentives to use the automation; manufacturers will have incentives to reduce crashes (see also Glancy et al. 2015, p.73-74). If a licensing and certification program is in place in the State, the placement of responsibility on manufacturers should also require that the C/AV at the time of the accident was properly licensed and legally permitted.

Although it is much more broad-reaching, the State could adopt a no-fault approach to liability for all cars or perhaps for C/AVs exclusively. It could also require alternative dispute resolution or other transaction-cost saving mechanisms for resolving responsibilities of actors involved in crashes that include at least one C/AV operating in autonomous mode. For more information on the pros and cons of these more systematic changes to the Texas liability rules, readers are referred to Anderson et al. (2014) and Funkhouser (2013).

The goal of these streamlining devices is to counteract the increased costs of litigation, particularly with respect to smaller scale crashes, associated with C/AVs. Without some type of anticipatory legislation, crash litigation will become more expensive, particularly for the victims harmed by C/AVs.

Several Other Difficult Liability Issues May Benefit from Legislative Attention

The ULC Subcommittee suggests that states may need legislation to address issues associated with consumer-imposed modifications to vehicles after-market (ULC 2014, p.5). Several states have already legislated immunity for manufacturers in cases where a third party modifies a C/AV and those changes, rather than a defect initially present in the vehicle, cause harm (Nev. Rev. Stat. § 482.090; Fla. Stat. § 316.86(2); D.C. Code § 50-2353; Mich. Comp. Laws § 257.817). The preliminary analysis in Section 2.4 suggests that these liability risks may be less significant in Texas, but this issue deserves fuller consideration since legislative codification of common law does provide added predictability for both manufacturers and those engaged in the modifications.

There are also difficult issues associated with post-market notifications and improvements (Walker-Smith 2014). The ease of software and electronic updates can create a “proximity” between manufacturer and consumer that leads to higher levels of tort responsibilities by OEMs for recalls, updates, and repairs.

Both issues, and likely others in the future, may ultimately benefit from some legislative guidance.

Clarifying State Responsibilities: The integration of C/AVs onto the roadways will also create uncertainties with respect to the responsibilities and liabilities of certain State agencies, particularly TxDOT. Several relatively minor legislative clarifications will enable TxDOT to better address this emerging technology.

Clarify What Constitutes “Notice” for Digital Infrastructure

As discussed, if a regional transportation agency does not make repairs to roadways, traffic signals, and similar devices and infrastructure in a reasonable period of time after “notice” of the defect, the agency may be liable in tort for all resulting damages (§ 101.060(a)(2)). Yet with connected infrastructure, an argument could be made that this notice occurs immediately since TxDOT or the municipality will in theory have immediate notification of the malfunction as a result of the digital technology. (Note that the “actual notice” required under Section (a)(3) for destruction of traffic control devices by third parties requires a “subjective awareness of fault,” which goes well beyond passive data collection.)

It seems likely that the courts will interpret “notice” in keeping with the “reasonable” expectations for agency action and provide TxDOT with additional time to process the data as part of its reasonable response time. Nevertheless, in an abundance of caution, the legislature could add interpretive words to “notice” in Section 101.060(a)(2) to signal that TxDOT is allowed time to reasonably process digital data of malfunctions after

¹¹² Strict liability on C/AVs manufacturers, as suggested by some commentators (Vladeck, 2014) is another option.

the data is received. Most straightforward would be an amendment that adds “actual” to modify “notice” in both Sections (a)(2) and (a)(3). Alternatively, “notice” in Section (a)(2) could be modified to accommodate digital infrastructure by adding a parenthetical “notice (or in the case of digital and connected infrastructure, notice must include a reasonable data processing time).” Finally, the legislature could simply clarify that connected infrastructure is simply not “real or personal property” for purposes of the Federal Tort Claims Act; instead, the “absence, condition, or malfunction” occurs with respect to the transmittal of data or other information.

While these options each constitute relatively small changes, some type of clarification will provide helpful predictability to TxDOT and municipalities in allocating their scarce resources. Such a clarification might encourage even more rapid integration and use of digital RSU since the liability risks will be reduced for the government entities operating them.

Create an Exception for Identifiable Travel Information under the State Open Records Act

Under current law, the privacy of individuals in the State is protected strongly for a narrow set of sensitive information and is effectively unprotected for most other information, including travel information that contains identifiable information. Indeed, agencies may be required to share the latter more general information with requestors under the State Open Records Act.

To produce more consistency in the protection of privacy, the legislature could limit the private information on citizens that must be disclosed through the Open Records Act. For example, the legislature could create a new exception to the Open Records Act that extends the information protected under Texas Transportation Code §§ 371.001 & 371.051 to all highways in the State. This extension would only prohibit the disclosure of the registration, licensing, and other identifying information under the Open Records Act (not restrict the use of the information by the agencies).

Require State Agencies to Alert Individuals that Their Privacy Has Been Breached

In situations where consumer confidentiality is breached in violation of State or federal law, the State agency responsible for the breach could be legislatively required to provide a notification to the individual. Similar requirements are in effect in more than half of the States (Froomkin 2009). Such a requirement need not be enforceable with private damages, but it would provide Texas citizens with added assurance that if breaches of sensitive information do occur, they will be alerted to that fact so that they can engage in preventative action.

Privacy and Security: Data privacy and hacking concerns are largely unaddressed by current laws and yet appear to rank among the most significant concerns regarding the use of the technology in the future. There are legitimate reasons for a “wait and see” approach with respect to gauging the need for state interventions given the national interest in these issues by Congress and NHTSA and the potential overlap of C/AVs with other technological innovations such as drones, which present similar types of risks to privacy and security (Glancy et al. 2015).

On the other hand, there are a few relatively modest steps the State of Texas could take to increase privacy and security without affecting the development of the technology itself. Both immediate and longer-term recommendations are offered here.

Privacy and Security Recommendations

There are several privacy and security recommendations that need to be taken into consideration.

Privacy

Consistent with the strong recommendations of NHTSA and the ULC Subcommittee, legislative prescriptions on privacy standards for C/AV technologies seem premature (ULC 2014). Yet the contrast between the protection of sensitive data in Texas and the unrestricted nature of all other identifying information, such as

license and registration information, suggests the need for some realignment of privacy protections within Texas law. Beyond amending the Open Records Act, as just discussed, there are several other ways that consumer privacy might be better protected in the State as C/AVs are assimilated onto Texas highways.

Improve Consumer Information on Collection and Use of Data by OEMs, Software Companies, and Others

The legislature could provide greater assurance for consumer privacy in the current, unregulated market of C/AVs in several ways. First, the legislature could supplement contract law by requiring that citizens at least be alerted to the types of information that will be collected on them as a result of the purchase of a C/AV from the OEM and others. California has passed such a law (see, e.g., Calif., Chapter 570, DIVISION 16.6. § 38750(h)). Complicated contracts of adhesion, such as Tesla's, may be legislatively determined to be insufficient to meet the legislative demands for clear disclosures. Contracts instead would need to be clear and accessible; with respect to potential intrusions on consumer privacy, a separate boldfaced explanation may be needed. The State legislature might also encourage OEMs, software developers, and others to provide consumers with "opt-out" provisions with respect to some of the data collection that is not essential to operation through a privacy rating system or other incentives. Finally, the State itself could request standardized information on the autonomy and privacy features of each new model marketed in the State (all vehicles; not simply C/AVs) and collate the information for Texas citizens to inform their purchasing choices.

Second, the Texas legislature could reward or encourage the development of vehicles that do offer added protection for the privacy of operators and occupants. For example, the State could provide a ranking system (such as on a scale of 1 through 3) on privacy protections that are available in C/AV models. Optional dashboards that identify when added information is being collected on a C/AV and opportunities to block that data gathering, for example, could earn three stars. A consumer's ability to readily block targeted advertisements that can be loaded into the computer systems could receive one star. However, the reward system is accomplished, Texas could serve as a leader in encouraging OEMs to make consumer privacy a high priority by rewarding privacy innovation in the Texas marketplace.

Finally, states could require all OEMs of new models of all vehicles sold in the state to provide a state agency like Texas' DOT with an annual report on the data collection enabled by various models and vehicles. The report could be structured so as to allow easy comparison among vehicles and reports. This information could then be used to inform future legislative activity.

Restrict the Sale or Sharing of Private Consumer Data by Businesses

The State could also expand its current prohibition against businesses from sharing or selling "sensitive" consumer information with third parties without their consent, codified in Section 521.052, to a broader range of consumer information that includes information about driving habits, entertainment preferences, or perhaps all information collected through C/AV technologies. Such a legislative amendment would thus preclude OEMs and software developers from selling or sharing all (not just sensitive) consumer data collected through C/AV technology to advertisers, insurers, etc.

Moreover, in cases where consumers may unwittingly consent to this third-party sharing in complicated contract clauses, the legislature could require that the contracts meet standardized plain language requirements. This could include a bold, underlined passage that signals that the consumer, for example, ***understands they are allowing the manufacturer to collect personal information and share it with third parties, including insurers and advertisers.***

Security

Although there appears to be little downside risk to a more specific criminal law that prohibits hacking of C/AVs or the criminal use of this data by third parties, this may be addressed in the near term by federal legislation.

Criminalization of Hacking

The need for anti-hacking laws in the context of C/AVs has generated national attention, as discussed in Section 8.3. Given the prominence of this issue at the national level, coupled with the existence of both federal and state laws that penalize this type of tampering, the criminalization of hacking may be an issue that does not require short-term legislative attention.

Encouraging Innovation in Cybersecurity

There are important federal developments regarding the cybersecurity of C/AVs that, even though not complete, signal a national interest in addressing at least some of these challenges. NHTSA and the USDOT, along with industry, are focused on addressing the security risks associated with C/AVs (Kohler & Colbert-Taylor 2015). NHTSA publicly announced its intent to set minimal standards governing cybersecurity protections for vehicles by 2017 (NHTSA 2013). In Congress, the Spy Car Act of 2015, is an indication of congressional attempts to mandate the promulgation of cybersecurity standards for all C/AVs sold in the United States. While the bill is unlikely to pass in this session, it provides a starting point for ongoing legislative discussions about cybersecurity.

Encouraging Technological Innovation in C/AV Development

The State's leadership in C/AV testing allows it to also play a leading role in influencing the development of the technology. These final recommendations position the State as a national leader in using the market to encourage even smarter technological innovation.

Collating Information about the Use of C/AVs in the State through Reporting

There are multiple social benefits to C/AVs. To ensure that they are well-understood, the State could require annual reporting of basic features of C/AVs used in the State that in turn is used to educate citizens and guide future policies. Several simple reporting requirements seem particularly fruitful in light of the large amount of information and data that OEMs of C/AVs are likely to obtain from each vehicle sold. Indeed, without a reporting requirement, this valuable information on social benefits may not be available to the State even though it is possessed by the manufacturers. The mandated reports could include, among other things, a report of all accidents that occur and general statistics, such as accident/miles traveled; emissions/miles traveled; ratio of urban/highway miles traveled; and other related information.

Incentivizing Still Greater Innovation in the C/AV Market

The legislature could also create stronger incentives for technological innovation in C/AVs by spurring greater demand in the consumer market for vehicles that include other socially beneficial features. For example, the legislature could subsidize the consumer purchase of C/AVs with added sensors for safety, extra low emissions, etc., through tax subsidies. The legislature could also require State agencies to purchase certain types of C/AVs (e.g., low emission) with additional, socially beneficial features.

Mandated or even voluntary reporting by OEMs on the extent to which various models meet "add-on" social goals could also be collected and collated by the State to enable more informed purchases by citizens.¹¹³ These disclosures, in turn, could spur positive research and development on related attributes of C/AVs by OEMs if add-on values are perceived to increase market power. Several "add-on" social benefits that could be calculated and disclosed by OEMs to facilitate a more informed consumer market in Texas include:

- Emissions reductions that are lower than comparable vehicles in non-automated categories
- Reduced transaction costs in tort litigation when OEMs contractually agree to bear all tort liability on behalf of a driver in a crash where the vehicle is in automated model and causes an accident,

¹¹³ Validation of the reports will be necessary, which could entail some costs through random audits; expert committee oversight; etc. But these costs may be more than offset by the gains to the market and to rewarding innovation in C/AVs for values that go beyond safety and convenience to the owner/operator.

- Quantification of lower transit costs for certain types of functions (shuttles) to make transportation more affordable for a wider group of citizens,
- Installation of sensors that avoid workers/pedestrians/cyclists (and/or development of helmets, etc. that provide easy recognition for these groups), and
- The provision of added privacy protections for consumers that go beyond what is required by law.

Summary

There are a number of different privacy, security and safety concerns that should be considered when implementing any AV system. A number of recommendations have been prepared to help address these concerns in Chapter 19.

CHAPTER 9 TRAFFIC MODELS FOR AUTOMATED VEHICLES

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9.1 Introduction

This chapter describes analyses of the traffic impacts of connected and automated vehicles under multiple scenarios. Section 9.2 describes how automated vehicles can be integrated into the traditional four-step planning process, including mode and route choice, using static traffic assignment. Section 9.3 shows how dynamic traffic flow models can represent capacity increases from closer following headways and reservation-based “smart intersection” control. Section 9.4 describes two traffic simulation models developed in this research project: the Autonomous Intersection Management microsimulator and a simulation-based dynamic traffic assignment application, as well as results from simulating arterial, freeway, and city networks. Finally, Section 9.5 discusses the traffic impacts of shared automated vehicles.

9.2 Static Four-Step Planning for Autonomous Vehicles

Much of the literature on AVs has addressed the technological hurdles in putting AVs safely on the road. Literature on transportation models for AVs includes the proposal of a reservation-based intersection control policy by Dresner and Stone (2004) that could increase road network capacity when AVs are a significant share of the traffic. A more aggregate question is how AV ownership will affect trip and mode choice. Recent workshop presentations at the meeting of the Transportation Research Board (2014) addressed this question from the perspective of activity-based travel behavior. However, there is yet to be any literature published on travel demand models to account for AV benefits. Therefore, the purpose of this section is to modify the four-step planning model to address the question of how AV ownership will affect transit demand during the highly congested peak hours. Trip and mode choice is analyzed through generalized costs of travel time, monetary fees, and fuel consumption. AVs are expected to increase trips because of the possibility of empty repositioning trips to avoid parking costs and allow other household members to share the vehicle. However, AVs also have the potential to increase road capacity. Therefore, an increasing capacity function is proposed based on Greenshields' (1935) speed-density relationship as the proportion of AVs increases.

The contribution of this section is the development of a multi-class four-step model using a generalized cost function of travel time, monetary fees, and fuel consumption to analyze the impact of AV ownership on trip, mode, and route choice. Three mode options of parking, repositioning, and transit are considered using a nested logit model. A continuum of AV ownership is considered to analyze not only the impacts of full AV ownership, but also the impact of gradually increasing availability to travelers. The model is analyzed on a city network to demonstrate the potential effects on actual planning predictions.

Methodology

The fact that travel cost may impact trip, mode, and route choice is well-known and fundamental in most combined demand and assignment models. AVs could conceivably affect all three aforementioned travel choices by changing the utility of personal vehicle travel. AVs can avoid parking costs by dropping off travelers, then returning to the owner's residence for free parking, thereby reducing the cost of driving relative to transit. These reduced costs may affect trip choice, not only because some travelers will have a reduced motivation to choose origins and destinations near transit to avoid parking costs, but also because travelers may partake in activities besides driving while traveling by AV. Finally, the change in demand on the road network due to changes in trip distribution and mode choice will affect travel times and equilibrium flow.

To model the effect of AVs on demand and route choice, this section presents a modified four-step planning model with the addition of an AV round trip instead of a one-way trip with parking. Road capacity is formulated as a function of a proportion of AVs on the road, based on Greenshields' (1935) speed-density relationship. To more accurately model the costs incurred by the additional driving, a fuel consumption model is incorporated into the generalized cost function.

Assumptions: Because AVs are still in the early stages of testing, experimental data on AV owner behavior and AV improvements in traffic network capacity is not available. Studies such as Dresner and Stone (2004) have predicted significant improvements in intersection flow, but link capacity changes, if any, have not been studied. Therefore, we make the following assumptions about traveler behavior and capacity:

- AV market penetration will occur over a number of years as the purchase price gradually becomes viable for travelers of all incomes. Therefore, our model is built on the four-step planning model, which is often used for long-term predictions. A long-term model may be useful to practitioners forecasting the impact of AVs in 20- or 30-year planning models.
- AV drivers have the option of parking (with a possible parking fee) or sending their AV back to the origin and incurring fuel costs. Although activity-based models (1999) may predict additional utility benefits by making the AV available to other travelers in the household, techniques to model such benefits in the four-step planning model are less clear. Repositioning to alternate parking locations other than the origin for a reduced parking cost is also a realistic option. However, without parking cost data, modeling the utility resulting from parking at different locations is difficult. This results in

three mode options: parking, repositioning, and transit. A nested logit model is used to decide between driving and transit, and parking and repositioning.

- Travelers seek to minimize a generalized cost of time, fuel, and tolls/parking fees. AVs are assumed to choose a route that minimizes this combined cost function, including fuel consumption. Travelers are divided into value-of-time (VOT) classes, and VOT is used to convert travel time to units of money. Incorporating fuel consumption into route choice, or “eco-routing”, has been previously studied by Rakha et al. (2012), and AV routing algorithms could incorporate eco-routing technology. Although requiring travelers to choose a VOT for their trip routing may seem restrictive, airlines already do this through their cost index.
- An STA model is used with four-step planning. Although Tung et al. (2010) and Duthie et al. (2013) have incorporated dynamic traffic assignment (DTA) into the four-step model, without literature on modifying the greater detail in DTA (such as intersection dynamics) for AVs, DTA could easily be less accurate. Additionally, trip distribution and mode choice have potential errors due to the possible behaviors of AV drivers. DTA is more sensitive to demand and departure time variability and may exacerbate any errors in demand predictions. Furthermore, DTA also requires more computational resources. Therefore, a STA model, which is commonly used with the four-step model, was chosen for this study.
- The shorter reaction times and greater precision of AVs are assumed to reduce the necessary following distance and correspondingly increase the jam density. Link jam density is then a function of the proportion of AVs on the link. Capacity is assumed to be linearly related to jam density, as in Greenshields’ (1935) model, to predict the increase in capacity as a function of AV proportion. This relationship was chosen because although AVs may have the reaction time to support minimal headways at any speed, the vehicle may not have the braking authority to match maximum braking behavior of the vehicle ahead. Therefore, as speed increases, headways must increase as well, even for AVs. Although Greenshields’ relationship is designed for use with hard capacities in DTA as opposed to the “capacity” of the Bureau of Public Roads (BPR) function, it is used here only to scale the original capacities in the static network. In the absence of studies estimating roadway capacity improvement as a function of AV proportion, we believe this assumption is reasonable. Greenshields’ model also results in the favorable property of the travel time function being monotone increasing with respect to increases in AV flow (despite increases in capacity).

These assumptions are made for the purposes of a long-term planning model because the impact of AVs has not been well studied. However, with AVs in testing on public roads, metropolitan planning organizations may soon wish to include the effects of AV ownership in their 20- or 30-year predictions of travel demand.

Impedance Function: The computer precision and reaction times of AVs allows reduction of headways while maintaining safety in the event of sudden deceleration of the vehicle ahead. These reduced headways increase density, permitting greater roadway capacity. The travel time is given by

$$t_{ij}(\mathbf{x}_{ij}) = \hat{t}_{ij} \left(1 + \alpha_{ij} \left(\frac{\sum_{y \in Y} x_{ij}^y}{Q_{ij}(\mathbf{x}_{ij})} \right)^{\beta_{ij}} \right) \quad (9-1)$$

where $t_{ij}(\mathbf{x}_{ij})$ is travel time when the flow is \mathbf{x}_{ij} , flow specific to class y is x_{ij}^y , \hat{t}_{ij} is the free flow travel time, Q_{ij} is the capacity, and α_{ij} and β_{ij} are calibration constants for link $[i, j]$.

Since the VOT varies across the population, the population of travelers is instead divided among a set of discrete classes Y , with each $y \in Y$ having a VOT of v_y . Each class uses AVs entirely or not at all, denoted by the Boolean variable ξ_{AV}^y . ξ_{AV}^y is exogenous in this model because ownership decisions depend also on AV pricing relative to individual household income and utilities. This is not restrictive because any traveler class with owners of both AVs and non-AVs can be separated into two classes with the same VOT. (If a VOT class includes owners of both AVs and non-AVs, we assume that the market penetration is known).

Below, we derive the conditions under which $t_{ij}(\mathbf{x}_{ij})$ is monotone increasing with respect to any x^y . This is necessary but not sufficient for formulating the multi-class traffic assignment problem as a convex program (2004). Indeed, we have

$$\frac{\partial t_{ij}}{\partial x^y} = \hat{t}_{ij} \alpha_{ij} \beta_{ij} \left(\frac{\left(\sum_{y' \in Y} x_{ij}^{y'} \right)^{\beta_{ij}-1} \left(\frac{1}{Q_{ij}(x_{ij})} \right)^{\beta_{ij}}}{\left(\sum_{y' \in Y} x_{ij}^{y'} \right)^{\beta_{ij}} \left(\frac{1}{Q_{ij}(x_{ij})} \right)^{\beta_{ij}+1} \frac{\partial Q_{ij}(x_{ij})}{\partial x^y}} \right) \quad (9-2)$$

$$\text{Then } \frac{\partial t_{ij}(\mathbf{x}_{ij})}{\partial x^y} > 0 \text{ if } Q_{ij}(\mathbf{x}_{ij}) > \left(\sum_{y' \in Y} x_{ij}^{y'} \right) \frac{\partial Q_{ij}(\mathbf{x}_{ij})}{\partial x^y} \quad (9-3)$$

Equation (9-3) implies that capacity must exceed the change in capacity due to additional x^y flow; otherwise $\frac{\sum_{y' \in Y} x_{ij}^{y'}}{Q_{ij}(\bar{x}_{ij})}$ may decrease resulting in a decrease in $t_{ij}(\mathbf{x}_{ij})$.

A capacity function based on the well-known Greenshields' (1935) speed-density relationship and a jam density function increasing in the proportion of AVs is shown to satisfy equation (9-3) under reasonable assumptions. Greenshields' relationship predicts

$$v_{ij} = \vartheta_{ij} \left(1 - \frac{k_{ij}}{K_{ij}} \right) \quad (9-4)$$

where v_{ij} is vehicle speed, ϑ_{ij} is free-flow speed, k_{ij} is density, and K_{ij} is jam density on link $[i, j]$. Based on equation (9-4) capacity is $Q_{ij} = \frac{K_{ij} \vartheta_{ij}}{4}$, a linear function of jam density. Therefore $Q_{ij}(\bar{x}_{ij})$ is also assumed to be a linear function of jam density:

$$Q_{ij}(\mathbf{x}_{ij}) = \rho K_{ij}(\mathbf{x}_{ij}) \quad (9-5)$$

Jam density is assumed to be a function of the proportion of AVs on the road. Human drivers are on average expected to require some headway ζ_{HV} including the length of the vehicle ahead, with AVs requiring a distance $\zeta_{AV} < \zeta_{HV}$. Jam density is then:

$$K_{ij}(\mathbf{x}_{ij}) = \frac{1}{\zeta_{HV}} \left(\frac{\sum_{y \in Y} (x_{ij}^y (1 - \xi_{AV}^y))}{\sum_{y \in Y} x_{ij}^y} \right) + \frac{1}{\zeta_{AV}} \left(\frac{\sum_{y \in Y} (x_{ij}^y (\xi_{AV}^y))}{\sum_{y \in Y} x_{ij}^y} \right) \quad (9-6)$$

The capacity function defined by equations (9-5) and (9-6) is shown to be monotone increasing with respect to any x^y under the assumption that $2\zeta_{AV} > \zeta_{HV}$. This assumption is reasonable considering highway vehicle spacing at jam density was estimated at $\zeta_{HV} = 27.3$ feet for one city by Van Aerde and Rakha (1995), and Elefteriadou et al. (1997) suggested $\zeta_{AV} > 17$ feet length for a passenger car equivalent, which is a lower bound on spacing.

Proof.

Since $2\zeta_{AV} > \zeta_{HV}$, $\zeta_{AV} > \zeta_{HV} - \zeta_{AV}$ and $\zeta_{AV} \sum_{y \in Y} x_{ij}^y > (\zeta_{HV} - \zeta_{AV}) \sum_{y \in Y} x_{ij}^y$. Since $\zeta_{HV} \geq \zeta_{AV}$,

$$\sum_{y \in Y} (\zeta_{AV} x_{ij}^y \xi_{AV}^y) + \sum_{y \in Y} (\zeta_{HV} x_{ij}^y (1 - \xi_{AV}^y)) > (\zeta_{HV} - \zeta_{AV}) \sum_{y \in Y} x_{ij}^y \quad (9-7)$$

Since capacity can be rewritten as

$$Q_{ij}(\mathbf{x}_{ij}) = \rho \frac{1}{\zeta_{HV}\zeta_{AV}} \frac{1}{\sum_{y \in Y} x_{ij}^y} \left(\sum_{y \in Y} (\zeta_{HV} x_{ij}^y (1 - \xi_{AV}^y)) + \sum_{y \in Y} (\zeta_{AV} x_{ij}^y \xi_{AV}^y) \right) \quad (9-8)$$

then

$$\frac{\partial Q_{ij}(\mathbf{x}_{ij})}{\partial x_{ij}^y} = \rho \frac{1}{\zeta_{HV}\zeta_{AV}} \left(\frac{\frac{1}{\sum_{y' \in Y} x_{ij}^{y'}} ((1 - \xi_{AV}^{y'}) \zeta_{AV} + \xi_{AV}^{y'} \zeta_{HV}) - \frac{1}{\left(\sum_{y' \in Y} x_{ij}^{y'} \right)^2} \left(\sum_{y' \in Y} (\zeta_{HV} x_{ij}^{y'} (1 - \xi_{AV}^{y'})) + \sum_{y' \in Y} (\zeta_{AV} x_{ij}^{y'} \xi_{AV}^{y'}) \right)}{\left(\sum_{y' \in Y} x_{ij}^{y'} \right)^2} \right) \quad (9-9)$$

$Q_{ij}(\mathbf{x}_{ij}) > \left(\sum_{y' \in Y} x_{ij}^{y'} \right) \frac{\partial Q_{ij}(\mathbf{x}_{ij})}{\partial x_{ij}^y}$ simplifies to

$$\sum_{y' \in Y} (\zeta_{AV} x_{ij}^{y'} \xi_{AV}^{y'} + \sum_{y' \in Y} (\zeta_{HV} x_{ij}^{y'} (1 - \xi_{AV}^{y'}))) > \sum_{y' \in Y} x_{ij}^{y'} (\zeta_{HV} - \zeta_{AV}) \quad (9-10)$$

which is satisfied because equation (9-7) is true.

Fuel Consumption: To incorporate the multiple types of costs incurred by different modes, such as transit fees and travel time, a generalized cost function is required. Monetary fees and travel time do not fully encompass the cost of an AV making a round trip instead of a one-way trip with parking. The associated cost to the traveler of the AV's return leg is not travel time (for the traveler is not in the vehicle), and road tolls can be avoided by route choice. However, regardless of the route, the return trip incurs additional fuel consumption. Therefore, the fuel consumption function found by Gardner et al. (2013), based on a regression equation from MOVES (2009) data, was used:

$$F_{ij}(v_{ij}) = 14.58(v_{ij})^{-0.6253} \quad (9-11)$$

where v_{ij} is vehicle speed in miles per hour and $F_{ij}(\cdot)$ is energy consumption in kilo-Watt hours per mile on link $[i, j]$. This function is monotone decreasing with speed, therefore monotone increasing with travel time, allowing its use as part of a generalized cost function for the standard user equilibrium assignment. Fuel consumption was included for all personal vehicle trips one-way with parking and AV round-trip, and converted into money through the price of gasoline, γ , which was assumed to be constant and the same for all vehicles on the network. For a link $[i, j] \in E$ (where E is the set of links) with length L_{ij} in miles, the fuel consumed over the link for a travel time of t_{ij} in hours, $F_{ij}(t_{ij})$, is then

$$F_{ij}(t_{ij}) = \frac{L_{ij}}{36.44 \text{ kW/gal}} \left(14.58 \left(\frac{L_{ij}}{t_{ij}} \right)^{-0.6253} \right) \quad (9-12)$$

where 36.44 kW/gal is the energy content of gasoline.

Generalized Cost: When creating generalized costs based on travel time and money, an important variable is the VOT. Travelers with a high VOT may burn more fuel and use tolled roads to reduce travel time, whereas travelers with a low VOT may be more reluctant to incur monetary costs. The generalized cost function for driving on link $[i, j]$, $c_{ij}^{y,DR}(\mathbf{x}_{ij})$ is a combination of travel time, fuel consumption, and road toll τ_{ij} :

$$c_{ij}^{y,DR} = v_y t_{ij}(\mathbf{x}_{ij}) + \gamma F_{ij}(t_{ij}(\mathbf{x}_{ij})) + \tau_{ij} \quad (9-13)$$

For a parking fee of ζ_s^{PK} , the cost of a one-way driving trip from r to s followed by parking is

$$C_{rs}^{y,PK}(\pi) = \zeta_s^{PK} + \sum_{(i,j) \in \pi} C_{ij}^{y,DK}(\mathbf{x}_{ij}) \quad (9-14)$$

where π is the route. Other per-mile costs could be incorporated as a fixed cost per link.

For the return leg of AV round-trips, with no passenger, travel time is not a factor, so the notation $c_{ij}^{0,DR}$ with $v_0 = 0$ is used to denote the cost of driving with 0 VOT. Cost of an AV round-trip, using path π_1 for travel from r to s and path π_2 for travel from s to r , is

$$C_{rs}^{y,AV}(\pi_1, \pi_2) = \sum_{(i,j) \in \pi_1} C_{ij}^{y,DR}(\mathbf{x}_{ij}) + \sum_{(i,j) \in \pi_2} C_{ij}^{0,DR}(\mathbf{x}_{ij}) \quad (9-15)$$

The cost of traveling on link $[i, j]$ using transit is similarly

$$c_{ij}^{y,TR}(\mathbf{x}_{ij}) = v_y t_{ij}(\mathbf{x}_{ij}) \quad (9-16)$$

with transit fees included in the origin-destination (OD) cost. When transit uses the same links as other vehicles, such as with many buses, travel time depends on total vehicular flow. Transit could also be given separate links with different travel time functions. Based on the cost per link, the cost of a transit trip is then

$$C_{rs}^{y,TR}(\pi) = \zeta_{rs}^{TR} + \sum_{(i,j) \in \pi} C_{ij}^{y,TR}(\mathbf{x}_{ij}) \quad (9-17)$$

where ζ_{rs}^{TR} is the transit fee for traveling from r to s . Multimodal routes are not permitted in this model.

Model Formulation

The commonly used four-step model was modified to incorporate AV round trips. The latter three steps incorporate a feedback element for convergence to a stable solution. The following subsections discuss each step in greater detail.

Trip Generation: The first step is trip generation, which determines productions \mathbf{P}_r and attractions \mathbf{A}_s based on survey data for each $r \in Z$, $s \in Z$, where Z is the set of zones. Productions and attractions for each zone are vectors in $\mathbb{R}_+^{|\mathcal{Y}|}$ to distinguish between VOT classes. Although the distribution among VOT classes may vary at each zone, system-wide consistency of $\sum_{r \in Z} \mathbf{P}_r = \sum_{s \in Z} \mathbf{A}_s$ is required.

Trip Distribution: Trip distribution uses a gravity model to determine the number of person trips \mathbf{d}_{rs} between every OD pair $(r, s) \in Z^2$, which is assumed to increase with productions and attractions and decrease with travel cost. As with trip generation, $\mathbf{d}_{rs} \in \mathbb{R}_+^{|\mathcal{Y}|}$ to distinguish between VOT class. Minimum cost used for determining person-trips is defined as

$$C_{rs}^y = \begin{cases} \min\{C_{rs}^{y,PK}, C_{rs}^{y,TR}, C_{rs}^{y,AV}\} & \text{if } \xi_{AV}^y = 1 \\ \min\{C_{rs}^{y,PK}, C_{rs}^{y,TR}\} & \text{otherwise} \end{cases} \quad (9-18)$$

Then

$$d_{rs}^y = \eta_r^y \mu_s^y P_r^y A_s^y \phi(C_{rs}^y) \quad (9-19)$$

where $\phi(\cdot)$ is a decreasing friction function, $\eta_r^y = \frac{1}{\sum_{s \in Z} \mu_s^y A_s^y \phi(C_{rs}^y)}$, and μ_s^y is adjusted iteratively to $\frac{1}{\sum_{r \in Z} d_{rs}^y}$ for consistency with productions and attractions, $\sum_{r \in Z} \mathbf{P}_r = \sum_{s \in Z} \mathbf{A}_s = \sum_{r \in Z} \sum_{s \in Z} \mathbf{d}_{rs}$.

Mode Choice: Mode choice splits the person trips per OD into mode-specific trips \mathbf{d}_{rs}^m per mode $m \in M$, with M the set of all modes. Travelers may choose between parking, repositioning, and transit. Mode splits are determined by a nested logit model on utility of each mode. To include the benefits of having a vehicle parked at the destination for immediate departure on short notice, an AV preference constant ψ^{AV} is included. ψ^{TR} denotes the traveler preference for transit.

Mode-specific trips per class are therefore defined as

$$d_{rs}^{y,TR} = \begin{cases} \frac{\exp(\psi^{TR} - c_{rs}^{y,TR})}{\exp(\min\{\psi^{AV} - c_{rs}^{y,AV}, -c_{rs}^{y,PK}\}) + \exp(\psi^{TR} - c_{rs}^{y,TR})} & \text{if } \xi_{AV}^y = 1 \\ \frac{\exp(\psi^{TR} - c_{rs}^{y,TR})}{\exp(-c_{rs}^{y,PK}) + \exp(\psi^{TR} - c_{rs}^{y,TR})} & \text{otherwise} \end{cases} \quad (9-20)$$

$$d_{rs}^{y,AV} = \begin{cases} \frac{\exp(\psi^{AV} - c_{rs}^{y,AV})}{\exp(\psi^{AV} - c_{rs}^{y,AV}) + \exp(-c_{rs}^{y,PK})} & \text{if } \xi_{AV}^y = 1 \\ 0 & \text{otherwise} \end{cases} \quad (9-21)$$

$$d_{rs}^{y,PK} = d_{rs}^y - d_{rs}^{y,TR} - d_{rs}^{y,AV} \quad (9-22)$$

To model return trips, additional demand is added for AV round-trips:

$$d_{sr}^{0,AV} = \sum_{y \in Y} d_{rs}^{y,AV} \quad (9-23)$$

Traffic Assignment: The traffic assignment formulation is multi-class because of the distinction between AV and non-AV vehicles. Marcott and Wynter (2004) demonstrated that multi-class formulations are not necessarily convex despite monotonicity of the travel time function with respect to the flow of any single class. Non-convexity can result in the existence of multiple equilibria as well as non-convergence of algorithms designed for convex objective functions. The weaker convexity requirement they develop of partial nested monotonicity, in general, requires the specification of the optimal link flows of one class as a function of link flows of second class. This is difficult for the city-size networks that this model is designed for. Even if these functions were determined, the somewhat arbitrary nature of the VOT parameter could prevent partial nested monotonicity in general, as shown by Marcott and Wynter's example network with three equilibria (2004). Nevertheless, this issue is not unique to this model, but common to all models incorporating multiple discrete VOT classes.

Multi-class user equilibrium assignment with fixed demand was formulated as a variational inequality (VI) in the form of Nagurney and Dong (2002) Let $\mathbf{x} = \{x_1^1, \dots, x_{|E|}^1, \dots, x_1^{|Y|}, \dots, x_E^{|Y|}\}$ be the vector of all class link flows, where E is the set of links. The VI problem is to find $\mathbf{x}^* \in \mathcal{K}$ such that

$$\sum_{(i,j) \in E} \mathbf{c}_{ij}^{DR}(\mathbf{x}^*) \cdot (\mathbf{x} - \mathbf{x}^*) \geq 0 \quad (9-24)$$

where \mathbf{c}_{ij}^{DR} is the vector of class-specific driving costs and \mathcal{K} is the feasible region defined by

$$\begin{aligned} \mathbf{x}_{ij} &= \sum_{\pi \in \Pi} \delta_{ij}^{\pi} \mathbf{h}_{\pi} & \forall (i,j) \in E \\ \mathbf{h}_{\pi} &\geq \mathbf{0} & \forall \pi \in \Pi \\ \mathbf{d}_{rs}^{DR} + \mathbf{d}_{rs}^{AR} &= \sum_{\pi \in \Pi_{rs}} \mathbf{h}_{\pi} & \forall (r,s) \in Z^2 \end{aligned} \quad (9-25)$$

\mathbf{x}^* satisfies user equilibrium (UE) due to Nagurney and Dong's proof (2002) on a more general form of this VI incorporating elastic demand and OD disutility. Due to the special behaviors of AVs, we include only assignment in the VI and solve trip distribution and mode choice separately as in the four-step model.

The Frank-Wolfe algorithm is used as a heuristic to solve this VI. The step size of λ is found by solving

$$\sum_{(i,j) \in E} \sum_{y \in Y} c_{ij}^y (\lambda \mathbf{x}_{ij}^* + (1 - \lambda) \mathbf{x}_{ij}) (x_{ij}^{y*} - x_{ij}^y) = 0 \quad (9-26)$$

where \mathbf{x}^* is the search direction for λ . The algorithms for multi-class VI formulations of traffic assignment studied by Nagurney and Dong (2002) and Marcott and Wynter (2004) may improve convergence. Optimal convergence of traffic assignment is not a major focus of this study, and a specific algorithm is not a requirement of the model.

Feedback Algorithm: The standard four-step algorithm with feedback as described in McNally (2008) is used. Productions and attractions, the output of are trip generation, are assumed to be known. The latter three steps are performed in a feedback loop for convergence. Trip distribution determines total person trips per OD pair and VOT class based on travel costs (initially free flow costs). Mode choice splits person trips into mode-specific trips using a nested logit model. Traffic assignment finds the routes for all vehicle trips, assuming user equilibrium behavior. As the assignment changes based on the personal vehicle trips, the feedback loop allows trip distribution and mode choice to be updated using the travel costs from the traffic assignment.

To improve convergence, the method of successive averages (MSA) algorithm is used for the four-step feedback. Let $\mathbf{d}_{rs}(n)$ be the person-trips and $\mathbf{d}_{rs}^m(n)$ be the trips using mode $m \in M$ from $r \in Z$ to $s \in Z$ at iteration n of the feedback loop, and $\mathbf{d}_{rs}^*(n+1)$ and $(\mathbf{d}_{rs}^m)^*(n+1)$ be the search direction at iteration $n+1$. A step size of $\frac{1}{n+1}$ is used, i.e.

$$\mathbf{d}_{rs}(n+1) = \frac{1}{n+1} \mathbf{d}_{rs}^*(n+1) + \frac{n}{n+1} \mathbf{d}_{rs}(n) \quad (9-27)$$

$$\mathbf{d}_{rs}^m(n+1) = \frac{1}{n+1} (\mathbf{d}_{rs}^m)^*(n+1) + \frac{n}{n+1} \mathbf{d}_{rs}^m(n) \quad (9-28)$$

Convergence was measured based on the root mean squared error of mode-specific trips, as suggested by Boyce et al. (1994):

$$RMSE^d = \sqrt{\frac{\sum_{r \in Z} \sum_{s \in Z} \sum_{y \in Y} \sum_{m \in M} (d_{rs}^{y,m}(n+1) - d_{rs}^{y,m}(n))^2}{|Z^2 \times Y \times M|}} \quad (9-29)$$

Summary: This section developed an initial model to analyze the impact of AV availability on AM peak transit demand. AVs allow the option of a drop-off and return trip to avoid parking costs, incurring only additional fuel consumption, so a generalized cost function of travel time, monetary fees, and fuel was created to model the cost of a trip. On the other hand, AV use increases road capacity, reducing travel times. This inspired a jam density function of the proportion of AVs on the road, with capacity assumed to be a linear function of jam density in accordance with Greenshields speed-flow density relationship. The resulting travel time function was proven to be monotone increasing for the specific jam density function used.

Roadway Capacity Improvement

CAVs have the potential to improve the capacity of the roads people are using. As for a typical highway, HVs provide a maximum throughput of about 2,200 vehicles per hour per lane, only 5% of utilization of the roadway space (2012). AVs, replacing drivers, can increase capacity by shortening vehicle-following gaps and narrowing lanes for light duty vehicles based on more accurate steering (2012). A similar conclusion is reached in the research of Pinjari et al. (2013), which asserts that AVs can allow for much shorter perception and reaction times, smoother braking, and shortening of vehicle-following gaps even at high speeds by sensing and anticipating the lead vehicles braking actions and acceleration/deceleration decisions better than human drivers. The capacity improvement stemming from AV technologies has been investigated by many researchers. Vehicle-to-vehicle (V2V) communication, particularly cooperative adaptive cruise control (CACC), is another critical technology for network improvement. Tientrakool et al. (2011) conducted simulations to investigate the influence of CACC on highway capacity. Their results indicated that CACC can increase a highway capacity, of 2,868 vehicles per hour per lane to 10,720 vehicles per hour per lane, when 100% are communicating vehicles and the speed of vehicles is fixed at 100 km/h—which is a capacity improvement of about 3.7 times. Xu et al. (2002) adopted three different simulation models of travel behavior to study the capacity improvement of CACC. Their study indicated that 100% CACC can provide a 120% improvement compared with manual driving. Although many researchers have obtained simulation results confirming the capacity improvements made possible by CAV technologies, their results are inconsistent because they are based on varying rates of implementation. For example, by assuming full or partial vehicle automation, Childress et al. (2014) applied a 30% increase of all freeway and major arterial capacities to analyze the travel demand model based on the Puget Sound regional area. Gućwa (2014) adopted capacity improvement of 0%, 10% and 100% to estimate the travel behavior in the context of the Bay Area Metropolitan agent-based activity model. To anticipate the travel impact of AVs in Metro Atlanta, Kim et al.

(2015) applied a 50% increase in roadway capacity to their activity-based model. Levin and Boyles (2015) proposed a heuristic model, based on Greenshield's model, to scale capacity with the proportion of AVs.

Given the uncertainty of the capacity improvement based on CAV technologies and inconsistent results from the research cited above, it is essential to incorporate a range of outcomes from 25% to 200% increase of roadway capacity into our model.

Travel Demand

AVs that do not need human drivers or monitors may substantially increase mobility for those who cannot (legally) drive themselves because of youth, age, disability, or incapacitation (Fagnant and Kockelman, 2015a) (Litman, 2015). However, poverty may be one of the most critical reasons that will prevent access to AVs for those potential users (Smith, 2012). If this is the case, the possible travel demand increase from that set of new travelers may be offset by the reality that they are not affluent enough to afford the new technology, which indicates that travel demand will stay the same. However, for those users who can afford CAV technology, automation could stimulate user travel needs (Gucwa, 2014) (Spieser et al., 2014), due to the reduction in perceived time costs and the increase in smoother and more comfortable trips (Cuddy et al., 2014).

While the introduction of SAVs will reduce the levels of private vehicle ownership, SAVs will also add more vehicle miles traveled (VMT) to the network (Fagnant and Kockelmana, 2016, Speiser et al., 2014). According to the information introduced above, in the scenarios involving CAVs, the trip generation rates of households above the median income groups are increasing by 20%, 40%, 60%, 80%, and 100%, respectively, in different scenarios.

Mode Choice

Value of Travel Time: The most significant difference between conventional vehicles and fully AVs is that no driver is needed to complete the trip, which means drivers are set free to perform other activities, such as using cell phones, reading, watching movies, preparing work reports, and even sleeping. This significant change will absolutely overturn the long-established perception of travel time. Traveling with fully AVs would be considered a productive activity, resulting in decreased value of travel time (VOTT).

VOTT is a critical factor that will be incorporated into the generalized costs to combine travel time and financial costs. The VOTT has the function to change the units of travel time to dollars, which leads to the same units for the travel time and financial costs.

Petersen and Vovsha (2006) found that higher income households tend to drive newer vehicles, and among household members, the new vehicles are allocated to workers first, and then to retirees and under-18 drivers.

A similar trend might initially occur with AV adoption (Childress et al., 2014). To test AV technology impact on travel time, trip-based VOTTs were reduced by 65% for highest-income households in the traffic assignment step, and in the travel demand model, the automobile travel time was directly modified to be 65% of skimmed travel time in the skims for the high VOTT trips. Burns et al. (2013) conducted a case study of SAVs in Ann Arbor, Michigan, that indicates an SAV fleet can provide the same mobility as personally owned vehicles at far less cost by reducing parking costs and VOTT. The U.S. median income is \$50,000 per year, which equates to \$25/hour, yielding a VOT of \$0.85 per mile. Combining the median time value of \$0.85 per mile, with the out-of-pocket cost of \$0.75 per mile for a medium sedan driven the median annual distance of 10,000 miles, we arrive at a cost-plus-time value of \$1.60 per mile to use a personally owned vehicle. Using an SAV could reduce that traffic cost to \$0.15 per mile.

Kim et al. (2015) maintained that AVs will allow users to perceive travel time disutility, because in-vehicle travel time (IVTT) becomes less onerous and more productive, which will affect mode choice. In order to reflect this characteristic of AVs, in their Metro Atlanta activity-based model, Kim et al. decreased IVTT coefficients for autos by 50%, yielding a 71% reduction in vehicle operating costs as compared to the base model.

Gucwa (2014) handled the uncertainty about automated time-costs by considering four different IVTT coefficient values across a range of scenarios. In the base scenario, the VOTT wasn't changed. In the extreme scenario, the VOTT was assigned to zero. In the other two scenarios, the VOTT of AVs was equal to 30% lower than that of conventional cars and 60% lower than that of transit.

In order to value the convenience of fully AVs, we included the following question in the project survey of Texans: "How much money you are willing to pay (WTP) to save 15 minutes of travel time during a typical 30-minute ONE-WAY journey you make at least once a week (for example, home to work)?" In all, 1,364 Texans completed the response of this question.

The resulting answers indicated that Texans' average WTP to save 15 minutes of travel time on a 30-minute one-way trip is \$6.80, but this figure increases to \$9.50 if we remove those respondents with \$0 WTP for this benefit (28.5%). This result also indicates that most Texans associate significant monetary value with their travel time and are ready to pay more to travel faster. The VOTT is \$27.20, as derived from this question.

Based on the literature review results and our survey, we considered four AV VOTT scenarios in our model. In our base model, the VOTT stayed the same as the conventional vehicles. In the extreme scenario, the VOTT was set up to zero to maximize the benefits of AVs. In other two scenarios, VOTT was equal to the transit VOTT of transit and 50% of the VOTT of conventional vehicles.

Parking Costs: Parking cost was considered in the utility equation of mode choice. It is reasonable that decreasing parking cost can attract more trips to an area. One critical impact of AVs on traffic behavior is a change in parking patterns, as AVs can self-park in less expensive areas (Fagnant and Kockelman, 2015b).

Childress et al. (2014) set parking costs to half the original level to reflect AVs self-parking in cheaper locations or better utilizing existing space. The change was made only in zonal parking costs and does not capture VMT generated from vehicles seeking more distant parking spaces or even roaming the streets waiting for pickup commands. Kim et al. (2015) further increase the AV parking benefits by setting the parking price to zero at the primary destination. A similar assumption was also made in the Levin's (2015) travel demand model, which allows AVs to avoid parking fees.

Table 9.1 Parameters Set Up for Model Scenarios

Capacity improvement	Trip generation	VOT	Parking costs
25%, 50%, 75%, 100%, 150% and 200%	Work-related stay the same, other trip purposes increased by 20%, 40%, 60%, 80%, and 100%	\$0, ¼ of autos, ½ of autos VOT and equal transit VOT	\$0 and ½ of current parking costs

An SAV will essential function as a kind of autonomous taxi, which can operate by itself without human manipulation, other than input regarding a traveler's destination. Although SAVs will stimulate VMT due to empty vehicle relocation trips, they can provide significant environmental benefits, particularly in the form of reduced parking and vehicle ownership needs (Fagnant and Kockelman, 2015a). Zhang et al. (2015) developed simulation model to test the change in parking needs created by an SAV system. Their results indicate a proper SAV fleet can reduce parking needs by 70% while still meeting travelers' needs. Therefore, in our study, when an SAV system (or autonomous taxi system) is investigated, the parking cost for this type of mode can be set at 30% of the current parking cost of automobiles. In all, based on the information we presented above, AV parking costs were set in our travel demand model to zero, one-half of the current price, and one-fourth of the current price. In addition, if SAVs are considered in the travel demand model, their parking fees are equal to zero.

Results from Static Traffic Assignment Simulations

This section presents results on the downtown Austin network, during the two-hour period of morning rush hour (2-hour AM peak). Although the model is computationally tractable for a larger network, the size of this network allowed study of multiple scenarios with high detail in analyses. First, the empirical convergence is

presented. Then, the effects of increasing CAV ownership on transit ridership, repositioning trips, and total personal-vehicle demand are studied.

Description of Experiments: The model was tested on the Austin downtown sub-network with 2-hour AM peak trip data provided by the Capital Area Metropolitan Planning Organization. Bus routes are included and were used for transit options for the mode choice model. In addition, walking at the speed of 3 mph was permitted along all links for connecting to transit because some zones are not directly served by bus. Although no distance constraint was included due to the complexity imposed on the shortest path algorithm, walking long distances would have a high penalty in travel time with respect to vehicular travel.

Due to lack of value-of-time (VOT) distribution data per zone, the same distribution (shown in Table 9.2) was used for each zone, with VOTs ranging from 1.15 to 22 in units of dollars per hour. Values of time were uniformly chosen from a range based on scaling an income distribution, and the log-normal expression with mean $\mathbb{E}[v]$ and standard deviation σ_v was used to determine the class distribution of demand, as suggested by Yang and Meng (2001) and Huang and Li (2007).

Table 9.2 Value-of-Time Distribution

Class	VOT (\$/hr)	Proportion
1	1.15	0.08
2	3.5	0.37
3	5.85	0.28
4	8.15	0.14
5	10.5	0.07
6	13	0.03
7	15	0.015
8	17.5	0.007
9	20	0.004
10	22	0.002

As shown in Table 9.2, the chosen range accommodates most variation in the distribution. The demand data did not include trip purpose. Since the data are for the AM peak, all trips are assumed to be for home-based work travel. Price may have different effects on commercial travel or other types of personal trips. The inverse friction function $\phi(C) = \frac{1}{C}$ was used in trip distribution and mode choice. Parking costs were estimated at \$5.00 per day for all zones due to more specific data not being available. Although downtown parking fees are often much higher, for long-term planning travelers are assumed to have the option of cheaper annual parking passes. Fuel cost was set at \$3.00 per gallon. If the price of gasoline increases, there will be a shift of users from personal vehicle use to public transit. The opposite is true if the gas price were to decrease.

On initial availability for public use, CAVs may have a high purchase cost because of the novelty of the technology. As production increases, the cost is expected to decrease so that CAVs become more affordable. The assumption was made that higher income travelers also have higher VOT, and that income affects affordability of CAVs.

Convergence of Static Traffic Assignment

Because of the multi-class formulation, the traffic assignment variational inequality (VI) does not necessarily have a unique or even existent equilibrium (Marcotte and Wynter, 2004), and therefore the commonly used Frank-Wolfe algorithm is not guaranteed to converge. However, empirical results of running Frank-Wolfe on the downtown Austin network suggest that it converges to an equilibrium. Figure 9.1 shows the convergence for the simulation case in which the eight highest VOT classes constituted 55% of the CAV demand use. Convergence is measured through the average excess cost—for example, the average difference between observed and shortest path travel costs. Similar convergence was observed for all scenarios in the gradual

expanding availability of CAVs experiment. Since there was convergence, one can be sure that an equilibrium was reached and the results are worthwhile.

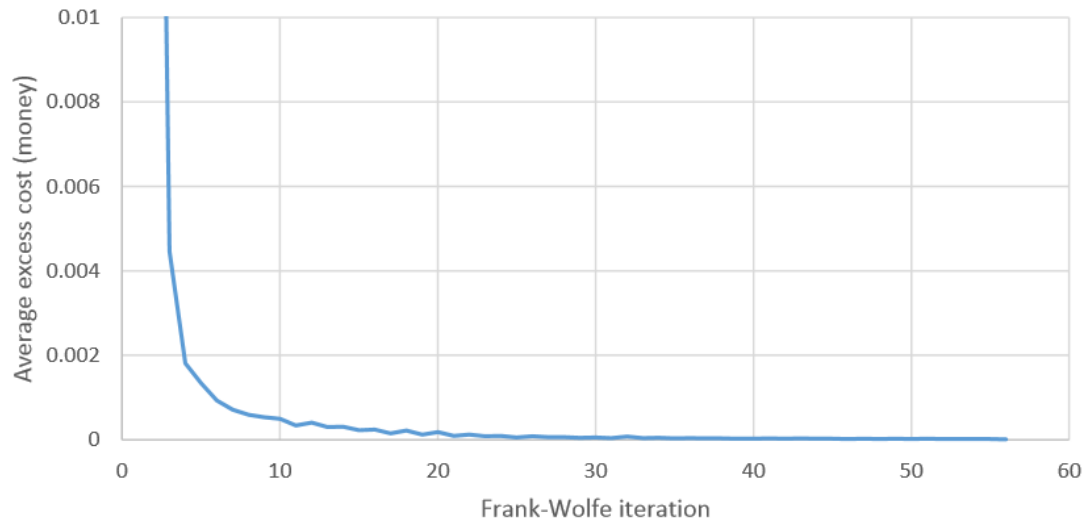


Figure 9.1 Convergence of Traffic Assignment

Autonomous Vehicle Demand: Figure 9.2 shows the decrease in transit demand as more VOT classes receive access to CAVs. Transit demand is high without CAVs because a high proportion of low VOT travelers, which are the majority of the demand choose transit. The pattern of decrease roughly follows the class proportions because the reduction in transit utility is primarily due to the lower cost of CAVs. When CAVs are available only to the upper classes, which comprise a small fraction of the population, the effect is small. However, as CAVs become available to lower-middle VOT classes, the rate of decrease in transit demand is much greater. Overall, the model predicts a reduction in transit ridership of 61% due to lower costs of CAVs for low VOT travelers (see Table 9.3 Table 9.4). CAV round-trip demand was a high fraction of the total personal vehicle demand, reaching 83% at full market penetration (Figure 9.3). This analysis also neglected the possible reduction in parking fees due to the economics of lower demand. However, because the alternative is a return trip, parking costs would likely need to be significantly lower to be competitive against the fuel cost of a return trip to the origin. Similarly, for transit to be competitive against CAVs, transit must provide benefits in cost or travel time. Transit costs in this model were \$1, so a reduction in cost sufficient to be competitive against the lack of parking costs would be difficult. Despite the removal of the parking fee, CAVs still carry their own cost in relation to fuel consumption. However, restricted-access routes for transit such as bus rapid transit or metro could provide advantages in travel time.

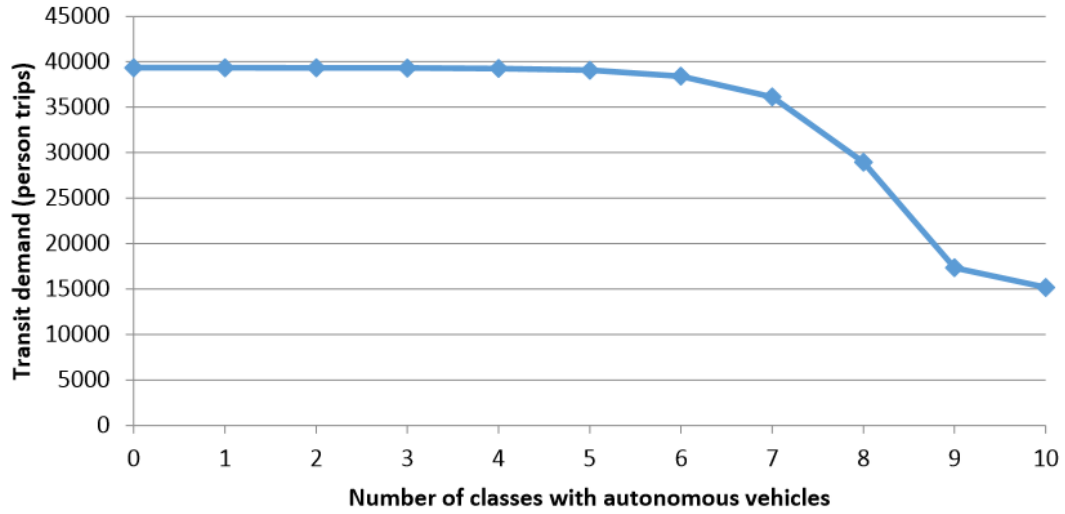


Figure 9.2 Total Transit Demand

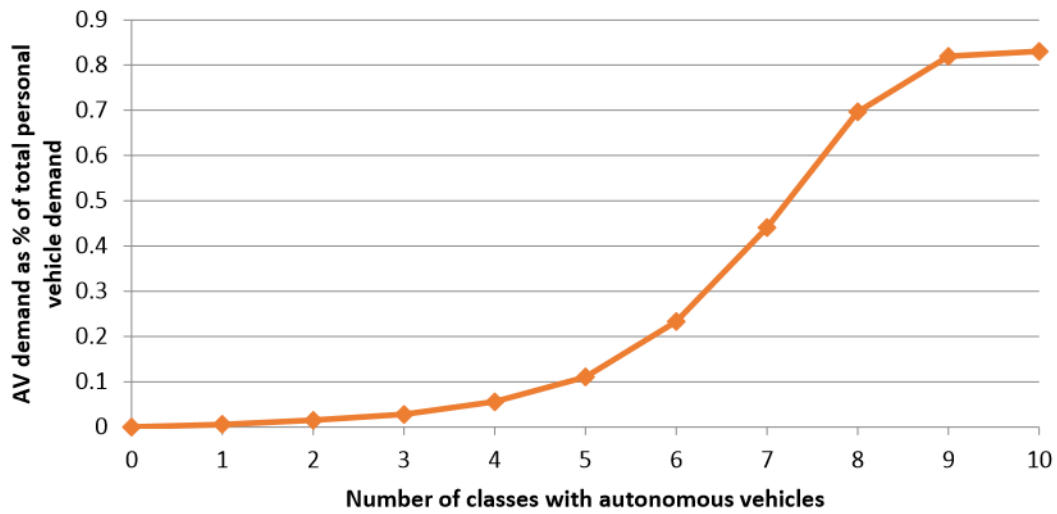


Figure 9.3 CAV Round-Trip Demand as a Percentage of Total Personal Vehicle Demand

Long-term Effects: Table 9.3 shows the mode split for each VOT class before any CAVs and after full CAV availability, and Table 9.4 shows the mode costs per class. The values shown in Table 10.4 are the costs associated with a single user’s travel based on their mode choice. Total demand for any personal vehicle mode changed from 23,500 person-trips to 47,676 trips, and with the shift to 39,592 CAV round-trips, the total number of trips made by personal vehicles increases to 87,275 an increase of 271%. Although many of these additional trips are traveling away from downtown, the network still experiences significant increases in link volume. However, average speed decreases are modest, as shown in Figure 9.4. This is encouraging because it suggests that the increases in demand are substantially offset by increases in capacity from CAVs.

Table 9.3 Comparison of Mode-Specific Demand Before and After CAV Availability

User Class	Trip Distribution without CAVs			Trip Distribution with CAVs		
	Park	Transit	Round-Trip	Park	Transit	Round-Trip
1	3.1%	96.9%	N/A for all Classes	1.4%	49.0%	49.6%
2	15.2%	84.8%		6.1%	33.0%	60.9%
3	41.4%	58.6%		15.1%	19.6%	65.4%
4	64.1%	35.9%		20.9%	12.0%	67.1%
5	78.9%	21.1%		24.3%	7.8%	67.8%
6	88.0%	12.0%		26.6%	5.3%	68.1%
7	92.3%	7.7%		27.8%	3.9%	68.2%
8	95.5%	4.5%		28.9%	2.8%	58.3%
9	97.3%	2.7%		29.6%	2.1%	68.3%
10	98.2%	1.8%		30.0%	1.7%	68.2%

Table 9.4 Comparison of Mode and User-Class-Specific Costs (in \$ [USD]) Before and After CAV Availability

User Class	Cost per User without CAVs			Cost per User with CAVs		
	Park	Transit	Round-Trip	Park	Transit	Round-Trip
1	5.9	2.0	\$2.7	6.1	2.0	0.6
2	6.1	3.9	2.6	6.3	3.8	0.8
3	6.2	5.7	2.6	6.6	5.5	1.0
4	6.3	7.7	2.7	6.9	7.3	1.2
5	6.5	9.6	2.7	7.2	9.1	1.4
6	6.6	11.7	2.7	7.6	11.1	1.7
7	6.8	13.4	2.7	7.8	12.6	1.9
8	6.9	15.4	2.7	8.2	14.6	2.1
9	7.0	17.5	2.7	8.5	16.5	2.3
10	7.2	19.1	2.7	8.7	18.0	2.5

Effects on Traffic Congestion: Figure 9.4 shows that average link travel speeds mirror the class proportions, indicating that the decrease in average link speeds is due to the switch to CAV round-trips. On the north/south

bound freeways and arterials, much of the CAV round-trip traffic travels in the opposite direction away from workplaces in downtown. Within the downtown grid itself, CAV round-trips contribute to congestion while leaving the area. However, the changes are relatively small, suggesting that roadway capacity increases negate some of the additional vehicular travel demand. Average link speeds may be higher than expected because of the lack of intersection penalties, which are a major factor in the downtown region.

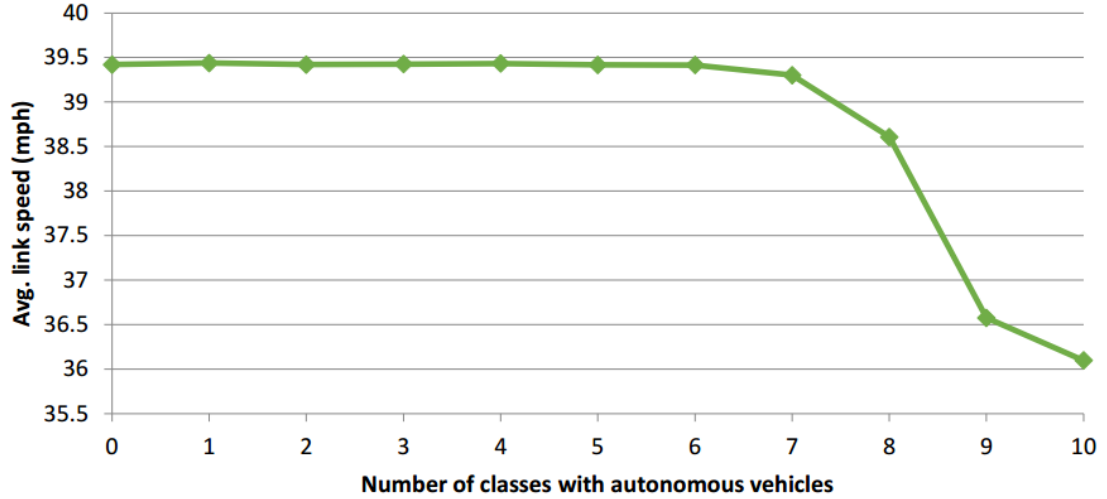


Figure 9.4 Change in Average Link Speed, Weighted by Length, as CAV Availability Increases

9.3 Link and node models

Multi-class Cell Transmission Model

This section presents a multi-class extension of the CTM developed for this project. The focus of this section is on roads with both HVs and personal AVs. In this model, the vehicles are differentiated by driver type but not by the physical performance characteristics. Therefore, we did not include the speed differences between vehicle classes, such as between heavy trucks and personal vehicles. The models in this section were defined for continuous flows, which some DTA models use. For these models, we made the following assumptions:

- 1) All vehicles travel at the same speed. Although in reality vehicle speeds differ, in DTA models the vehicle speed behavior model is often assumed to be identical for all vehicles. This is reasonable even with multiple vehicle classes because AVs may match the speed of surrounding vehicles even if it requires exceeding the speed limit. Although Tuerprasert & Aswakul (2010) consider different vehicle speeds in CTM, in this study of HVs and AVs most of the differences in speed would come from variations in HV behavior that are often not considered in DTA models.
- 2) Uniform distribution of class-specific density per cell. Single-class CTM assumes the density within a cell is uniformly distributed. We extend that assumption to class-specific densities.
- 3) Arbitrary number of vehicle classes. Although this chapter focuses on the transition from HVs to AVs, different types of AVs may be certified for different reaction times, and thus may respond differently in their car-following behavior.
- 4) Backwards wave speed is less than or equal to free-flow speed. This is necessary to determine cell length by free-flow speed.

We first define the multi-class hydrodynamic theory, then, following the presentation of Daganzo (1994), we state the cell transition equations and show that they are consistent with the multi-class hydrodynamic theory.

Multi-class Hydrodynamic Theory: Let \mathbf{M} be the set of vehicle classes. Let $\mathbf{k}_m(\mathbf{x}, \mathbf{t})$ be the density of vehicles of class m at space-time point (\mathbf{x}, \mathbf{t}) with total density denoted by $\mathbf{k}(\mathbf{x}, \mathbf{t}) = \sum_{m \in \mathbf{M}} \mathbf{k}_m(\mathbf{x}, \mathbf{t})$. Similarly, let

$u\left(\frac{k_1}{k}, \dots, \frac{k_{|M|}}{k}\right)$ denote the speed possible with class proportions of $\frac{k_1}{k}, \dots, \frac{k_{|M|}}{k}$, and let $\mathbf{q}_m(\mathbf{x}, \mathbf{t}) = u\left(\frac{k_1}{k}, \dots, \frac{k_{|M|}}{k}\right) \mathbf{k}_m(\mathbf{x}, \mathbf{t})$ be the class-specific flow, with the total flow given by $\mathbf{q}(\mathbf{x}, \mathbf{t}) = \sum_{m \in M} \mathbf{q}_m(\mathbf{x}, \mathbf{t})$.

Speed is limited by free-flow speed, capacity, and backwards wave propagation:

$$u(k_1, \dots, k_{|M|}) = \min \left\{ u^f, \frac{q^{max}\left(\frac{k_1}{k}, \dots, \frac{k_{|M|}}{k}\right)}{k}, w\left(\frac{k_1}{k}, \dots, \frac{k_{|M|}}{k}\right) (k^{jam} - k) \right\} \quad (9-30)$$

where u^f is free-flow speed, $w\left(\frac{k_1}{k}, \dots, \frac{k_{|M|}}{k}\right)$ is the backwards wave speed, $q^{max}\left(\frac{k_1}{k}, \dots, \frac{k_{|M|}}{k}\right)$ is the capacity when the proportions of density in each class are $\frac{k_1}{k}, \dots, \frac{k_{|M|}}{k}$, and k^{jam} is jam density. k^{jam} is assumed not to depend on vehicle type, as the physical characteristics (such as length and maximum acceleration) of HVs and AVs are assumed to be the same. For consistency, conservation of flow must be satisfied, i.e., $\frac{\partial q_m(x,t)}{\partial x} = \frac{\partial k_m(x,t)}{\partial t}$ for all $m \in M$ (2002).

Cell Transition Flows

As with Daganzo (1994), to form the multi-class CTM we discretize time into time steps of dt . Links are then discretized into cells labeled by $i = 1, \dots, I$ such that vehicles traveling at free-flow speed will travel exactly the distance of one cell per time step. Let $n_i^m(t)$ be vehicles of class m in cell i at time t , where $n_i(t) = \sum_{m \in M} n_i^m(t)$. Let $y_i^m(t)$ be vehicles of class m entering cell i from cell $i - 1$ at time t . Then cell occupancy is defined by

$$n_i^m(t + 1) = n_i^m(t) + y_i^m(t) + y_{i+1}^m(t) \quad (9-31)$$

with total transition flows given by

$$y_i(t) = \sum_{m \in M} y_i^m(t) = \min \left\{ \sum_{m \in M} n_{i-1}^m(t), Q_i(t), \frac{w_i(t)}{u^f} (N_i - \sum_{m \in M} n_i^m(t)) \right\} \quad (9-32)$$

where N_i is the maximum number of vehicles that can fit in cell i and $Q_i(t)$ is the maximum flow.

Equation (9-32) defines the total transition flows, which will now be defined specific to vehicle class. To avoid dividing by zero, assume $n_{i-1}(t) > 0$. (If $n_{i-1}(t) = 0$, there is no flow to propagate). As stated in Assumption 2, class-specific density is assumed to be uniformly distributed throughout the cell. Then class-specific transition flows are proportional to $\frac{n_{i-1}^m(t)}{n_{i-1}(t)}$:

$$y_i^m(t) = \frac{n_{i-1}^m(t)}{n_{i-1}(t)} \min \left\{ \sum_{m \in M} n_{i-1}^m(t), Q_i(t), \frac{w_i(t)}{u^f} (N - \sum_{m \in M} n_i^m(t)) \right\} \quad (9-33)$$

Equation (9-33) may be simplified to

$$y_i^m(t) = \min \left\{ n_{i-1}^m(t), \frac{n_{i-1}^m(t)}{n_{i-1}(t)} Q_i(t), \frac{n_{i-1}^m(t)}{n_{i-1}(t)} \frac{w_i(t)}{u^f} (N - \sum_{m \in M} n_i^m(t)) \right\} \quad (9-34)$$

which shows that flow of class m is restricted by three factors:

- 1) class-specific cell occupancy;
- 2) proportional share of the capacity; and
- 3) proportional share of congested flow.

In the general hydrodynamic theory, class proportions may vary arbitrarily with space and time, which includes the possibility of variations within a cell. Therefore, assuming uniformly distributed density results in the possibility of non-FIFO behavior within cells. One class may have a higher proportion at the end of the cell, and thus might be expected to comprise a higher proportion of the transition flow. However, as discussed by Blumberg & Bar-Gera (2009), even single class CTMs may violate the principle of first-in-first-out (FIFO). The numerical experiments in this paper use discretized flow to admit reservation-based intersection models. The discretized flow also allows vehicles within a cell to be contained within a FIFO queue, which ensures FIFO behavior at the cell level. Total transition flows for discrete vehicles are determined as stated above for continuous flow.

Consistency with Hydrodynamic Theory: As with Daganzo (1994) we show that these transition flows are consistent with the multi-class hydrodynamic theory defined in Section 9.3. We assume class-specific flow is proportional to density (i.e., $\frac{k_m}{k}$) and that all classes travel at the same speed. Also assume that $k > 0$, because, if $k = 0$, then flow is also 0 . Thus,

$$q_m(x, t) = \frac{k_m}{k} \min \left\{ u^f k, q^{\max} \left(\frac{k_1}{k}, \dots, \frac{k_{|M|}}{k} \right), w k \left(\frac{k_1}{k}, \dots, \frac{k_{|M|}}{k} \right) (k^{\text{jam}} - k) \right\} \quad (9-35)$$

Let dt be the time step and choose cell length such that $u^f \cdot dt = 1$. Then, cell length is 1, u^f is 1, $x = i$, $k^{\text{jam}} = N$, $q^{\max}(t) = Q(t)$, and $k(x, t) = n_i(t)$. Cell length is chosen so that flow may traverse at most one cell per time step to satisfy the Courant-Friedrichs-Lewy conditions (Courant et al., 1928).

$$q_m(x, t) = \frac{n_i^m(t)}{n_i(t)} \min \left\{ n_{i+1}(t), q_i^{\max}(t), \frac{w_i(t)}{v} (N - n_i(t)) \right\} = y_{i+1}^m(t) \quad (9-36)$$

(See Daganzo (1995) for more discussion on this issue.) Therefore $\frac{\partial q_m(x,t)}{\partial x} = y_{x+1}^m(t) - y_x^m(t)$. Since $\frac{\partial k_m(x,t)}{\partial t} = n_i^m(t+1) - n_i^m(t)$ is the rate of change in cell occupancy with respect to time, the conservation of flow equation $\frac{\partial q_m(x,t)}{\partial x} = \frac{\partial k_m(x,t)}{\partial t}$ is satisfied by the cell propagation function of equation (9-32).

Link Capacity and Backwards Wave Speed: We now present a car-following model based on kinematics to predict the speed-density relationship as a function of the reaction times of multiple vehicle classes. Car-following models can be divided into several types, as described by Brackstone et al. (1999) and Gartner et al. (2005). Some of these predict fluctuations in the acceleration behavior of an individual driver in response to the vehicle ahead. However, for DTA a simpler model is more appropriate to predict the speed of traffic at a macroscopic level. Newell (2002) greatly simplified car following to be consistent with the hydrodynamic theory, but the model does not include the effects of reaction time. Instead, the car-following model used here builds from the collision avoidance theory of Kometani & Sasaki (1900) to predict the allowed headway for a given speed, which varies with driver reaction time. The inverse relationship predicts speed as a function of the headway, which is determined by density. This car-following model results in the triangular fundamental diagram used by Newell (1993) and Yperman et al. (2005).

Although this car-following model is useful in predicting the effects of a heterogeneous vehicle composition on capacity and wave speed, other effects (such as roadway conditions) are not included. Furthermore, CTM assumes a trapezoidal fundamental diagram that enables a lower restriction on capacity. Therefore, the effect of reaction times on capacity and backwards wave speed are used to appropriately scale link characteristics for realistic city network models. Although AVs may be less affected by adverse roadway conditions than human drivers, this paper assumes similar effects for the purposes of developing a DTA model of shared roads. Other estimates of capacity and wave speed may also be included in the multi-class CTM model developed in Section 9.3.

Safe Following Distance: Suppose that vehicle **2** follows vehicle **1** at speed u with vehicle lengths ℓ . Vehicle **1** decelerates at a to a full stop starting at time $t = 0$, and vehicle 2 follows suit after a reaction time of Δt . The safe following distance, L , is determined by kinematics.

The position of vehicle 1 is given by

$$x_1(t) = \begin{cases} ut - \frac{1}{2}at^2 & t \leq \frac{u}{a} \\ \frac{u^2}{2a} & t > \frac{u}{a} \end{cases} \quad (9-37)$$

where $\frac{u}{a}$ is the time required to reach a full stop. For $t > \frac{u}{a}$, the position of vehicle 1 is constant after its full stop. The position of vehicle 2, including the following distance of L , is

$$x_2(t) = \begin{cases} ut - L & t \leq \Delta t \\ ut - \frac{1}{2}a(t - \Delta t)^2 - L & t > \Delta t \end{cases} \quad (9-38)$$

The difference is

$$x_1(t) - x_2(t) = \begin{cases} u - \frac{1}{2}at^2 + L & t \leq \Delta t \\ -at\Delta t + \frac{1}{2}a(\Delta t)^2 + L & \Delta t < t \leq \frac{u}{a} \\ \frac{u^2}{2a} - ut + \frac{1}{2}a(t - \Delta t)^2 + L & t > \frac{u}{a} \end{cases} \quad (9-39)$$

and the minimum distance occurs when both vehicles are stopped, at $\frac{u}{a} + \Delta t$. To avoid a collision,

$$L \geq -\frac{u^2}{2a} + u\left(\frac{u}{a} + \Delta t\right) - \frac{1}{2}a\left(\frac{u}{a}\right)^2 + \ell = u\Delta t + \ell \quad (9-40)$$

Flow-density Relationship

Long-term Effects: Table 9.3 shows the mode split for each VOT class before any CAVs and after full CAV availability, and Table 9.4 shows the mode costs per class. The values shown in Table 9.4 are the costs associated with a single user’s travel based on their mode choice. Total demand for any personal vehicle mode changed from 23,500 person trips to 47,676 trips, and with the shift to 39,592 CAV round-trips, the total number of trips made by personal vehicles increases to 87,275 an increase of 271%. Although many of these additional trips are traveling away from downtown, the network still experiences significant increases in link volume. However, average speed decreases are modest, as shown in Figure 9.4. This is encouraging because it suggests that the increases in demand are substantially offset by increases in capacity from CAVs.

Table 9.5 Comparison of Mode-Specific Demand Before and After CAV Availability

User Class	Trip Distribution without CAVs			Trip Distribution with CAVs		
	Park	Transit	Round-Trip	Park	Transit	Round-Trip
1	3.1%	96.9%	N/A for all Classes	1.4%	49.0%	49.6%
2	15.2%	84.8%		6.1%	33.0%	60.9%
3	41.4%	58.6%		15.1%	19.6%	65.4%
4	64.1%	35.9%		20.9%	12.0%	67.1%
5	78.9%	21.1%		24.3%	7.8%	67.8%
6	88.0%	12.0%		26.6%	5.3%	68.1%
7	92.3%	7.7%		27.8%	3.9%	68.2%

8	95.5%	4.5%		28.9%	2.8%	58.3%
9	97.3%	2.7%		29.6%	2.1%	68.3%
10	98.2%	1.8%		30.0%	1.7%	68.2%

Table 9.6 Comparison of Mode and User-Class-Specific Costs (in \$ [USD]) Before and After CAV Availability

User Class	Cost per User without CAVs			Cost per User with CAVs		
	Park	Transit	Round-Trip	Park	Transit	Round-Trip
1	5.9	2.0	\$2.7	6.1	2.0	0.6
2	6.1	3.9	2.6	6.3	3.8	0.8
3	6.2	5.7	2.6	6.6	5.5	1.0
4	6.3	7.7	2.7	6.9	7.3	1.2
5	6.5	9.6	2.7	7.2	9.1	1.4
6	6.6	11.7	2.7	7.6	11.1	1.7
7	6.8	13.4	2.7	7.8	12.6	1.9
8	6.9	15.4	2.7	8.2	14.6	2.1
9	7.0	17.5	2.7	8.5	16.5	2.3
10	7.2	19.1	2.7	8.7	18.0	2.5

Effects on Traffic Congestion: Equivalently, equation (9.40) may be expressed as

$$u \leq \frac{L-\ell}{\Delta t} \tag{9-41}$$

which restricts speed based on following distance (from density). Flow may be determined from the relationship $q = \left(\frac{L-\ell}{\Delta t}\right) k$ with $L = \frac{1}{k}$, which is linear with respect to density. Figure 9.5 shows the resulting relationship between flow and density for different reaction times for a characteristic vehicle of length 20 ft (6.1 m) that decelerates at 9 ft/s^2 (2.7 m/s^2) for a free-flow speed of 60 mi/hr (96.6 km/hr). Since speed is bounded by free-flow speed and available following distance, the triangular fundamental diagram is described by $= \min \left\{ u^f k, \left(\frac{L-\ell}{\Delta t}\right) k \right\}$. Reaction times of 1 to 1.5 seconds correspond to human drivers (1971).

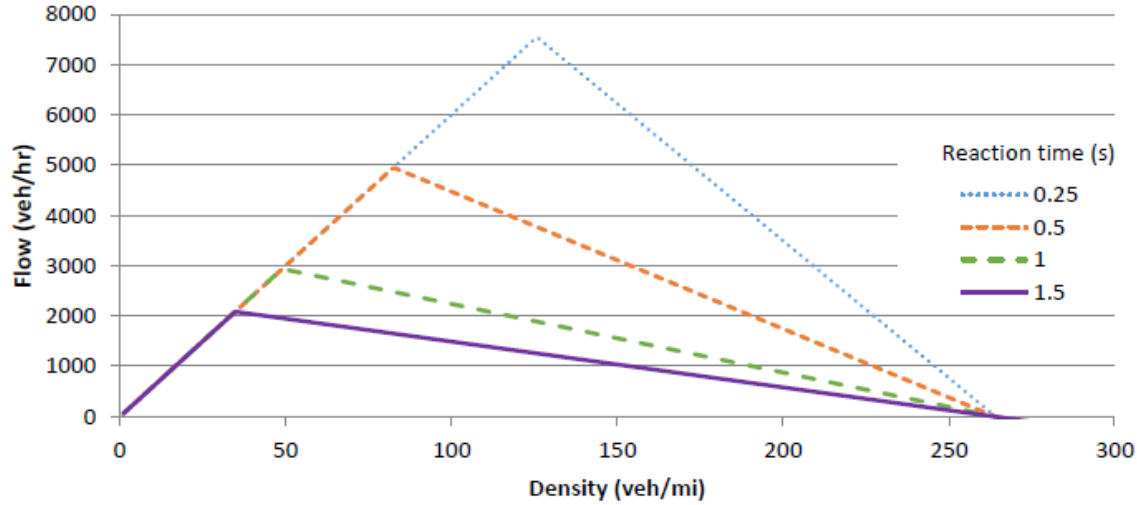


Figure 9.5 Flow-density Relationship as a Function of Reaction Time

The maximum density at which a speed of u is possible is $\frac{1}{u\Delta t + \ell}$ from equation (9-41), so capacity under free-flow speed (u^f) is

$$q^{\max} = u^f \frac{1}{u^f \Delta t + \ell} \quad (9-42)$$

And the backwards wave speed is:

$$w = -\frac{\frac{u^f}{u^f \Delta t + \ell}}{\frac{1}{u^f \Delta t + \ell} - \frac{1}{\ell}} = \frac{\ell}{\Delta t} \quad (9-43)$$

which increases as reaction time decreases. The direction of this relationship is consistent with micro-simulation results by Schakel et al. (2010). Note that if $\Delta t < \frac{\ell}{u^f}$, which may be possible for computer reaction times, then backwards wave speed exceeds free-flow speed. If $w > u^f$ for CTM, then the cell lengths would need to be derived from the backward wave speed, not the forward. That would complicate the cell transition flows. To avoid this issue, this paper assumes that $w \leq u^f$.

Flow for Heterogeneous Vehicles: The car-following model in the previous section is designed to estimate the capacity and backwards wave speed when the reaction time varies, but it is uniform across all vehicles. This section expands the model for heterogeneous flow with different vehicles having different reaction times. Let the density be disaggregated into k_m for each vehicle class m . Consider the case where speed is limited by density. Assuming that all vehicles travel at the same speed, for all vehicle classes,

$$u = \frac{L_m - \ell}{\Delta t_m} \quad (9-44)$$

where L_m is the headway allotted and Δt_m is the reaction time for vehicles of class m . Also, with appropriate units,

$$\sum_{m \in M} k_m L_m = 1 \quad (9-45)$$

is the total distance occupied by the vehicles. Thus

$$\sum_{m \in M} k_m (L_m - \ell) = 1 - k\ell \quad (9-46)$$

By equation (9-44),

$$\sum_{m \in M} k_m u \Delta t_m = 1 - k\ell \quad (9-47)$$

which results in

$$u = \frac{1 - k\ell}{\sum_{m \in M} k_m \Delta t_m} \quad (9-48)$$

Equation (9-47) may be rewritten as $u \sum_{m \in M} k_m \Delta t_m = 1 - k\ell$. Dividing both sides by k yields

$$u \sum_{m \in M} \frac{k_m}{k} \Delta t_m + \ell = \frac{1}{k} \quad (9-49)$$

Assuming that vehicle class proportions $\frac{k_m}{k}$ remain constant because all vehicles travel at the same speed, the maximum density for which a speed of u^f is possible is

$$k = \frac{1}{u^f \sum_{m \in M} \frac{k_m}{k} \Delta t_m + \ell} \quad (9-50)$$

which follows by taking the reciprocal of equation (9-49). Capacity is

$$q^{\max} = u^f \frac{1}{u^f \sum_{m \in M} \frac{k_m}{k} \Delta t_m + \ell} \quad (9-51)$$

Backwards wave speed is thus

$$W = - \frac{\frac{u^f}{u^f \sum_{m \in M} \frac{k_m}{k} \Delta t_m + \ell}}{\frac{1}{u^f \sum_{m \in M} \frac{k_m}{k} \Delta t_m + \ell} \frac{1}{\ell}} = \frac{\ell}{\sum_{m \in M} \frac{k_m}{k} \Delta t_m} \quad (9-52)$$

Equations (9-48) through (9-52) reduce to the previous model in the single vehicle class scenario. Figure 9.6 shows an example of how capacity and wave speed increase as the AV proportion increases when human drivers have a reaction time of 1 second and AVs have a reaction time of 0.5 second. The cases of 0% AVs and 100% AVs are identical to the 1-second reaction time and 0.5-second reaction time fundamental diagrams in Figure 9.5, respectively.

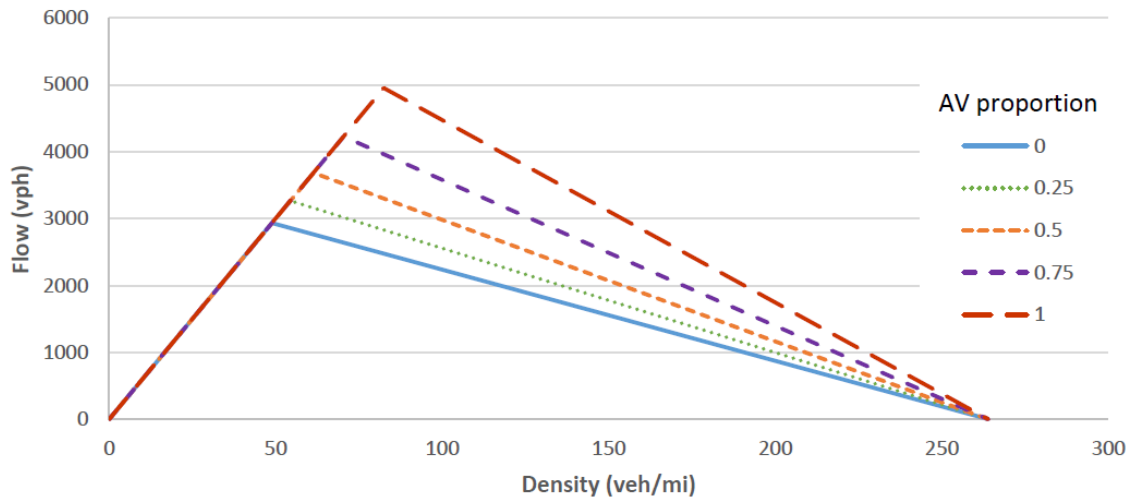


Figure 9.6 Flow-density Relationship as a Function of AV Proportion.

Other Factors Affecting Capacity: In reality, factors such as narrow lanes and road conditions affect capacity as well. These factors are usually in Highway Capacity Manual estimates of roadway capacity used for city network models. The model described above, however, does not include factors beyond speed limit. To

include these factors, we scale existing estimates on capacity and wave speed in accordance with equations (9-51) and (9-52). Although the model in Section 9.2 predicts a triangular fundamental diagram, as used by Newell (1993) and Yperman et al. (2005), other flow-density relationships are often used. CTM, the basis for multi-class DTA in this paper, uses a trapezoidal fundamental diagram.

Here, estimates of roadway capacity and wave speed are \hat{q}^{\max} and \hat{w} , respectively, and the reaction time for human drivers is Δt_{HV} . Human reaction times may vary depending on the location of the road; for instance, reaction times on rural roads are often longer than those in the city. Because capacity is affected by reaction time through equation (9-51), scaled capacity \tilde{q}^{\max} is

$$\tilde{q}^{\max} = \frac{u^f \Delta t_{HV} + \ell}{u^f \sum_{m \in M} \frac{k_m}{k} \Delta t_m + \ell} \hat{q}^{\max} \quad (9-53)$$

Similarly, wave speed is affected by reaction time through equation (10.52), so scaled wave speed \tilde{w} is

$$\tilde{w} = \frac{\Delta t_{HV}}{\sum_{m \in M} \frac{k_m}{k} \Delta t_m} \hat{w} \quad (9-54)$$

Equations (9-53) and (9-54) provide a method to integrate capacity and backwards wave speed scaling with other factors and realistic data.

Summary: Maturing AV technology suggests that AVs will be publicly available within the next few decades. To provide a framework for studying the effects of AVs on city networks, this section developed a shared road DTA model for human and autonomous vehicles. A multi-class CTM is presented for vehicles traveling at the same speed with capacity and backwards wave speed a function of class proportions. A collision avoidance car-following model incorporating vehicle reaction time is used to predict how reduced reaction times might increase capacity and backwards wave speed. These models are generalized to an arbitrary number of classes because different AVs may be certified for different reaction times. These models also use continuous flow so that SBDTA models built on continuous flows may incorporate these multi-class predictions.

Conflict Region Modeling

Tile-based reservation (TBR) intersection control for AVs has the potential to reduce intersection delays beyond optimized traffic signals. A major question in implementing reservations is the underdetermined problem of resolving conflicting reservation requests. Previous work studied prioritizing requests on a first-come-first-served (FCFS) basis or holding auctions at intersections, but there are many possibilities. Furthermore, although selfish routing behavior could affect the benefits of the reservation prioritization, reservation control has not been studied with user equilibrium routing due to its microsimulation definition. This chapter addresses these issues by presenting an integer program (IP) formulation of the conflict point simplification of reservations. The feasible region is transformed resulting in a more tractable IP on *conflict regions* for DTA. Because the IP may be NP-hard, we present a polynomial time heuristic. Finally, we demonstrate the potential utility of this heuristic by demonstrating objective functions that reduce congestion or energy consumption on a city network.

One major issue with TBR is the computational tractability of simulating vehicle movements through the grid of tiles. Smaller tiles result in greater intersection utilization but correspondingly greater computational requirements. TBR in its original form is therefore intractable for solving DTA. This issue has been addressed by two recent papers: Zhu and Ukkusuri (2015) and Levin and Boyles (2015). Zhu and Ukkusuri proposed a conflict point simplification, which focuses only on the intersections between turning movement paths in the grid of tiles. However, intersections with a large number of lanes and turning movements would have a correspondingly large number of conflict points, limiting the computational efficiency. Alternately, Levin and Boyles (2015) proposed to aggregate the tiles into larger *conflict regions* constrained by capacity. While effective for DTA, the justification for using conflict regions instead of tiles or conflict points was less clear. In addition, although the conflict region model admits an arbitrary priority function for resolving conflicts in reservation requests, the priority function does not directly correspond to an objective function for the intersection policy.

The work of Dresner and Stone (2004, 2006, 2005) on the TBR control used the advantages computers have over human drivers to improve utilization of intersection supply at the cost of greater complexity in vehicle-to-intersection communication and protocols. Experiments by Fajardo et al. (2011) on a variety of demand scenarios for a single intersection confirmed that TBR with the FCFS priority improves the level of service experienced by vehicles.

One major potential issue for TBR is that its communication complexity restricts usage by human drivers. Since it is likely that AVs will not be in exclusive use for many decades, extensions that allow humans to use reservation-based controls have been studied. Dresner and Stone (2006, 2007) proposed periodically providing a green light to specific lanes or links for human drivers. Qian et al. (2014) extended the reservation system to HVs and semi-AVs under certain assumptions about path and car-following behaviors, and Bento et al. (2013) proposed reserving larger sections of the intersection for HVs. Such interventions should be compatible with general TBR strategies by requiring occasional allowances for non-AVs. Therefore, this paper focuses on the scenario in which all vehicles are autonomous.

Optimizing TBR is further complicated by the effects of UE routing, which can produce system inefficiencies such as the well-known Braess paradox (1968). Network studies of TBR have been complicated by its computational requirements. Previous network models by Carlino et al. (2012) and Vasirani and Ossowski (2012) have not included traffic assignment, and in some cases were forced to reduce the number of tiles for computational tractability at the cost of intersection efficiency. Zhu and Ukkusuri (2015) developed a linear program for flow through the conflict point model, albeit with some further restrictions on conflicting flow. Levin and Boyles (2015) developed the conflict region model of TBR for SBDTA, which was shown to be tractable for solving SBDTA on large city networks. For a more general model of reservation-based intersection control, we combine the conflict point and conflict region approaches by developing a discrete vehicle-based integer program (IP) for the conflict point model and transforming its feasible region to achieve the conflict region model.

Derivation of the Conflict Region Model: This section presents an IP of the conflict point model in microsimulation. This IP models vehicles sequentially passing through conflict points while traversing their turning movements in continuous time. This section models vehicle movement similarly to the work on TBR.

- We transform the conflict point IP for microsimulation to a conflict point IP for DTA. This involves replacing continuous time with discrete time steps. As is typical with SBDTA, vehicles crossing the intersection are assumed to begin and complete their turning movement within one-time step. Therefore, we constrain conflict points by capacity rather than occupancy.
- The conflict region IP is presented by aggregating conflict points into conflict regions. Conflict points are constrained by capacity rather than occupancy for DTA. For computational tractability, we combine conflict points into larger conflict regions, which are also constrained by capacity.

Conflict Point Model for Microsimulation: The TBR control policy of Dresner and Stone (2004) operates on a grid of tiles in space-time. As noted by Zhu and Ukkusuri (2015), the tile conflict analysis of TBR may be simplified through the definition of conflict points. As illustrated in Figure 9.7, the paths for any two turning movements (i, j) and (i', j') first intersect at some point c . Ensuring adequate spacing at c for vehicles traveling from (i, j) and (i', j') will guarantee that no conflict occurs at c or anywhere in the intersection between vehicles moving from i to j and from i' to j' . For vehicles uniform in physical characteristics and acceleration behaviors, these conflict points are fixed. However, in terms of practical implementation, tiles may be required instead of conflict points to handle vehicles of different shapes and turning behaviors. Nevertheless, in many DTA models, physical uniformity of vehicles is assumed.

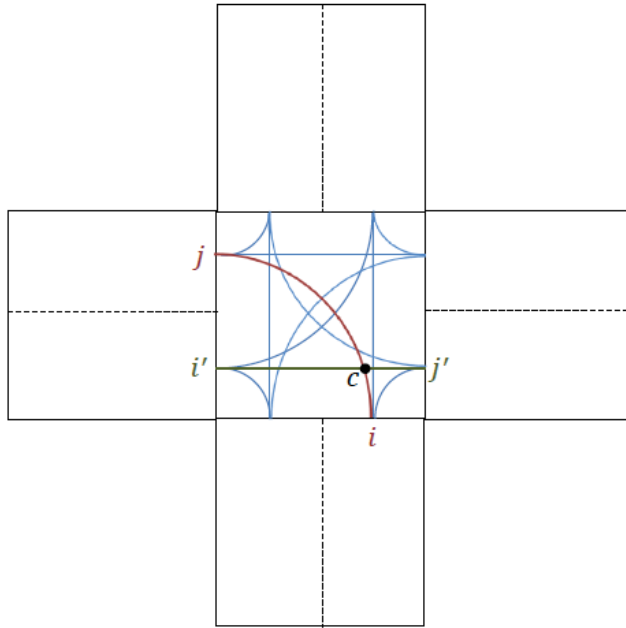


Figure 9.7 Illustration of Intersections Between Turning Movement Paths.

Previous work on TBR by Fajardo et al. (2011) studied tiles with width as small as 0.25 meters to improve intersection efficiency. Assuming 3-meter-wide lanes, the intersection in Figure 9.7 requires 676 such tiles in space. With 3 turning movements per link, and 4 links, there are a total of 12 paths through the intersection. In the worst case, in which each turning movement conflicts with all movements from other links, each turning movement has only 9 conflicts, for a total of 108 conflict points. In general, for a rectangular intersection with n lanes along the width and m lanes along the height, the number of tiles is $\Theta(nm)$. Assuming vehicles are not permitted to change lanes in the intersection, the number of turning movements is $O(n + m)$, and thus the number of conflict points is $O((n + m)^2)$. Therefore, the conflict point model may scale worse than the tile model. However, as demonstrated by the analysis of Figure 9.7, the conflict point model may be significantly more efficient for small intersections. The conflict point model also admits mathematical programming methods, as demonstrated by Zhu and Ukkusuri (2015).

Zhu and Ukkusuri (2015) assume that vehicles cannot simultaneously propagate through two conflicting lane movements. Depending on the magnitude of the time step, this may or may not be the most accurate assumption. For sufficiently large time steps allowing adequate spacing, two vehicles from conflicting turning movements should be able to traverse a single conflict point. This assumption is relaxed in the following IP formulation.

Let C_P be the set of conflict points. For any lanes i and j denote by π_{ij} the subset of C_P that vehicles traveling from i to j will pass through. The conflict point model is built on lane-specific turning movements because the intersection points may differ depending on which lanes vehicles are traveling between. Assume for this conflict point model that all vehicles enter the intersection at the same speed so that the travel time between conflict point c and the next point on path π is denoted τ_{π}^c . Although this is an unrealistic assumption for micro-simulation, it is sufficient for first-order SBDTA models (predicting speeds but not accelerations), which is the focus of this paper.

We present an original IP formulation for the conflict point model in microsimulation on a single intersection. In later sections it will be transformed to be used for a single DTA time step. Let S be the set of vehicles wanting to cross the intersection and S_i the subset of S departing lane i . For any vehicle v , denote by $\gamma^{-1}(v)$ the incoming lane for v , let $\theta(v)$ be the time v arrives at the intersection, let π_v be the path traversed by v , and let $t_v(c)$ be the time v crosses conflict point c . $t_v(c)$ are the decision variables for the intersection manager. We use t to denote continuous time decision variables and t for the discretized time in SBDTA. Let Γ^{-1} and Γ be the sets of incoming and outgoing lanes, respectively.

For any $c \in C_p$, let $\Delta\tau_c(i)$ be the required separation for other vehicles after a vehicle from lane i passes through c . The separation may depend on the directional orientation of the vehicle; a vehicle in the midst of a turn may cause greater separation requirements for following vehicles. Therefore, for any v, v', c with $c \in \pi_v$ and $c \in \pi_{v'}$, if $t_v(c) > t_{v'}(c)$ then $t_v(c) - t_{v'}(c) \geq \Delta\tau_c(\gamma^{-1}(v'))$. This is modeled by the ordering variable $\eta_{v,v'}^c \in \{0,1\}$ with $\eta_{v,v'}^c \leq 1 + \frac{t_v(c) - t_{v'}(c)}{M}$ and $\eta_{v,v'}^c \geq \frac{t_v(c) - t_{v'}(c)}{M}$, where M is a large positive constant. These constraints result in $\eta_{v,v'}^c = 1$ if and only if $t_v(c) > t_{v'}(c)$. Then separation is ensured by the constraint $t_v(c) - t_{v'}(c) \geq \Delta\tau_c(\gamma^{-1}(v'))$. Note that if two vehicles conflict at multiple points, separation need only be checked at the first conflict. However, this formulation is presented for analytical, not computational, purposes as a more efficient model will be derived later.

The model below also assumes that flow into outgoing lanes is restricted only by a conflict point at the start of the lane. As this is unrealistic, this is replaced by a receiving flow constraint to be compatible with general SBDTA models. The intersection reservations may then be modeled as the following IP:

$$\max \quad Z(\boldsymbol{t}) \quad (9-55)$$

$$\text{s.t.} \quad t_v(c) = t_v(c-1) + \tau_{\pi_v}^{c-1} \quad \forall v \in S, \forall c \in \pi_v \quad (9-56)$$

$$t_v(c) - t_{v'}(c) \geq \Delta\tau_c(\gamma^{-1}(v')) + M\eta_{v,v'}^c \quad \forall v \in S, \forall c \in \pi_v, \forall v' \in S: c \in \pi_{v'} \quad (9-57)$$

$$\eta_{v,v'}^c \leq 1 + \frac{t_v(c) - t_{v'}(c)}{M} \quad \forall v \in S, \forall c \in \pi_v, \forall v' \in S: c \in \pi_{v'} \quad (9-58)$$

$$\eta_{v,v'}^c \geq \frac{t_v(c) - t_{v'}(c)}{M} \quad \forall v \in S, \forall c \in \pi_v, \forall v' \in S: c \in \pi_{v'} \quad (9-59)$$

$$\eta_{v,v'}^c \in \{0,1\} \quad \forall v \in S, \forall c \in \pi_v, \forall v' \in S: c \in \pi_{v'} \quad (9-60)$$

$$\frac{t_v(0) - t_{v'}(0)}{\theta(v) - \theta(v')} \geq 0 \quad \forall v \in S, \forall v' \in S_{\gamma^{-1}(v)} \quad (9-61)$$

$$t_v(c) \geq 0 \quad \forall v \in S, \forall c \in \pi_v \quad (9-62)$$

where \boldsymbol{t} is the vector of $t_v(c)$ decision variables. Constraint (9-56) enforces travel time between conflict points, constraints (9-57) through (9-59) ensure separation, and constraint (9-61) enforces FIFO behavior for each lane: if $\theta(v) - \theta(v') > 0$, then $t_v(0) - t_{v'}(0) \geq 0$ as well in FIFO behavior. If, for all lanes i , and for all vehicles $v, v' \in S_i$, $\theta(v) = \theta(v') \Rightarrow v = v'$ then $\theta(v) = \theta(v') \neq 0$ admitting the constraint. The objective function Z is left unspecified for generality. Previous studies have considered FCFS policies, priority for emergency vehicles (2006), and intersection auctions (Schepperle et al. 2007 and 2008, Vasirani and Ossowski 2010, and Carlino et al. 2013). However, other strategies are worth consideration as well.

The above IP could potentially contain many variables because it is not restricted to a time interval, which could make it difficult to solve. We will now transform the feasible region to be solved within a single time step in SBDTA.

Conflict Point Model for DTA

This section transforms the IP formulated previously to be solved for individual time steps in SBDTA models. Let $x_v(t)$ denote whether vehicle v enters the intersection in time step t . $S(t)$, the set of vehicles that are waiting to enter the intersection in time step t , is the sending flow in time t . We assume that $S(t)$ includes vehicle order. $S_i(t)$ is the sending flow disaggregated by lane.

In most SBDTA models, vehicles are assumed to begin and complete turning movements within the same time step. Turning movements spanning multiple time steps are normally not considered. However, constraint (s.t. $t_v(c) = t_v(c-1) + \tau_{\pi_v}^{c-1} \quad \forall v \in S, \forall c \in \pi_v$ (9-56)) of conflict point arrival times could violate this assumption because vehicles entering the intersection late in one-time step would not be able to complete their turning movement within the same time step. Therefore, instead of constraining the arrival times of individual vehicles at conflict points, we constrain the total flow through each

conflict point during each time step. This is equivalent to a major difference between micro-simulation and DTA: in car-following models, vehicles decelerate to avoid colliding with the vehicle in front; in DTA, speed decreases as density increases to model vehicle deceleration to avoid collisions.

Constraints (9-57) through (9-60) on conflict point arrival spacing are not meaningful without constraint (9-56). Therefore, we transform conflict point spacing to a capacity-based restriction. Although this reduces the power of the model to prevent intersection conflicts, conflicting movements still constrain flow at an aggregate level consistent with SBDTA flow models. Let δ_v^c denote whether $c \in \pi_v$, and let Q_c be the capacity of conflict region c . Vehicles from $\gamma^{-1}(v)$ require a spacing headway of $\Delta\tau_c(\gamma^{-1}(v'))$ where $Q_c(i)$ is the capacity for vehicles from lane i moving through c . Then the separation constraint becomes $\sum_{v \in S(t)} x_v(t) \delta_v^c \frac{1}{Q_c(\gamma^{-1}(v))} \leq \Delta t$, where Δt is the simulation time step. This may be written as $\sum_{v \in S(t)} x_v(t) \delta_v^c \frac{Q_c}{Q_c(\gamma^{-1}(v))} \leq Q_c \Delta t$, which yields the capacity reduction in Levin and Boyles (2015). In addition, we add a receiving flow constraint for all lanes j : $\sum_{v \in S(t)} x_v(t) \delta_v^j \leq R_j(t)$, where δ_v^j denotes whether v enters lane j .

The FIFO constraint must also be transformed because SBDTA may not assign each vehicle a unique arrival time at the intersection. However, assume that SBDTA determines arrival order for discrete vehicles. Let $\tilde{S}_v(t) = \{v' \in S_{\gamma^{-1}(v)}(t) : \theta(v) > \theta(v')\}$ be the set of vehicles that arrived at the intersection before v . Then all $v' \in \tilde{S}_v(t)$ must move before v due to FIFO, which may be written as $x_v(t) \leq 1 - \frac{|\tilde{S}_v(t)| - \sum_{v' \in \tilde{S}_v(t)} x_{v'}(t)}{M}$. If $|\tilde{S}_{\gamma^{-1}(v)}(t)| - \sum_{v' \in \tilde{S}_v(t)} x_{v'}(t) > 0$ then at least one vehicle in front of v has not yet moved, and the lane is blocked for v .

The result of these transformations is the following IP. Note that this program is for every time step t , so t is assumed fixed.

$$\text{Max} \quad Z(\mathbf{x}(t)) \quad (9-63)$$

$$\text{s.t.} \quad \sum_{v \in S(t)} x_v(t) \delta_v^c \frac{1}{Q_c(\gamma^{-1}(v))} \leq \Delta t \quad \forall c \in C_p \quad (9-64)$$

$$\sum_{v \in S(t)} x_v(t) \delta_v^j \leq R_j(t) \quad \forall j \in \Gamma \quad (9-65)$$

$$x_v(t) \leq 1 - \frac{|\tilde{S}_v(t)| - \sum_{v' \in \tilde{S}_v(t)} x_{v'}(t)}{M} \quad \forall c \in C_p \quad (9-66)$$

$$x_v(t) \in \{0,1\} \quad \forall v \in S(t) \quad (9-67)$$

where $\mathbf{x}(t)$ is the vector formed by the decision variables $x_v(t)$.

Conflict Region Model: With the relaxation of the constraint on arrival time sequencing to capacity, conflict points may be combined in the model for computational efficiency. This could result in a capacity reduction due to modeling a conflict between two turning movements that do not intersect, but if all points in a sufficiently large conflict region are combined it is likely that the paths would have intersected at one of those points. With the aggregation of conflict points into conflict regions, denoted by the set C_R , lanes may similarly be aggregated into links. Thus, from this point forward, $\gamma^{-1}(v)$ and $\gamma(v)$ refer to the incoming and outgoing links for vehicle v , respectively. Denote by ℓ_i the number of lanes link i has. The number of lanes affects the FIFO constraint because vehicles cannot enter the intersection unless they are at the front of a lane. This results in the following IP:

$$\text{Max} \quad Z(\mathbf{x}(t)) \quad (9-68)$$

$$\text{s.t.} \quad \sum_{v \in S(t)} x_v(t) \delta_v^c \frac{Q_c}{Q_c(\gamma^{-1}(v))} \leq Q_c \Delta t \quad \forall c \in C_p \quad (9-69)$$

$$x_v(t) \leq 1 + \frac{\tilde{Q}_{\gamma^{-1}(v)} - 1}{M} \quad \forall v \in S(t) \quad (9-70)$$

$$\sum_{v \in S(t)} x_v(t) \delta_v^j \leq R_j(t) \quad \forall j \in \Gamma \quad (9-71)$$

$$x_v(t) \in \{0,1\} \quad \forall v \in S(t) \quad (9-72)$$

where

$$\tilde{Q}_{\gamma^{-1}(v)}(v) = \left(Q_i - \sum_{v \in \tilde{S}_v(t)} x_v(t) \right) \left(\frac{\ell_{\gamma^{-1}(v)} - (|\tilde{S}_v(t)| - \sum_{v' \in \tilde{S}_v(t)} x_{v'}(t))}{\ell_{\gamma^{-1}(v)}} \right) \quad (9-73)$$

Constraints (9-70) and (9-73) are the generalization of constraint (9-66) for multiple lanes. When a vehicle blocks a lane due to a rejected reservation, the capacity for vehicles behind is restricted. This is modeled by the function $\tilde{Q}_{\gamma^{-1}(v)}(v)$, which is the remaining capacity for v as a function of whether vehicles ahead of v moved through the intersection.

The number of lanes available for use for v is $\ell_{\gamma^{-1}(v)} - \left(|\tilde{S}_v(t)| - \sum_{v' \in \tilde{S}_v(t)} x_{v'}(t) \right)$. $Q_i - \sum_{v \in \tilde{S}_v(t)} x_v(t)$ is the remaining capacity of the link, which is reduced proportionally by the number of available lanes remaining. When $\tilde{Q}_{\gamma^{-1}(v)}(v) \geq 1$, then $x_v(t) = 1$ satisfies constraint (9-70). Note that $\tilde{Q}_{\gamma^{-1}(v)}(v) < 0$ is possible in a sufficiently large queue. If $\ell_{\gamma^{-1}(v)}$ or more vehicles in front of v have not moved, then $\tilde{Q}_{\gamma^{-1}(v)}(v) \leq 0$, and v cannot enter the intersection. Nevertheless, this IP always has a feasible solution:

Proposition 1. Let $\mathcal{X}(t)$ be the set of feasible solutions to the conflict region IP. Then $\mathcal{X}(t) \neq \emptyset$.

Proof. Consider $x(t) = 0$. $R_j(t) \geq 0$ and $Q_c \Delta t \geq 0$, so constraints (9-71) and (9-72) are satisfied. $1 + \frac{\tilde{Q}_{\gamma^{-1}(v)} - 1}{M} \geq 0$ so constraint (9-69) is satisfied. Therefore $0 \in \mathcal{X}(t)$.

Satisfaction of Requirements for DTA Intersection Models: As an intersection model for DTA, it is relevant to study the conflict region IP in equations (9-69) through (9-73) in the context of the requirements for generic DTA intersection models described by Tampère et al. (2011):

- 1) general applicability;
- 2) maximizing flows;
- 3) non-negativity;
- 4) conservation of vehicles;
- 5) satisfying demand and supply constraints; and
- 6) obeying conservation of turning fractions.

As stated, the conflict region IP satisfies all requirements except the invariance principle. We show that the algorithm of Levin and Boyles (2015), which satisfies the invariance principle, creates a feasible solution for the IP.

General applicability is challenging for the many possibilities of intersection geometries. However, Levin and Boyles (2015) proposed a radial division of the intersection into conflict regions, which specifies the set C_R and the indicator variables δ_v^c for all $v \in S$, $c \in C_R$. That radial division may be used for this IP.

For general applicability, we assume, as with Levin and Boyles (2015), that in the absence of other flow, flow between any $(i, j) \in \Gamma^{-1} \times \Gamma$ is constrained only by sending and receiving flows. Let Q_i be the capacity of link i ; if $Q_i = Q_j$, then flow of Q_i should saturate the conflict region. This can be satisfied by choosing $Q_c = \max_{(i,j) \in \Gamma^{-1} \times \Gamma: c \in \pi_{ij}} \{\min\{Q_i, Q_j\}\}$, where π_{ij} is the set of conflict regions flow from i to j will pass through. With $Q_c(\gamma^{-1}(v)) = Q_i$, then flow of $Q_i \Delta t$ through any conflict region c will result in equality on the constraint (9-69) because $\frac{Q_c}{Q_i} Q_i \Delta t = Q_c \Delta t$. Constraint (9-69) can then be written as

$$\sum_{v \in S(t)} x_v(t) \delta_v^c \frac{Q_c}{Q_{\gamma^{-1}(v)}} \leq Q_c \Delta t \quad \forall c \in C_R \quad (9-74)$$

Tampère et al. (2011) note that DTA intersection models should maximize flow as drivers will move whenever possible. In a reservation-based context, vehicles may be prevented from moving even if it is possible for them to move. However, it is reasonable to assume that many practical intersection strategies will allow a vehicle to move if its reservation request does not conflict with the reservation of another vehicle and the downstream link has sufficient space. To achieve this, the objective function in (9-70) should satisfy the following:

Property 1. For any $x(t) \in \mathcal{X}(t)$, if for all $v \in S(t)$ $x'_v(t) \geq x_v(t)$ and there exists a $v \in S(t)$ with $x'_v(t) > x_v(t)$, then $Z(x(t)) < Z(x'(t))$.

Objective functions satisfying Property 1 yield the desired characteristic of the solution to the conflict region IP:

Proposition 2. Let $x^*(t)$ be an optimal solution to the conflict region IP and let $Z(\cdot)$ satisfy Property 1. For any $v \in S(t)$, if $x_v^*(t) = 0$, form $x'(t)$ with $x'(t) = x^*(t)$ except with $x_v^*(t) = 1$. Then $x'(t)$ is not feasible.

Proof. Suppose $x'(t)$ is feasible. Since $Z(\cdot)$ satisfies Property 1, then $Z(x'(t)) < Z(x^*(t))$, which contradicts $x^*(t)$ being optimal.

Property 1 can be satisfied by $Z(x(t)) = \mathbf{z} \cdot \mathbf{x}(t)$ for some $\mathbf{z} > \mathbf{0}$ or more complex functions. It does not, however, require that the objective is to maximize flow. For instance, FCFS can be modeled through the conflict region IP.

Proposition 3. The FCFS policy may be modeled through the IP in equations (9-68) through (9-69). Specifically, there exists an objective function $Z(\cdot)$ satisfying the following: Let $\hat{\theta}(v)$ be the reservation time of v . If, for all $v_1, v_2 \in S(t)$, $v_1 \neq v_2 \Rightarrow \hat{\theta}(v_1) \neq \hat{\theta}(v_2)$ and $x^*(t)$ is chosen by FCFS, then for all $x \in \mathcal{X}$, $Z(x(t)) < Z(x^*(t))$.

Proof. By induction on $|S(t)|$. Sort $S(t)$ by reservation request so that for any indices i, j , if $i < j$ then $\hat{\theta}(v_i) < \hat{\theta}(v_j)$. Let t^* be the reservation time of the last vehicle, and let

$$Z(x(t)) = \sum_{i=1}^n M^{t^* - \hat{\theta}(v_i)} x_{v_i}(t) \quad (9-75)$$

be the objective function. (This satisfies Property 1). We show that $\sum_{i=1}^n M^{t^* - \hat{\theta}(v_i)} x_{v_i}^*(t) \geq \sum_{i=1}^n M^{t^* - \hat{\theta}(v_i)} x_{v_i}(t)$ for all $x(t) \in \mathcal{X}(t)$, for all $1 \leq n \leq |S|$.

Base case: If v_1 can move, then $\sum_{i=1}^1 M^{t^* - \hat{\theta}(v_i)} x_{v_i}^*(t) = M^{t^* - \hat{\theta}(v_1)}$ because FCFS prioritizes by request time, and $M^{t^* - \hat{\theta}(v_1)} \geq \sum_{i=1}^1 M^{t^* - \hat{\theta}(v_i)} x_{v_i}^*(t)$ for all $x(t)$. If v_1 is blocked, then $\sum_{i=1}^1 M^{t^* - \hat{\theta}(v_i)} x_{v_i}^*(t) = 0$ for all $x(t)$.

Inductive step: If $x_{v_{n+1}}^* = 1$ or $x_{v_i}^* = 0$ for all $1 \leq i \leq n+1$, then this holds trivially. The remaining case is that $x_{v_{n+1}}^* = 0$ because of higher priority vehicle(s) blocking its movement, i.e., if $x_{v_{n+1}} = 1$ then for some vehicle $i < n+1$, $x_{v_i} = 0$. Because $M^{t^* - \hat{\theta}(v_i)} > \sum_{v \in S_{\gamma^{-1}(v)}, t_v > t_{v_i}} M^{t^* - \hat{\theta}(v)}$, $\sum_{j=i}^{n+1} M^{t^* - \hat{\theta}(v_j)} x_{v_j}^* > \sum_{j=i}^{n+1} M^{t^* - \hat{\theta}(v_j)} x_{v_j}$.

Then by the inductive hypothesis, $\sum_{j=i}^{n+1} M^{t^* - \hat{\theta}(v_j)} x_{v_j}^* > \sum_{j=i}^n M^{t^* - \hat{\theta}(v_j)} x_{v_j}^*$.

Proposition 3 proves that the oft-studied FCFS policy falls within the general framework of the IP developed here. Setting $M = \Delta t$ should be sufficiently large, although that may still result in impractically large numbers due to the exponential. We prove in Proposition 6 that the polynomial-time algorithm of Levin and Boyles

(2015) can solve the IP with objective $(Z(x(t)) = \sum_{i=1}^n M^{t^* - \hat{\theta}(v_i)} x_{v_i}(t)$
(9-75).

Tampère et al. (2011)'s requirement of non-negativity is satisfied because $x(t) \geq 0$. Tracking discrete vehicles also satisfies conservation of flow and of turning fractions. Demand constraints are satisfied by the implicit definition of the set of sending flow, and supply constraints are explicitly satisfied by equation

$$(\tau_v(0) - \tau_{v'}(0)) \theta(v) - \theta(v') \geq 0 \quad \forall v \in S, \forall v' \in S_{\gamma^{-1}(v)} \quad (9-61)(9-76)$$

The remaining requirement is the invariance principle, which essentially states that the intersection flow should be invariant to the constraint on sending flow changing from the number of waiting vehicles to the link capacity. The invariance principle may not be satisfied for general objective functions, although it is for some objectives, including FCFS (1971). If $|S_i(t)| < Q_i$ changes to $|S'_i(t)| = Q_i$, if one $v \in S'_i - S_i$ has a very high weight in the objective function, the optimal solution to the conflict region IP may need to include v . The invariance principle can be satisfied by an additional constraint (2010), or as a corollary of alternate solution algorithms. For instance, the conflict region algorithm of Levin and Boyles (1971) satisfies the invariance principle. With a small change to better model FIFO constraints, shown in Algorithm [alg1], the conflict region algorithm finds a feasible solution to the conflict region IP. Specifically, $\tilde{\ell}_i$ tracks the number of lanes blocked. These are combined in line 20 to satisfy constraint (9-73)

Proposition 4. The conflict region algorithm (Algorithm 1) produces a feasible solution to the conflict region IP in equations (9-68) through (9-72).

Proof. For any $v \in S(t)$, let V' be the set of vehicles considered before v in the loop on line 7. If $x_v = 1$, then v can move from i to j according to line 8. Line 9 results in h_{ij} , being the number of vehicles in v' moving from i' to j' . This results in line 19 requiring that $R_j \geq 1 + \sum_{v' \in V'} \delta_{v'}^j x_{v'}(t)$, so constraint (9-71) is satisfied. For all conflict regions c that v passes through, line 21 requires that $Q_c \geq \frac{Q_c}{Q_i} + \sum_{v' \in V'} \delta_{v'}^j x_{v'} \frac{Q_c}{Q_{\gamma^{-1}(v)}}$, satisfying constraint (9-69). Constraints (9-70) and (9-73)—FIFO—are satisfied because vehicles either move through the intersection or block a lane (line 17). Blocked lanes detract from outflow (line 19) and vehicles are considered for movement in FIFO order. Finally, constraint (9-72) is satisfied because each vehicle is only considered once in the loop on line 6.

Algorithm 1 Conflict region algorithm

- 1: Set $V = \emptyset$
- 2: **for** all $i \in \Gamma^{-1}$ **do**
- 3: Sort $S_i(t)$ by arrival time at i
- 4: Remove first ℓ_i vehicles in $S_i(t)$ and add them to V
- 5: Set $\tilde{\ell}_i = 0$
- 6: **for** all $j \in \Gamma$ **do**
- 7: Set $y_{ij}(t) = 0$
- 8: **end for**
- 9: **end for**
- 10: Sort V by $f(v)$
- 11: **for** all $v \in V$ **do**
- 12: Let (i, j) be the turning movement of v
- 13: **if** $canMove(i, j)$ **then**
- 14: Set $y_{ij}(t) = y_{ij}(t) + 1$
- 15: **for** all $c \in C_{ij}$ **do**
- 16: Set $y_c(t) = y_c(t) + \frac{Q_c}{Q_i}$
- 17: **end for**

```

18:     Remove first vehicle in  $S_i(t)$  and add it to  $V$  in sorted order
19:     Set  $x_v(t) = 1$ 
20:   else
21:     Set  $x_v(t) = 0$ 
22:     Set  $\tilde{l}_i = \tilde{l}_i + 1$ 
23:   end if
24: end for
25:
26: function canMove( $i \in \Gamma^{-1}, j \in \Gamma$ )
27:   if  $R_j - \sum_{i' \in \Gamma^{-1}} y_{i'j} < 1$  or  $(Q_i - \sum_{j' \in \Gamma} y_{ij'}) \frac{\ell_i - \tilde{\ell}_i}{\ell_i} < 1$  then
28:     Return False
29:   end if
30:   for all  $c \in C_{ij}$  do
31:     if  $(Q_c - y_c(t)) < \frac{Q_c}{Q_i}$  then
32:       Return False
33:     end if
34:   end for
35:   Return True
36: end function

```

Proposition 5. The running time of the conflict region algorithm is $O(|S(t)| \log|S(t)| |C_R| + |\Gamma^{-1}| |\Gamma|)$.

Proof. Initialization of V (lines 1 through 9) iterates through each vehicle in $S(t)$. Sorting V (line 10) is therefore $O(|S(t)| \log|S(t)|)$. Initializing $y_{ij}(t)$ requires $O(|\Gamma^{-1}| |\Gamma|)$. Therefore initialization is $O(|S(t)| \log|S(t)| + |\Gamma^{-1}| |\Gamma|)$.

The main loop (lines 11 through 24) iterates through each vehicle at most once, scaling with $|S(t)|$. It may add vehicles to V in sorted order, requiring $O(\log|S(t)|)$ time to find the appropriate index. For each vehicle, the destination link and the conflict regions it passes through is checked once for conflicts in the *canMove()* subroutine, which is $O(|C_R|)$. If *canMove()* returns true, the flow through each conflict region is updated, also requiring $O(|C_R|)$. Therefore, the main loop is $O(|S(t)| \log|S(t)| |C_R|)$.

Although the conflict region algorithm produces a feasible solution in polynomial time, it may not be optimal. It takes as input some priority $f(\cdot)$ to each vehicle, and it moves the highest priority vehicle able to enter the intersection. It does not consider the value of moving a vehicle to allow vehicles behind to cross the intersection sooner. However, for specific objective functions, such as FCFS, the priority function will result in an optimal solution to the IP.

Proposition 6. The conflict region algorithm, using reservation time as the prioritization ($f(v) = \hat{\theta}(v)$), produces an optimal solution for the FCFS policy.

Proof. From Proposition 4, the solution created by the conflict region algorithm is feasible. Since vehicles can only request a reservation if they are not blocked from entering the intersection, for any two vehicles $v_1, v_2 \in S(t)$, $\theta(v_1) < \theta(v_2) \implies f(v_1) \leq f(v_2)$. Therefore, if $v_1 \in V$ and $v_2 \notin V$, then $f(v_1) \leq f(v_2)$. Once at the front of the intersection, reservations are ordered by $f(\cdot)$ for consideration. Therefore, if the reservation of v_1 is rejected, there must be some v_2 with $f(v_2) \leq f(v_1)$ blocking the movement of v_1 , which is the definition of FCFS.

Division of Intersection into Conflict Regions: A proper division of the intersection into conflict regions is vital to the proposed algorithm. Division into a grid of small tiles is more computationally demanding, and also requires more precise predictions of vehicle paths to determine which conflict regions are occupied.

Tampère et al. (2011) in particular noted the necessity of intersection models to be as independent as possible of specific intersection geometry due to the potentially high number of intersections in city networks. Division into tiles of high granularity, such as one tile at the intersection of every two lanes, requires lane-specific vehicle paths. At the other extreme, no division at all (i.e., the entire intersection is one conflict region) may not properly capture vehicle interactions between specific turning movements. Capacity may be incorrectly borrowed from other areas of the intersection.

We propose a *radial division* into conflict regions at incoming and outgoing links. This division does not require lane-specific turning movements but limits supply of specific areas of the intersection. This division can also be determined geometrically when link angles are known by the method below. Link angles can be determined through node coordinates, which are readily available from internet-based geographic information systems.

The radial division method divides a circle into conflict regions through radii along incoming and outgoing link angles. Therefore, any angle ϕ can be mapped to a conflict region; let $r(\phi)$ be this mapping. Let ϕ_i be the angle of directed link i . The path from $i \in \Gamma^{-1}$ to $j \in \Gamma$ is assumed to be composed of two lines. Starting and ending coordinates of are shifted to the right by ϵ (for countries in which vehicles travel on their right, or $-\epsilon$ for vehicles traveling on their left), so that the paths do not follow conflict region boundaries. This results in starting coordinate \mathbf{s}_i and ending coordinate \mathbf{s}_j defined by

$$\mathbf{s}_i = (\cos(\phi_i + \pi), \sin(\phi_i + \pi)) + \epsilon \left(\cos\left(\phi_i - \frac{\pi}{2}\right), \sin\left(\phi_i - \frac{\pi}{2}\right) \right) \quad (9-77)$$

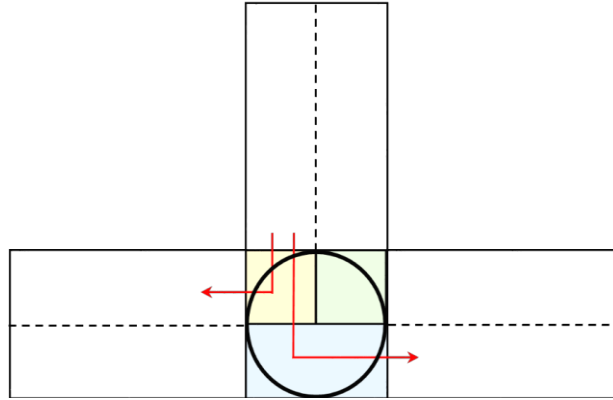


Figure 9.8 Illustration of Radial Division on a Three-Approach Intersection

The inner circle is divided by radii to the incoming and outgoing links.

$$\mathbf{s}_i = (\cos(\phi_i), \sin(\phi_i)) + \epsilon \left(\cos\left(\phi_i - \frac{\pi}{2}\right), \sin\left(\phi_i - \frac{\pi}{2}\right) \right) \quad (9-78)$$

where π in this context is the ratio of a circle's circumference to its diameter, not a path.

Paths are defined by the intersection of the lines $\mathbf{l}_i(\zeta_i) = \mathbf{s}_i + \zeta_i(\cos(\phi_i), \sin(\phi_i))$ and $\mathbf{l}_i(\zeta_j) = \mathbf{s}_j + \zeta_j(\cos(\phi_j), \sin(\phi_j))$.

All conflict regions crossed by the turning movement path (determined through angles to the center of the circle) are added to $(C_R)_{ij}$, the set of conflict regions used by vehicles traveling from i to j . Choose ζ_i^* and ζ_j^* such that $\mathbf{l}_i(\zeta_i^*) = \mathbf{l}_j(\zeta_j^*)$. Then

$$(C_R)_{ij} = \left\{ r\left(\tan^{-1}\left(\frac{s_2}{s_1}\right)\right) \mid (s_1, s_2) \in \{\mathbf{l}_i(\zeta) \mid 0 \leq \zeta \leq \zeta_i^*\} \cup \{\mathbf{l}_j(\zeta) \mid 0 \leq \zeta \leq \zeta_j^*\} \right\} \quad (9-79)$$

Although this path may not model the curves traced by real vehicles, such curves are unnecessary for this division because conflict regions are not lane-specific. Figure 9.8 demonstrates this method applied to a typical three-approach intersection.

Summary: This section developed and optimized a simplification of the TBR described by Dresner and Stone (2004) for autonomous vehicles. We first formulated an IP for the conflict point transformation of TBR proposed by Zhu and Ukkusuri (2015). After transforming the IP for use in SBDTA, the spacing constraints were found to naturally reduce to capacity limitations on each conflict point. For computational tractability on large networks, we aggregated conflict points into conflict regions, resulting in a model similar to that of Levin and Boyles (2015) formulated as an IP. This admits arbitrary objective functions and can therefore be used to optimize the order that vehicles cross the intersection for a more general class of policies. Since IPs in general are NP-hard, we derived theoretical results about the conflict region algorithm of Levin and Boyles (2015). It solves the IP for the FCFS objective and admits a polynomial-time greedy heuristic based on the MCKS problem for general objective functions.

9.4 Microsimulation Modeling

Team member Peter Stone has developed two open-source traffic simulation simulators for AVs: AIM, which provides highly detailed representations of small networks of intersections; and AORTA, which provides a more aggregate representation of a much larger (city-scale) network. Both accommodate mixed (traditional + CAV) traffic streams, traditional traffic control (signals), and reservation-based control for CAVs (who wish to reserve a safe path through the intersection without much delay).

The objectives for microsimulation modeling were defined as follows:

- **Semi-AVs:** Inclusion of new, transitional vehicle types. The transition from current technologies to CAVs will occur gradually (along with retrofitting and addition of smart devices on board conventional vehicles), with vehicles gaining increasing autonomy and connectivity. For instance, a vehicle may have the ability to autonomously follow the car in front of it by staying in its lane and maintaining a constant following distance while traveling between intersections, but they require a human driver to steer while turning through an intersection. We intend to adapt both AIM and AORTA to be able to model traffic that includes a mix of HVs, semi-AVs, and fully-AVs.
- **Extending intersection control to handle mixed technology levels:** In the case of vehicles that can follow autonomously, but not steer, such vehicles may be able to communicate with the intersection manager and obtain a reservation in more limited circumstances than a vehicle with higher autonomy. For the case of HVs, we aim to add traffic light signaling that will coexist with the autonomous intersection management, thus allowing communication with both human drivers and AVs. These settings will be coded into the existing software, allowing for a wide range of scenario analyses.
- As a first step in this research, we evaluated the appropriateness of both AIM and AORTA as simulations of mixtures of HVs, semi-AVs, and fully AVs. We found that the AIM simulator is well-suited to such an adaptation due to its prior modeling of both fully AVs and HVs. We therefore determined that it was feasible to implement a variety of hybrid types of semi-AVs and study a range of traffic mixtures as described below. On the other hand, we found that the AORTA simulator does not meaningfully distinguish between HVs and AVs, and we did not see a straightforward path to implementing the sort of studies proposed within AORTA. We therefore focused our subsequent research efforts associated with this entirely on the AIM simulator.

Autonomous Intersection Management

The objective of the original *Autonomous Intersection Management* (AIM) project was to create a scalable, safe, and efficient multiagent framework for managing AVs at intersections. AIM is designed for a time when all vehicles will be fully autonomous. The AIM protocol exploits the fine control of AVs to allow more vehicles simultaneously to cross an intersection, thus effectively reducing the delay of vehicles by orders of magnitude compared to traffic signals (2011).

In order to test the impact of the AIM protocol the AIM simulator was developed. The AIM simulator validated that by leveraging the control and network capabilities of AVs the AIM intersection control protocol is much more efficient compared to traditional traffic signals (2014).

Summary of Work: In order to achieve the above objectives with regards to AIM, the research focused on two main sub-objectives:

- SemiAIM Protocol:** We devised an enhanced version of the AIM protocol denoted SemiAIM. As opposed to the AIM protocol, the SemiAIM protocol can correspond with semi-AVs and HVs as well as fully AVs. Figure 9.9 summarizes the interaction model of the SemiAIM protocol between human drivers, driver agents (with AV or semi-AV capabilities), and the Intersection Manager (IM). We require the inclusion in the vehicle of a single button that signals the driver agent to ask for a reservation. After pressing the button, the driver agent will automatically send a request message to the IM on behalf of the human driver. It is also important that there is a clear Okay indicator (such as a green light) installed in the car that indicates when the request has been confirmed. After seeing the Okay signal, the driver would have to actively pass control to the driver agent, again by pressing a single button. This way the driver will not be surprised by any sudden autonomous actions of the vehicle. The driver’s involvement in this procedure depends on the level of autonomous capabilities installed in the car. The different classifications of autonomous capabilities are described in Table 9.5. SemiAIM only requires the human driver to perform relatively simple driving maneuvers such as holding the steering wheel at a certain angle (types SA-ACC and SA-CC vehicles) or driving as if under a traffic signal (type SA-Com vehicles). These tasks are much simpler than other maneuvers such as lane changing and passing other vehicles, and thus should not be taxing to experienced human drivers.
- SemiAIM Simulator:** In order to experiment with the SemiAIM protocol we developed the SemiAIM simulator. Based on the AIM simulator, SemiAIM is able to simulate semi-AVs and HVs as well as fully AVs. Using the SemiAIM simulator, we have performed experiments to test the efficiency of the SemiAIM protocol. We observed that (as expected) as the percentage of cars with autonomous capabilities increases then each vehicle suffers less delays.

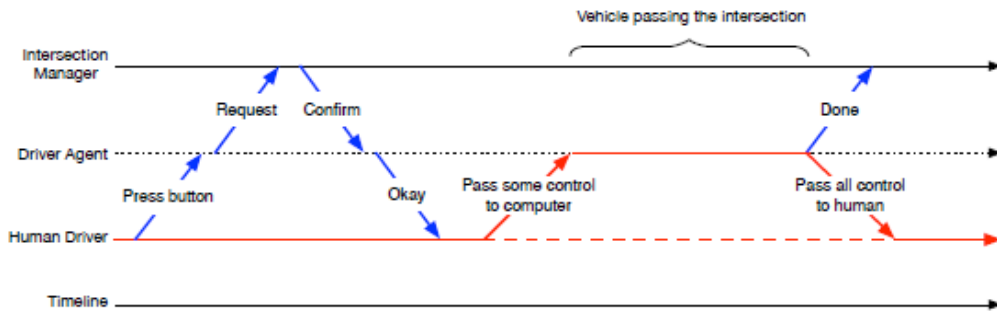


Figure 9.9 The Interaction between Human Drivers, Driver Agents, and the IM.

Note: The blue lines are message passing, and the red lines are transfer of control. Note that human drivers retain some control of the vehicle inside the intersection (the dashed red line).

Table 9.7 Semi-autonomous Vehicle Technologies

Vehicle Type	Communication Device	Cruise Control	Adaptive Cruise Control
SA-ACC	X	X	X
SA-CC	X	X	
SA-Com	X		

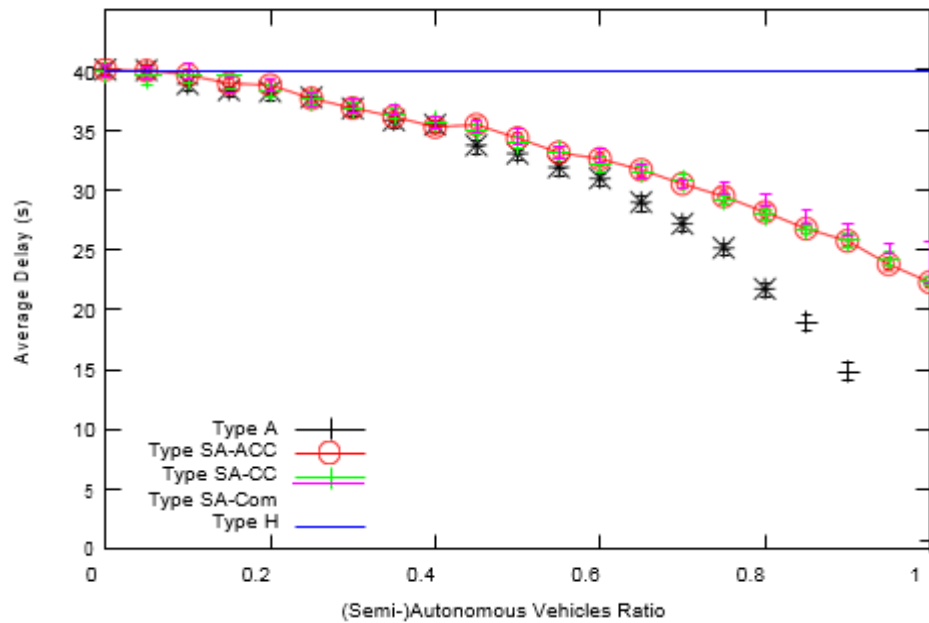


Figure 9.10 Average Delay (y -axis) vs. Different Ratio of Autonomous/Human Drivers (x -axis).

Note: Traffic level = 360 vehicles/lane/hour.

Dynamic Traffic Assignment Methodology

DTA models have become a widely accepted tool to support a variety of transportation network planning and operation decisions. The ability of these models to produce stable and meaningful solutions is crucial for practical applications, particularly for those involving the comparison of modeling results across multiple scenarios. DTA is particularly relevant for modeling AVs, due to their effects on many different time dependent variables. For instance, unlike fixed-phase traffic signals, reservation-based intersection efficiency is highly dependent on the demand at each approach and will vary over time. In addition, when mixed (AV and HVs) flows are considered, time-varying proportions of AVs on a road will result in the road capacity changing over time. This section describes the solution methodology used for solving DTA.

Two main processes are repeated multiple times during the solution of an SBDTA framework: the simulation of traffic conditions for a given assignment of vehicles to paths, and the search for new shortest paths based on the simulated traffic conditions. Both may involve significant computational effort, depending on the characteristics of specific SBDTA implementations. The computational efficiency of the analyzed techniques is not explicitly described, as it will highly depend on implementation-stage decisions that involve other components of a SBDTA model.

User Equilibrium in Simulation-Based DTA Models: The typical solution framework for SBDTA models seeks to attain UE conditions. UE is based on Wardrop (1952) and is related to equilibrium strategies of game theory. It refers to a state in which no traveler can improve his or her travel time by switching paths. For STA models with link performance functions, UE is typically found by solving a convex program. When the link performance functions are monotone increasing with link flow, the solution to the convex program is unique and exists. For SBDTA, travel times are determined by simulation, and travel times depend on departure time due to traffic congestion waves that evolve over time. Therefore, SBDTA solves for a modified UE state known as a dynamic user equilibrium (DUE), in which travelers only consider travel times of paths for their specific departure time. Furthermore, travel times are not well-behaved functions of link flows. Therefore,

proving that a DUE exists, or is unique, is not possible. In practice, though, many of the algorithms used for STA convergence have been shown to be effective for DTA.

To find UE, many STA models have relied on the MSA as described in Sheffi (1985), which has been shown to converge to the equilibrium solution in STA problems with well-behaved link-cost functions (Powell and Sheffi, 1982). The framework used for the static case may be easily extended to the solution of SBDTA problems. However, although MSA does not guarantee convergence for SBDTA due to the complex and discontinuous nature of link costs after accounting for traffic dynamics (Robbins and Monro, 1951), practical results indicate a convergence pattern.

Simulation: The simulation model of SBDTA is an approximation method to solving equations describing dynamic traffic flow, such as the kinematic wave theory (Lighthill and Whitham 1955; Richards 1956). The complexity has resulted in discrete solution methods such as the CTM (Daganzo 1994, Daganzo 1995) and the link transmission model (Yperman 2007). The models are solved by iterating through discrete time steps and updating flows accordingly. SBDTA can model continuous or discrete flow and does not introduce stochastic driver behavior. Given roadway parameters, flow route, and departure time choice, simulation output is deterministic. For the methodology of this task, the SBDTA for this task uses the multi-class CTM described above.

Solution Framework: In the context of DTA, MSA algorithms involve finding the time-dependent shortest paths under prevalent conditions and shifting a pre-determined fraction of vehicles to such routes. The fraction of vehicle set to be re-assigned, called the step size, decreases as the algorithm progresses, and is equal to $\frac{1}{n}$ (where n is the iteration number) for all ODTs.

SBDTA models are typically chosen for practical applications over their analytical counterparts, which are typically suitable only for the study of very small networks. Moreover, SBDTA models are appealing because they can realistically capture the impact of a variety of traffic control devices, network operation strategies, and time dependent changes in traffic conditions. Typical SBDTA frameworks include three main components: a traffic simulator, a path generator, and an assignment module. A traffic simulator is used to evaluate the network performance based on a specific assignment of vehicles to paths. The path generator uses simulation results to find the time-dependent least-cost path under prevalent conditions per OD pair and assignment interval tuple (ODT). The assignment module adjusts the allocation of vehicles to paths with the goal of attaining DUE. Assignment often follows an iterative approach based on updated travel times from the traffic simulator. Initially, a certain number of cars are prescribed for paths that have the least amount of travel time. The simulator runs and determines the travel times for each path. New paths are created by the path generator that perform better than the previous iteration and the assignment module, based on some predetermined method, takes a certain volume of vehicles from one path and places them in others. This process is visually represented in Figure 9.11.

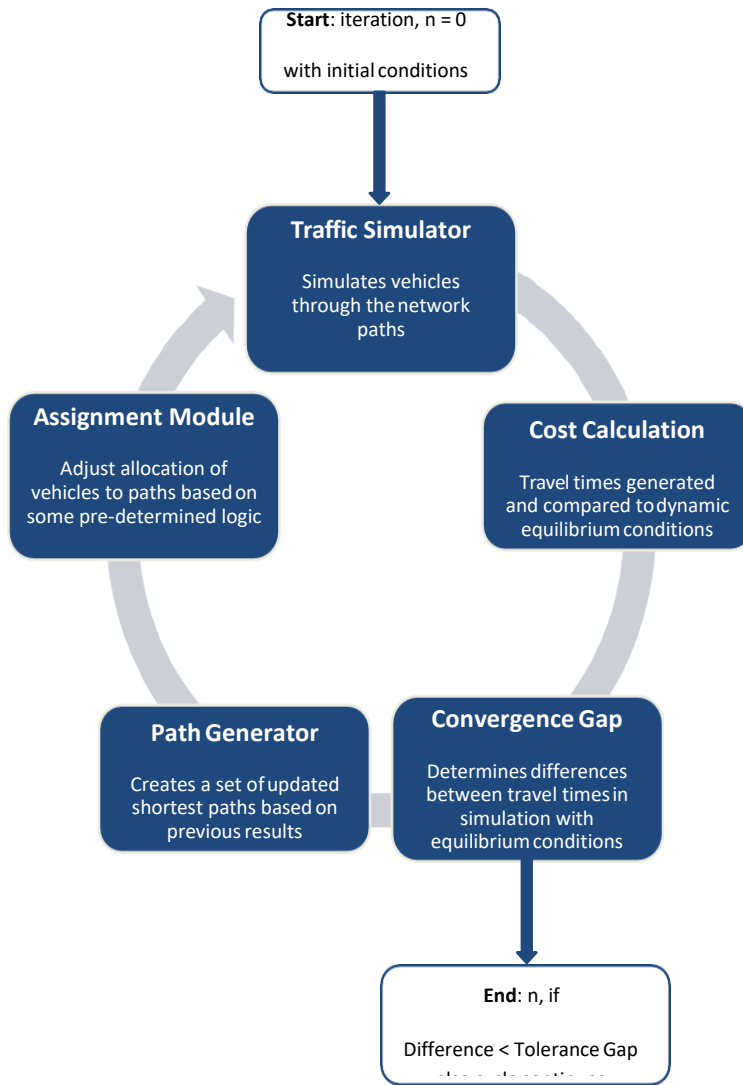


Figure 9.11 Process of SBDTA Framework

This process continues until the convergence criteria is met which is determined by equation (9-80). Convergence criteria are assessed and the assignment of vehicles to paths is adjusted based on some pre-defined logic. The process is repeated until an acceptable solution is found. In order to evaluate convergence, most SBDTA applications define a gap function that measures the proximity of a given solution to the equilibrium conditions. SBDTA models differ mostly in the type and refinement of the selected traffic simulator, and on the rationale behind the assignment adjustments.

$$\gamma(i) = \frac{\sum_{(r,s,t) \in Z^2 \times T} \sum_{\pi \in \Pi_{rs}} (c_t^\pi - c_{rst}) h_t^\pi}{\sum_{(r,s,t) \in Z^2 \times T} \sum_{\pi \in \Pi_{rs}} c_t^\pi h_t^\pi} \tag{9-80}$$

Test Networks Used for Link-Based Meso-Simulations

This section presents the test networks used in the multiclass CTM meso-simulation to model the effects of CAVs on congestion and different types of road networks. These networks included two arterial networks, three freeway networks, and one downtown city network. These networks are also among the top 100 congested roadways in Texas, which made them particularly interesting candidates for observing the effects of CAVs on congestion and traffic (TxDOT 2015).

Arterial Networks: Two arterial networks, including the intersection of Lamar and 38th Street as well as a strip of Congress Avenue, were used for simulations and are shown in Figure 9.12. The first arterial network, Lamar & 38th Street, contains the intersection between the Lamar & 38th Street arterials, as well as five other local road intersections. This network contains 31 links, 17 nodes, and 5 signals - with a total demand of 16,284 vehicles over a 4-hour time window. Congress Avenue in Austin was also studied. This network has a total of 25 signals in the network, 216 links, and 122 nodes with a total demand of 64,667 vehicles in a 4-hour period. These arterial networks used fixed-time signals for controlling flow along the entire corridor.

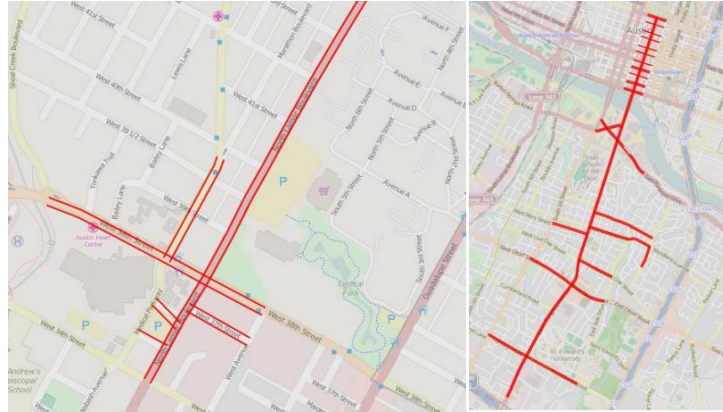


Figure 9.12 Lamar and 38th Street and Congress Avenue Networks (from left to right)

Freeway Networks: The three total freeway networks are shown in Figure 9.13. The first freeway network is the I-35 corridor in the Austin region, which includes 220 links and 220 nodes with a total demand of 128,051 vehicles within a 4-hour span. (Due to the length, the on- and off-ramps are difficult to see in the image.) All intersections are off-ramps or on-ramps. The I-35 network is by far the most congested of the freeway networks and one of the most congested freeways in all of Texas, especially in the Austin Region. The US-290 network in the Austin region was studied, with 97 links, 62 nodes, 5 signals, and a total demand of 11,098 vehicles within 4 hours. Finally, research was conducted on Texas State Highway Loop 1, also known as the MoPac Expressway after the Missouri Pacific Railroad that runs alongside the expressway, in the Austin region. This network contains 45 links, 36 nodes, and 4 signals with a total demand of 27,787 vehicles within 4 hours. On this network, there are a mixture of merging and diverging ramps and signals, which allows for some interesting analyses. This network was chosen due to the large number of signals around the freeway. All freeway networks are also among the 100 most congested roads in Texas (TxDOT 2015).

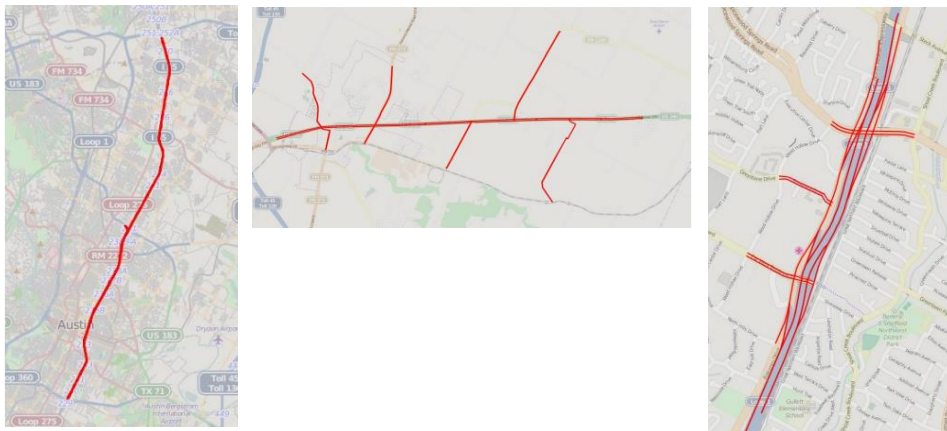


Figure 9.13 I 35, Hwy 290, and MoPac Networks (from left to right)

City Networks: The last network studied was the Austin downtown network (Figure 9.14), as this would be the largest network tested to show us the effects of TBR and CAVs as they apply to an entire downtown structure. Downtown Austin differs from the previous networks in that there are many route choices available.

Therefore, DTA was solved using the method of successive averages, a method that assigns vehicles to paths based on the iteration number in order to obtain an optimal system path for the vehicles. All scenarios were solved to a 2% gap, which was defined as the ratio of average excess cost to total system travel time. This gap was deemed sufficient to return the realistic results. Any decrease in the gap would incur larger amounts of computation time that would not alter the results significantly. Route choice admits issues such as the Braess and Daganzo paradoxes (1968, 1998), in which capacity improvements induce selfish route choice that increase travel times for all vehicles. The downtown network also contains both freeway and arterial links, with part of I-35 on the east side, a grid structure, and several major arterials.

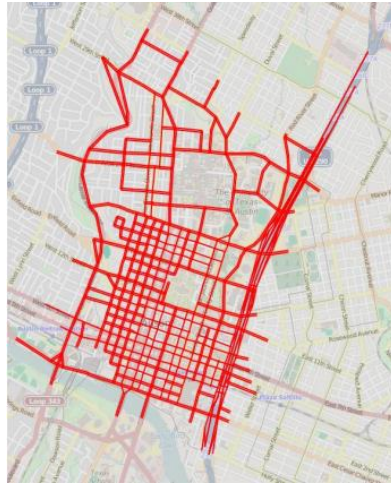


Figure 9.14 Downtown Austin Network

Effects of Autonomous Vehicles on Networks

This section presents results of the DTA simulation to analyze the effects of different proportions of CAVs on a network with human drivers. In addition, simulations were run with 100% CAVs using a TBR system on chosen test networks to see if there were travel time improvements in comparison with those of typical traffic signals. The results were analyzed by comparing travel times in vehicles/minute as well as the total travel time (TTT) of all vehicles in the network. The two main objectives of these simulations were to measure the effects on congestion of increasing the proportion of CAVs to HVs and of implementing a TBR system instead of a traditional signal system with 100% CAVs.

It is important to note that these simulations assume zero pedestrians and cyclists, along the routes and at intersections. Non-instrumented, non-motorized travelers using crosswalks will disrupt intersection operations and reduce vehicle flows. Both pedestrians and cyclists will probably not be able to use the tiles in TBR system, unless they wear special glasses (giving path and timing requests to them), they can be trusted to follow the guidance, and their slower speeds are accounted for.

In most simulations, perception reaction times of 0.5s and 1s were assumed for CAVs and HVs respectively, however, these times can be seen as something to be achieved farther into the future by autonomous vehicles whereas reaction times of 1s and 2s for CAVs and HVs respectively is a nearer and more achievable goal presently. Due to this ideology, several simulations were run using these 1s and 2s reaction times including the following networks: I-35, MoPac Expressway, Lamar & 38th Street, and Congress. After running simulations, it was observed that the slower perception reaction times showed the same trends and most of the time, nearly the same travel times with a few exceptions. For these reasons, only the previously listed four networks were simulated using the 1s and 2s reaction times. The purpose of these simulations involving analyzing effects of reaction times is to observe changes in road capacity as these reaction times can reduce following headways and backwards wave propagation. Capacities for HVs have been directly taken from models calibrated for VISTA.

CAV Effects on Arterial Networks: The travel time results for arterial networks are shown in Figure 9.15. The general trend for the arterial networks is that the use of the TBR reduced travel times. Although reservations helped most arterial networks, such as Congress Avenue, at high demands the reservations increased travel times for Lamar & 38th Street. The lower 0.5-second reaction time for CAVs, compared to the 1-second reaction time for HVs, decreased travel times for every network tested. The 1s and 2s reaction times also decreased travel times for every network tested and followed similar trends for traditional signal systems with CAVs. However, the slower perception reaction times decreased travel times under the TBR system more so than with the faster 0.5s and 1s reaction times. This is primarily because 1s and 2s reaction times results in a greater benefit from CAVs relative to HVs, compared with 0.5s and 1s reaction times. As the proportion of CAVs in the network was increased, the travel times decreased. Reduced reaction times were more beneficial in some scenarios than in others, but all yielded a benefit. The reaction time difference was analyzed by running simulations of each network at a moderate 85% demand and by changing the proportion of CAVs ranging from 0%-100%.

In the Lamar & 38th Street network, the TBR significantly decreased travel times for a 50% demand simulation as compared to traffic signals at 50% demand; however, once the demand was increased to 75%, reservations began increasing travel times relative to signals. This is most likely due to the close proximity of the local road intersections. On local road-arterial intersections, the FCFS reservations grant greater capacity to the local road than traffic signals. Because these intersections are so close together, reservations likely induced queue spillback on the arterial with the larger capacity. The longer travel times might also be linked by reservations removing signal progression on 38th Street. During high congestion, FCFS reservations tended to be less optimized than signals for the local road-arterial intersections. On the other hand, during low demand, intersection saturation was sufficiently low for reservations to reduce delays and travel times.

The Lamar & 38th Street network responded well to an increase in the proportion of CAVs with dramatic decreases in travel times, due to the CAV low reaction times. At 85% demand and at 25% CAVs, the TTT was reduced by 50%, and when all vehicles were CAVs, the TTT was reduced by 87%. Each demand proportion was then simulated with only CAVs. As demand increased, the improvements from reduced reaction times also increased. At 50% demand, reduced reaction times decreased travel times by 44%, whereas at 100% demand, reduced reaction times decreased travel times by 93%. The effect of greater capacity improved as demand increased because as demand increased, the network became more limited by intersection capacity. At low congestion (50% demand), signal delays hurt travel times because reservations made significant improvements. At higher congestion, intersection capacity was the major limitation and, therefore, reduced reaction times were of greater benefit.

Congress Avenue responded well to the introduction of reservations, showing decreases in travel times at all demand scenarios. These improvements are due to the large number of streets intersecting Congress Avenue, each with a signal not timed for progression. The switch to reservations therefore reduced the intersection delay. However, the switch to reservations could result in greater demand on this arterial in the future. Included in these simulations were the effects of route choice in the downtown Austin network.

CAVs also improved travel times and congestion due to reduced reaction times. At 85% demand, using reaction times of 0.5s and 1s for CAVs and HVs respectively, a 25% proportion of CAVs on roads decreased travel times by almost 60%. This increased to almost 70% reduction in travel time when all vehicles were CAVs. On Lamar & 38th Street, as demand increased, the reductions in travel times increased as well due to the CAV reaction times. For example, at a 50% demand level, the Lamar and 38th Street interchange experienced decreased travel time by about 10% when all vehicles were modeled as CAVs. The same network at 100% demand and assuming all vehicles are CAVs, reduced the travel time by nearly 82%. The reduced reaction times did not improve travel times as much as TBR, however - except for the 100% demand scenario. This indicates that at lower demands, high travel times were primarily caused by signal delay. However, travel time was still improved by lower CAV reaction times.

It is important to note that, except in the case of %100 CAVs with TBR, the reduced travel time and congestion is exclusively due to the reduced reaction time of 0.5s for CAVs, versus 1s for HVs, allowing for reduced following headway. Effectively, this allows for higher throughput for both links and intersections by increasing the maximum density of vehicles. This is an important assumption to the analysis, but it may not

be valid in the early stages of CAV adoption. While CAVs will experience reduced reaction times relative to HVs, it is likely that, either due to transportation norms, an abundance of caution on behalf of manufactures, or issues with integrating CAVs with HVs, CAVs will not realize reduced following headways until CAV adoption is quite high. If it is the case that CAVs do not realize reduced headways, then average travel times and congestion will not decrease due to the presence of increased numbers of trips brought about by the lower cost of travel for CAVs and the presence of CAV round-trips. Fundamentally, if CAV behavior mimics that of HVs, then using existing infrastructure and intersection management policies is unlikely to lead to lower average travel times or reduced congestion. However, the results presented here assume that CAVs can take full advantage of their reduced reaction times.

Overall, these results show consistent, significant improvements from reduced reaction times of CAVs at all demand scenarios. As shown in Figure 9.15, reducing the reaction time to 0.5 seconds nearly doubles road and intersection capacity. However, the effects of reservations were mixed. At low congestion, traffic signal delays had a greater effect on travel time, and in these scenarios, reservations improved the traffic flow. Reservations also improved the traffic flow when signals were not timed for progression (although this may be detrimental to the overall system). However, as seen on Lamar & 38th Street, during high demand, reservations performed worse than signals, particularly around local road-arterial intersections.

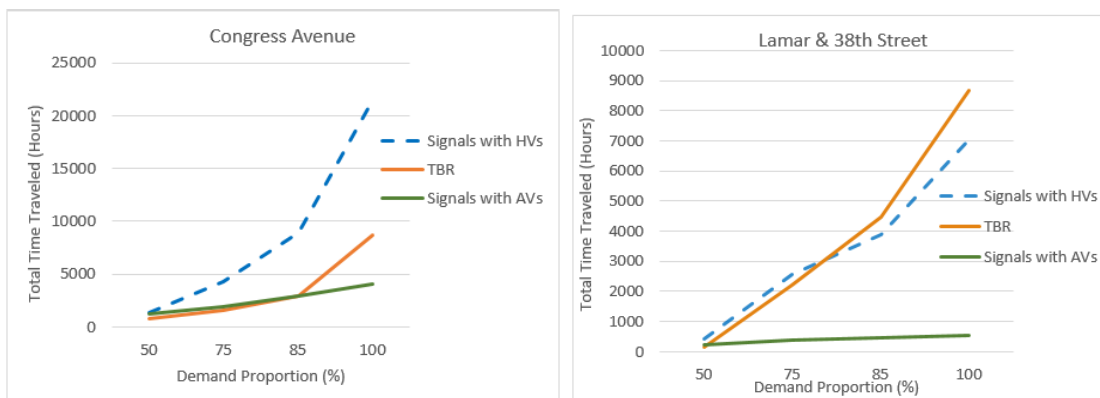


Figure 9.15 Arterial Network Travel Time Results for Lamar & 38th Street and Congress Avenue

CAV Effects on Freeway Networks: Results for the freeway networks are presented in Figure 9.16. Although there were some observed improvements in travel times for the US-290 network using reservations, the improvements were modest. On the other hand, observing the I-35 and MoPac networks, reservations made travel times worse for all demand scenarios. Most of the access on US-290 is controlled by signals, which explains the improvements observed when reservations were used there. Reservations seem to have worked more effectively with arterial networks, probably because on- and off-ramps do not have signal delays. Therefore, the potential for improvement from reservations is smaller.

Overall, greater capacity from CAVs' reduced reaction times improved travel times in all freeway networks tested, with better improvements at higher demands. Reduced reaction times improved travel times by almost 72% at 100% demand on I-35. On US-290 and I-35, as with the arterial networks, the improvement from CAV reaction times increased as demand increased. This is because freeways are primarily capacity restricted and the faster reaction times increase this capacity. On MoPac, reaction times had a smaller impact, but the network overall appeared to be less congested.

Links and nodes were chosen to study how reservations affected travel times at critical intersections or spans on the freeways, such as high demand on- or off-ramps. For these specific links, average link travel times were compared between 120 and 135 minutes into the simulation, at the peak of the demand. Researchers compared HVs, CAVs with signals, and different CAV proportions with signals at 85% demand, which resulted in moderate congestion. In the I-35 network, very few changes in travel times for the critical groups of links were observed from the different intersection controls.

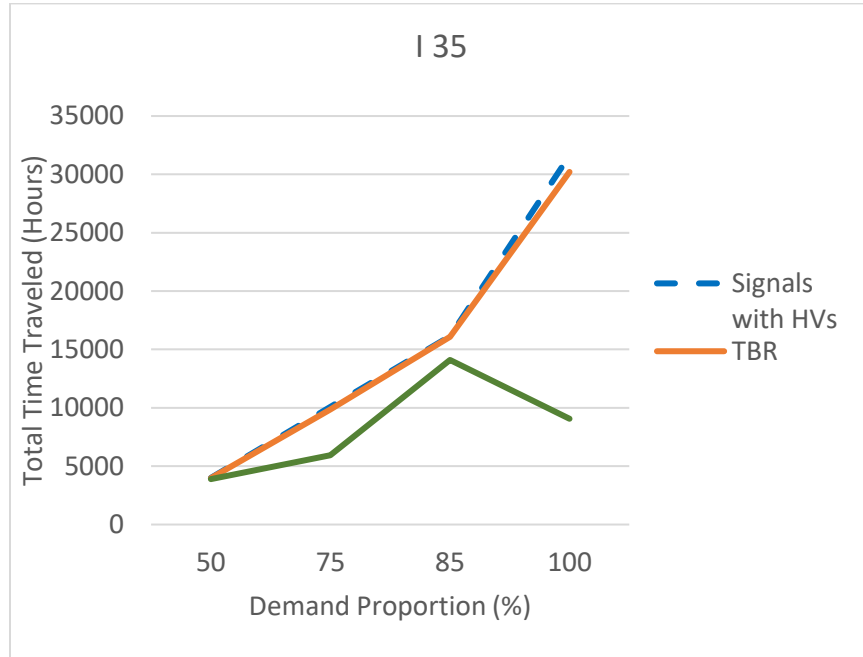


Figure 9.16 Freeway Network Travel Time Results for I-35

The differences appear greater in the US-290 corridor with more overall improvements in critical groupings of links near intersections. Interestingly, the largest improvements in travel times going from traffic signals to reservations occurred at queues for right turns onto the freeway. A possible explanation for this result is that making a right turn conflicts with less traffic than going straight or making a left turn. Although signals often combine right-turn and straight movements, reservations could combine turning movements in more flexible ways. Although larger improvements in travel times occurred at the observed right turns, improvements at left turns were also observed. Because US-290 has signals intermittently spaced throughout its span, vehicles are frequently stopping at lights causing signal delays, which can increase as the demand increases. Using the reservation system, the flow of traffic is stopped less frequently, if at all, reducing congestion along the freeway. Also, in the 290 network, analyzing the effects of reduced reaction times showed that improvements to travel times were made due to the reaction times and their respective capacity increases, but these improvements were less than those experienced due to reservations. It is also important to note that the use of 1s and 2s reaction times rather than 0.5s and 1s reaction times for the CAVs and HVs respectively did not affect travel times or any trends seen in the original reaction time simulations. In most cases, using reservations instead of signals doubled the improvements resulting from using CAVs. Reservations appear to have a positive effect on traffic flow and congestion in networks (freeway and arterial) that use signals to control intersections.

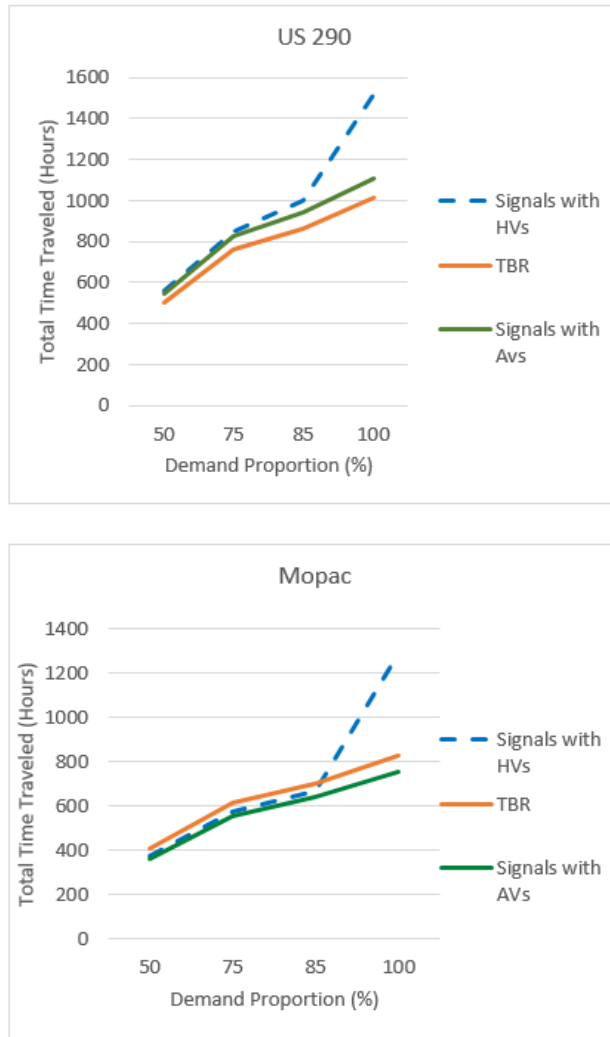


Figure 9.17 Freeway Network Travel Time Results for MoPac and US 290

CAV Effects on City Networks

Tests were performed on the downtown network of Austin with 100% demand at different proportions of CAVs in a traditional signal system, as well as with the TBR system, as shown in Table 9.8. Downtown Austin differs from the previous networks in that many route choices are available. Therefore, DTA was solved using the method of successive averages. All scenarios were solved to a 2% gap, which was defined as the ratio of average excess cost to total system travel time. Route choice admits issues such as the Braess and Daganzo paradoxes (1968, 1998), in which capacity improvements induce selfish route choice that increase travel times for all vehicles. The downtown network also contains both freeway and arterial links, with a section of I-35 on the east side, a grid structure, and several major arterials.

Reservations greatly helped travel times and congestion in the downtown network, cutting travel times by an additional 55% at 100% demand. When combined with reduced reaction times, the total reduction in travel time was 78%. Reservations were highly effective in downtown Austin—more effective than in the freeway or arterial networks, even under high congestion. In downtown Austin, most intersections are controlled by signals with significant potential for improvement from reservations. Although many intersections are close together, congested intersections might be avoided by dynamic user equilibrium route choice decisions, avoiding the issues seen with reservations in Lamar & 38th Street. The increased capacity from 100% CAVs also contributed to much less congestion, reducing travel times by around 51%.

Table 9.8 Downtown Austin City Network Travel Time Results

Downtown Austin				
Simulation Type	Demand	Proportion of CAVs	TTT (hr)	min/veh
Signals	100%	0	18040.2	17.23
Signals with CAVs	100%	0.25	13371.4	12.77
Signals with CAVs	100%	0.5	11522.3	11
Signals with CAVs	100%	0.75	9905.1	9.46
Signals with CAVs	100%	1	8824.7	8.43
TBR Reservation System	100%	1	3984.3	3.8

As mentioned earlier, all these simulations assume zero pedestrians and cyclists, along the routes and at the intersections. Non-instrumented, non-motorized travelers using crosswalks will disrupt intersection operations and reduce vehicle flows. Both pedestrians and cyclists will probably not be able to obtain a reservation within the TBR system, unless they wear special glasses (giving path and timing requests to them), they can be trusted to follow the guidance, and their slower speeds are accounted for.

9.5 Shared Autonomous Vehicles

Shared Autonomous Vehicle Framework

This section presents a general framework for dynamic simulation of SAVs to admit the latest developments in traffic flow modeling and SAV behavior. The framework is built on two events that can be integrated into most existing simulation-based traffic models. The purpose of this framework is to encourage future studies on SAVs to make use of existing traffic models for effective comparisons with current traffic conditions. As we will demonstrate in our case study, replacing personal vehicles with SAVs for the same number of travelers could increase congestion. To determine whether SAVs are beneficial, it is therefore necessary to compare SAV and personal vehicle scenarios in the same traffic model.

In this section, we discuss the key events defining this framework and the types of responses they warrant. However, the specific responses depend on the dispatcher logic, and for generality we do not require specific dispatcher behaviors. This framework is based on a traffic simulator operating on a *network* $G = (N, A, Z, V, D)$, where N is the set of nodes, A is the set of links, and $Z \subset N$ is the set of centroids. The network has a set of SAVs V that provide service to the demand D . Note that D is in terms of person trips, not vehicle trips, since travelers will be serviced by SAVs. The integration of the framework with the traffic simulator is illustrated through the simulator logic in Figure 9.18 with simulator time t and time step Δt . Events and responses are indicated with double lines; the remainder is the standard traffic simulator. The simulation steps are grouped into three modules:

- 1) demand;
- 2) SAV dispatcher; and
- 3) traffic flow simulator. The remainder of this section discusses these modules in greater detail.

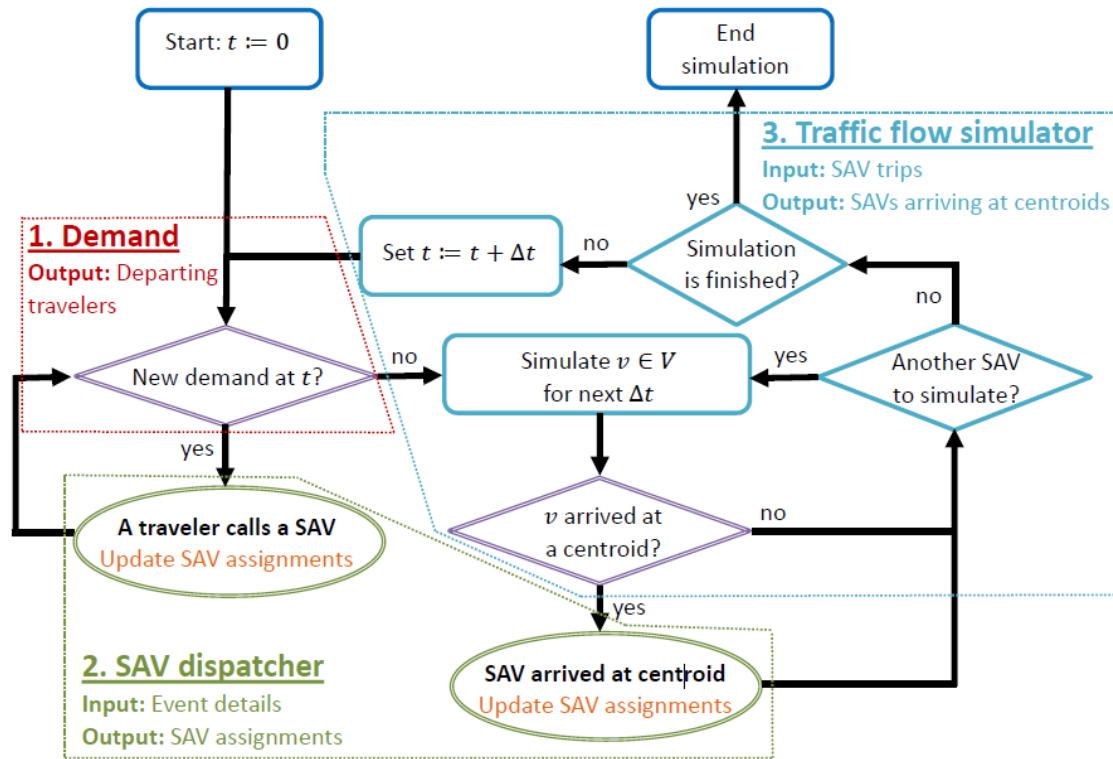


Figure 9.18 Event-based Framework Integrated into Traffic Simulator

Demand: The demand module introduces demand into the simulation and outputs the set of travelers that request an SAV at time t (This does not include waiting travelers). The demand module of existing traffic simulators may be adapted for this purpose, with the caveat that the demand is in the form of travelers, not personal vehicles. If new demand appears at t , this triggers the corresponding event: a traveler calls an SAV. Because SAV actions are triggered by a traveler calling an SAV, this framework admits a very general class of demand models. The major requirement is that demand must be separated into packets that spawn at a specific time with a specific origin and destination. Although in this paper we primarily refer to demand as individual travelers, these packets could also represent a group of people traveling together. Demand cannot be continuous over time because that would trigger a very large number of events. However, in our case study demand and traffic flow are simulated at a time step of 6 seconds, which is demonstrated to be computationally tractable for city networks.

As a result, this framework can handle both real-time and pre-simulation demand generation. Real-time demand may be randomly generated every simulation step, triggering the event of a traveler calling an SAV when the demand is created. For models with dynamic demand tables, each packet of demand spawns at its departure time and calls an SAV then. In addition, if demand is assumed to be known prior to its departure time, SAVs may choose to preemptively relocate before the traveler appears. However, this requires that travelers plan ahead to schedule an SAV before they depart. A less restrictive assumption is that the productions at each zone are known, and SAVs may preemptively relocate in response to expected travelers. This requires less specific information about the traveler, and trip productions are usually predicted by metropolitan planning organizations.

SAV Dispatcher: For this framework, we assume the existence of an SAV dispatcher that knows the status of all SAVs and can make route and passenger assignments. With the range of wireless communication available today, the existence of a central dispatcher is a reasonable assumption for SAVs. However, if desired the dispatcher logic could also be chosen to simulate individual SAVs making decisions on their own limited information.

The SAV dispatcher module determines SAV behavior, including trip and route choice, parking, and passenger service assignments. The dispatcher operates as an *event handler* responding to the events of a traveler calling an SAV or an SAV arriving at a centroid, and takes as input the event details. The dispatcher is responsible for ensuring that all active travelers are provided with SAV service.

The output of the dispatcher is the SAV behaviors in response to the event. These include SAV vehicle trips (which are passed to the traffic flow simulator), passenger pick-up and drop-off, and parking SAVs that are not needed. At any given time, each SAV is either parked at a centroid or traveling. If an SAV is parked, its exact location must be known.

This framework is event-based, meaning that SAV actions are assigned when one of the following events occurs:

- 1) A traveler calls an SAV.
- 2) An SAV arrives at a zone centroid.

The first event is triggered in response to demand departing (or requesting to depart), and the second is in response to an SAV completing its assigned trip. These can be implemented in most simulation-based frameworks. Instead of a traveler departing by creating a personal vehicle, the traveler calls an SAV. When an SAV completes travel on a path (which should end in a centroid), this also triggers an event so the simulator can check for arriving or departing passengers at that centroid and assign the SAV on its next trip.

A Traveler Calls an SAV: When a traveler $d \in D$ calls an SAV, the dispatcher should ensure that the demand will be satisfied by an SAV. This could occur in several ways:

- If an empty SAV $v \in V$ is parked at d 's origin, the dispatcher might assign v to immediately pick up d .
- If an empty SAV $v \in V$ is parked elsewhere, the dispatcher may assign v to travel to d 's origin. In this case, the dispatcher might choose to wait to optimize the movement of SAVs. For instance, Fagnant & Kockelman (2014) use a heuristic to move SAVs to a closer waiting traveler rather than the first waiting traveler. The dispatcher might also change the path of a traveling SAV to handle the demand.
- If an SAV $v \in V$ is inbound to d 's location, the dispatcher might assign v to service d if possible. However, the dispatcher should consider v 's estimated time of arrival (ETA). If v 's ETA results in unacceptable waiting time for d , the dispatcher may also send an empty SAV to d in order to reduce waiting time.

Regardless of the conditions chosen for each action, the dispatcher must ensure that the demand will be handled.

An SAV Arrives at a Centroid: When an SAV $v \in V$ arrives at a centroid $i \in Z$, it has finished its assigned trip. This should result in two types of actions. First, if v is carrying any travelers destined for i , they should exit v . Second, the dispatcher should assign v to park at i or depart on another trip. There are several possibilities for this assignment:

- If v still has passengers, it should continue to the next destination. If ride sharing is allowed and the capacity of v permits it, other passengers at i may wish to take v to reduce their waiting time.
- If v is empty, and a traveler $d \in D$ is waiting at i for an SAV, it is reasonable to assign v to accept d . v may then proceed directly to d 's destination or, if dynamic ride-sharing is allowed, to another centroid to pick up another passenger.
- If no travelers are waiting at i and v is empty, the dispatcher might assign v to pick up a traveler at a different centroid.

- The dispatcher could also assign v to wait at i until needed for future demand, contingent on parking availability. If i does not have available parking, v cannot wait at i and must travel elsewhere.

Finally, the dispatcher might assign v to preemptively relocate to handle predicted demand.

The conditions given above are reasonable but may not be necessary. Optimizing the assignment of actions for the existing and predicted demand could use the possible actions in different ways. For example, v might be assigned to park at i and wait for expected demand even if v is already carrying passengers. This optimization problem is similar to the class of vehicle routing problems, which are NP-hard. Therefore, solving this optimization is outside the scope of this paper, but we will study heuristic rules in later sections.

Traffic Flow Simulator: The traffic flow simulator takes as input SAV trips and their departure times and determines the arrival times of SAVs at centroids. The primary output of the simulator is to trigger the event that an SAV arrived at a centroid at the appropriate time.

Because the SAV framework is built on the events of a traveler calling an SAV, and an SAV arriving at a centroid, the framework admits many flow propagation models. The major requirement is that the model be integrated into simulation. After departing, an SAV travels along its assigned path until reaching the destination centroid, at which point it triggers the arrival event. Therefore, the framework must track the SAV travel times to determine arrival times, but its travel time may be evaluated by a variety of flow models. For instance, the travel time could be set as a constant or through link performance functions. Alternatively, SAV movement may be modeled through micro- or meso-simulation. Any uncertainty in the model is compatible with this framework; the SAV triggers the event only when it arrives at its destination. Note that this framework is compatible with other vehicles on the road affecting congestion through link performance functions or simulation-based flow propagation. Therefore, this SAV framework can be implemented with existing traffic models by modifying them to trigger demand and centroid arrival events. To demonstrate this flexibility, the case study implements this framework on the simulation-based DTA model of Levin & Boyles (2015).

Case Study: Framework Implementation

This section describes the implementation of the SAV framework on a CTM-based traffic simulator. Although we discussed how to implement SAVs in existing traffic simulators, the responses of the dispatcher to events were not specified for generality. The purpose of this section is to describe the specific traffic flow simulator and dispatcher logic used in our case study, including the heuristics for dynamic ride-sharing and preemptive relocation.

In this case study, we assume that all vehicles are SAVs: travelers do not have personal vehicles available. This setting was chosen in order to study the feasibility of switching to an entirely SAV-based travel model. Furthermore, a mix of SAVs and personal vehicles would complicate the route choice. Finding routes for personal vehicles would require solving DTA, and the many simulations needed to solve DTA would add computation time and complexity to the theoretical model.

Demand: For this case study, we converted personal vehicle trip tables into SAV traveler trip tables. These trips are discretized with specific departure times. Although some of these vehicle trips may encompass multiple person trips, that information was not available. Furthermore, multiple persons using the same vehicle would likely use the same SAV. Therefore, it would only affect situations in which SAV capacity was a limitation, such as dynamic ride-sharing.

For each trip, the demand module creates a traveler at the origin at the appropriate time. Although the demand is completely known in advance, the SAV dispatcher is not programmed to take advantage of demand information. The dispatcher only responds to demand when a traveler is created.

Traffic Flow Simulator: The traffic flow simulator uses the CTM (Zhang et al. 2015, Lighthill and Whitham 1995), which is a space and time discretization of the hydrodynamic theory of traffic flow (Powell and Sheffi 1982, Robbins and Monro 1951). CTM has been used in, and allows direct comparisons with, large-scale DTA simulators (Daganzo, 1995). Because all vehicles are SAVs, we assume that intersections were

controlled using the reservation-based protocol of Dresner & Stone (2004) for AVs. For computational tractability, we use the conflict region model of reservation-based intersection control proposed by Levin & Boyles (2015).

DTA models typically assume that route choice is based on driver experience. Each vehicle individually seeks its shortest route, resulting in a DUE in which no vehicle can improve travel cost by changing routes. Although this concept is based on the analytical STA models, it requires further study to be formulated for SAV behavior because SAV trips may depend on stochastic demand. Therefore, we use a dynamic network loading-based route assignment. Let π_{rs} be the path stored by the dispatcher for travel from r to s . When an SAV departs to travel from r to s , it is assigned to the stored path π_{rs} . During simulation, when $t \equiv 0 \pmod{\Delta\mathcal{T}}$, where $\Delta\mathcal{T}$ is the update interval, π_{rs} is updated to be the shortest path from r to s based on average link travel times over the interval $[t - \Delta\mathcal{T}, t)$. Our experiments use $\Delta\mathcal{T} = 1$ minute.

SAV Dispatcher

This section describes the specific logic used to assign SAVs in our case study. Although this is only a heuristic for the vehicle routing problem of servicing all travelers, vehicle routing problems in general are NP-hard and solving them in real time is unrealistic. Instead, we describe reasonable behaviors that SAVs could choose.

A Traveler Calls an SAV

When a traveler $d \in D$ calls an SAV at centroid $i \in Z$, we first check whether there are any SAVs already en-route to i . If an SAV en-route to i is free or will drop off its last passenger at i , and its ETA at i is less than 10 minutes away, we allow that SAV to service d . This is to reduce the congestion that would result from sending more SAVs. (As we demonstrate below, moving SAVs more frequently can result in a net travel time increase while decreasing waiting times due to congestion.) If there are multiple travelers waiting at i , we assume that travelers get SAVs in a FCFS order — with some exceptions for dynamic ride-sharing. Therefore, we look at the ETA of the SAV that would be assigned to d , if one exists.

Otherwise, we search for the parked SAV that is closest (in travel time) to i . If it could arrive sooner than the ETA of the appropriate en-route SAV, it is assigned to travel to i in order to provide service to d . This is a FCFS policy: the traveler that requests an SAV first will be the first to get picked up, even if the SAV could sooner reach a traveler departing later. Although Fagnant & Kockelman 2015 initially restricted SAV assignments to those within 5 minutes of travel to improve the system efficiency, FCFS is also a reasonable policy for dispatching SAVs. If all SAVs are busy, then d is added to the list of waiting travelers \mathcal{W} .

An SAV Arrives at a Centroid

If an SAV $v \in V$ is free after reaching centroid $i \in Z$ (either because v is empty, or because v drops off all passengers at i), and there are waiting travelers at i , then it is assigned to carry the longest waiting traveler. Note that v may not be the same SAV that was dispatched to that traveler. Due to stochasticity in the flow propagation model, it is possible that the order of arrival of SAVs may differ. However, there is no significant difference between two free SAVs in terms of carrying a single traveler. Therefore, we assign them to travelers in FCFS order.

If v still has passengers after reaching i (which is possible when dynamic ride-sharing is permitted), then v is assigned to travel to the next passenger's destination. However, travelers waiting at i have the option of entering v if it helps them in reaching their destination.

If v is free after reaching i and no demand is waiting at i , then v is dispatched to the longest-waiting traveler in \mathcal{W} . If multiple SAVs become free at the same time, the one closest to the longest-waiting traveler in \mathcal{W} will be sent. If \mathcal{W} is empty, then v will park at i until needed. We assume for this study that centroids have infinite parking space, as there are no personal vehicles in this network. However, it would be possible to model limited parking by assigning v to travel somewhere else if parking was not available at i .

Dynamic Ride-sharing: We also consider the possibility of dynamic ride-sharing. Following the principle of FCFS, we give precedence to the longest-waiting traveler. However, we allow other passengers to enter the SAV if they are traveling to the same, or a close destination. Specifically, suppose that the SAV $v \in V$ is initially empty, and the longest-waiting traveler at $i \in Z$ is d_0 , seeking to travel from i to $j \in Z$. If there is another traveler d_1 also seeking to travel from i to j , then d_1 may take the same SAV. If there is a traveler d_2 seeking to travel from i to $k \in Z$, and there is room in the SAV, d_2 may also take the same SAV if the additional travel time is sufficiently low. Let t_{ij} be the expected travel time from i to j . Then d_2 will take the SAV if $t_{ij} + t_{jk} \leq (1 + s)t_{ik}$. Otherwise, d_2 will wait at i . If d_2 decides to take the SAV, then any other waiting travelers at i also traveling from i to k may enter the SAV. Although this violates FCFS, this is permitted because it does not impose any additional travel time on the SAV.

This offer is extended, in FCFS order, for all travelers waiting at i until v is full. For instance, suppose a passenger d_3 departing after d_2 is traveling from i to $l \in Z$. Because of FCFS, v must service d_2 first, but if $t_{ij} + t_{jk} + t_{kl} \leq (1 + s)t_{il}$, then d_3 will still take SAV v from i .

The logic is slightly different when v arrives at i already carrying a passenger. In that case, precedence is given to all passengers already in v because they have been traveling. However, travelers in i may enter v — at the back of the queue — if the additional travel time is less than s of the direct travel time.

The problem of dynamic ride-sharing is a vehicle routing problem with all SAVs. In general, vehicle routing problems can admit solutions in which an SAV picks up several passengers before dropping any off. The heuristic in this case study does not do that due to complexity, although that behavior could certainly be implemented within this framework. In practice, due to the necessity of tractability when solving vehicle routing problems in real-time in response to demand, similar simple heuristics are likely to be used. Even with this restricted form of dynamic ride-sharing, the benefits over non-ride-sharing SAVs are significant, as shown below.

Preemptive Relocation: Preemptive relocation can reduce waiting times by starting to move SAVs to travelers' locations before they depart. Fagnant & Kockelman 2015 studied four strategies for preemptive relocation and found that the best performing heuristic distributed SAVs to each centroid according to the proportion of productions. Since productions are typically determined by a survey of land use, the total expected trip productions at any centroid is likely to be known even if specific traveler departure times are not. Formally, let \mathcal{P}_i be the productions and V_i the set of SAVs parked at $i \in Z$. The number of SAVs to be moved to i is

$$\Delta V_i = \frac{|V_i|}{|V|} - \frac{\mathcal{P}_i}{\sum_{i' \in Z} \mathcal{P}_{i'}}$$

If $\Delta V_i > 0$, ΔV_i SAVs are moved from i ; if $\Delta V_i < 0$, $-\Delta V_i$ SAVs are moved to i . Let $Z^+ = \{i \in Z | \Delta V_i > 0\}$ and $Z^- = \{i \in Z | \Delta V_i < 0\}$. Z^+ is sorted in decreasing order. For each $i \in Z^+$, ΔV_i SAVs from i are distributed to the nearest centroids (by travel time) in Z^- . This attempts to minimize the congestion caused by relocation.

Summary

This section presented an event-based framework for implementing SAV behavior in existing traffic simulation models. The framework relies on two events: travelers calling SAVs, and SAVs arriving at centroids, that are orthogonal to traffic flow models. This allows comparisons with personal vehicle scenarios through solving traffic assignment in the same simulator. We implemented this SAV framework within a cell transmission model-based dynamic traffic assignment simulator as well as heuristic approaches to preemptive relocation and dynamic ride-sharing.

Shared Autonomous Vehicle (SAV) Simulation Results

Many sets of experiments were undertaken to study how SAVs perform relative to personal vehicles, and how preemptive relocation and dynamic ride-sharing affect performance. Experiments were performed primarily

on the downtown Austin network. This is only a subnetwork of the larger Austin region, which has 1.2 million trips. This subnetwork was used because computation times were around 30–40 seconds per scenario on an Intel Xeon running at 3.33 GHz (with the SAV framework and CTM implemented in Java), allowing many scenarios to be studied. However, many trips bound for the downtown grid originate from outside the subnetwork region. They were approximated as arriving from one of the subnetwork boundaries. The data was provided by the Capital Area Metropolitan Planning Organization.

Initially, SAVs were distributed proportionally to zones based on the number of productions in each zone. The assumption is that all SAVs could be relocated overnight to fulfill these proportions at the start of the AM peak. This reallocation is different than preemptive relocation which is relocating SAVs during the AM peak, while travelers are requesting SAVs. Fagnant & Kockelman (2014) used a seeding run to determine the number of SAVs necessary to service all travelers. Instead of a seeding run, a sensitivity analysis was performed to study how increasing numbers of SAVs affected travel time. A seeding run may have biased the number of SAVs to be lower. In some scenarios (such as dynamic ride-sharing) it was observed that lower numbers of SAVs performed better due to lower congestion. However, in other scenarios, higher numbers of SAVs improved service. The following charts contain experiments using between 4,000 and 40,000 SAVs, with increments of 500. For some scenarios, the range was reduced to the number of SAVs that could provide service to all travelers within 6 hours, because service was limited by having too few SAVs or too much congestion.

Personal Vehicles

First, to create a base scenario, DTA was solved on downtown Austin, assuming that all travelers use privately owned CAVs for their trips. Although SAVs use a dynamic network loading-style route choice, the DTA model assumed drivers based their routes on past experience to find a dynamic user equilibrium. Therefore, the routing strategy in DTA is likely more efficient than the routing strategy for SAVs. Overall, when using personal vehicles with traffic signals, travelers experienced an average travel time of 15 minutes. When signals were replaced with reservation controls, average travel times were reduced to 7 minutes. Since the adoption of reservation controls may be difficult or inefficient if a significant proportion of personal vehicles are not autonomous, both DTA scenarios may be reasonable for comparison against SAVs. The assumption made here was that if SAVs were to replace all personal vehicles, reservation controls would be used.

Shared Autonomous Vehicles:

The initial SAV scenario did not include preemptive relocation or dynamic ride-sharing. Figure 9.19 shows travel time results with 28,500 to 40,000 total SAVs available. (Lower numbers of SAVs were found to be insufficient to service all travelers after 6 hours.) As the number of SAVs increased, waiting time decreased linearly. Vehicle miles traveled (VMT) and empty VMT—miles traveled while not carrying any passengers—decreased at the same rate as the number of SAVs increased (Figure 9.19). This indicates that the difference was primarily due to fewer repositioning trips to pick up the next traveler. It is intuitive that as the number of SAVs increased, the average distance between a waiting traveler and the closest available SAV would decrease. Overall travel times in this base SAV scenario were much higher than with personal vehicles. In-vehicle travel time, interestingly, decreased for around 31,000 to 32,000 SAVs, then remained nearly constant thereafter. This may be due to a reduction in congestion when SAVs were traveling less for repositioning trips. In-vehicle travel times of 33–35 minutes, however, are double that of DTA with signals, and five times that of DTA with CAVs. Previous studies predicted that each SAV can service multiple travelers with acceptable waiting times—that is still true in these experiments, but the travel times experienced are more similar to those of public transit. Travelers may be unwilling to use SAVs if the travel times are this high.

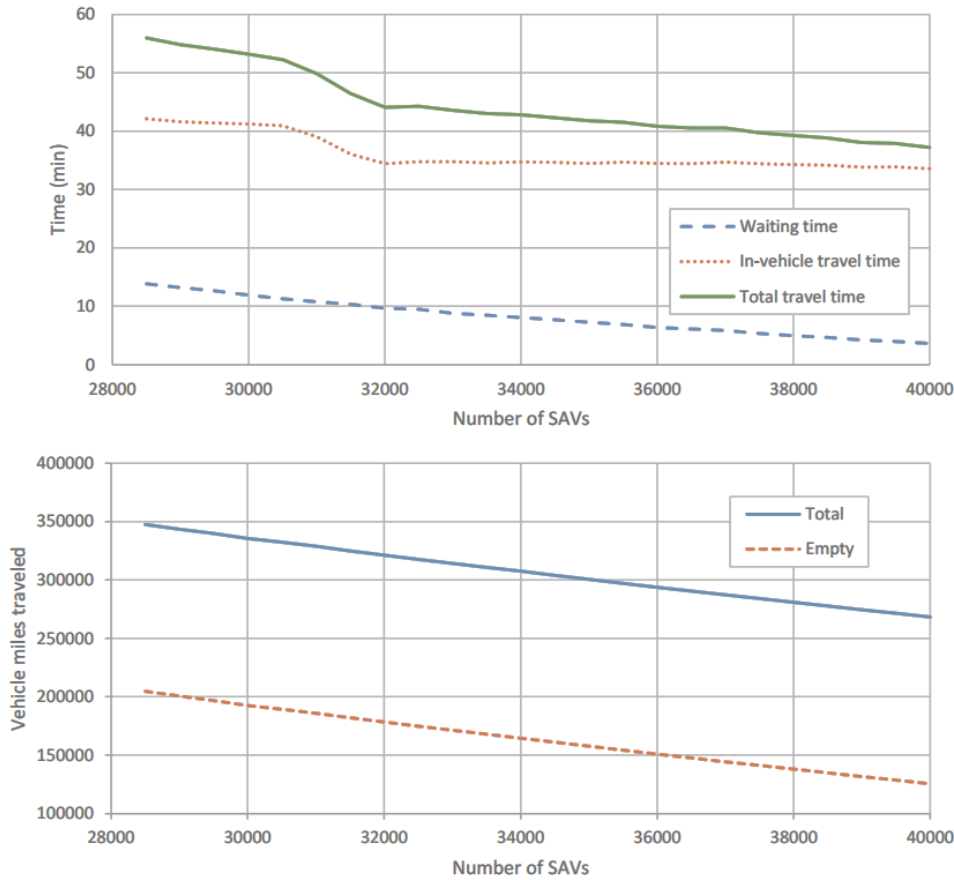


Figure 9.19 Travel Time and VMT for the Base SAV Scenario

The difference in travel time is most likely due to additional congestion from empty repositioning trips made to pick up the next traveler. The downtown Austin network is already fairly congested during the AM peak, and the addition of repositioning trips makes matters worse. This is an important result, however, because it demonstrates the value in using a realistic traffic flow model for analyzing congestion. For less congested networks, SAVs might cause only modest increases in congestion. However, for a high-traffic city in the AM peak, these results are not encouraging for a switch to SAVs.

Preemptive Relocation

Next, the effects of preemptively relocating SAVs to match the proportion of productions of each centroid was studied. This resulted in very high waiting times with few SAVs available. This is likely due to the fairness of assigning SAVs: travelers are prioritized by the time spent waiting. Unless a traveler was waiting at the destination of the relocating SAV, it would be re-assigned to service a different traveler, which is likely why the waiting time was so high when few SAVs were available. Although this is a reasonable policy, alternatives such as that of Fagnant and Kockelman (2015b), in which travelers are prioritized according to distance from the available SAV, could improve average waiting time.

As the number of SAVs increased, waiting time decreased linearly, although it was still much higher than the base scenario. One potential reason is the additional congestion resulting from relocating SAVs. This is illustrated by the much higher empty VMT resulting from relocations, shown in Figure 9.20. Relocating resulted in around 400,000 vehicle miles of empty travel. This did not decrease as the number of SAVs increased, as it did in the base scenario, which likely contributed to the increasing in-vehicle travel times. The in-vehicle travel time increased linearly with the number of SAVs, which is indicative of those additional SAVs contributing significantly to congestion. In fact, beyond 20,500 SAVs, congestion prevented effective

service for all travelers. Although waiting time decreased, the increases in travel time resulted in only small decreases in TTT.

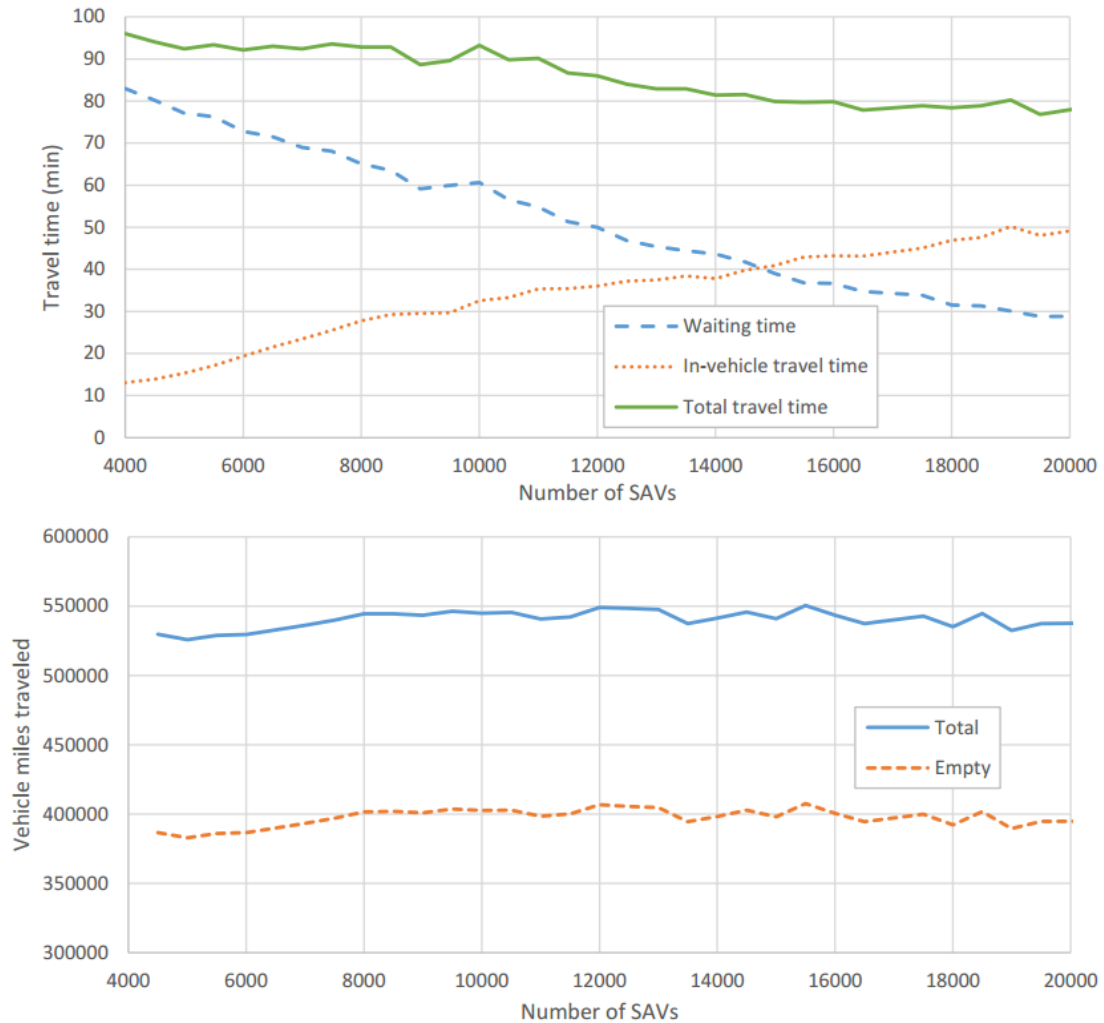


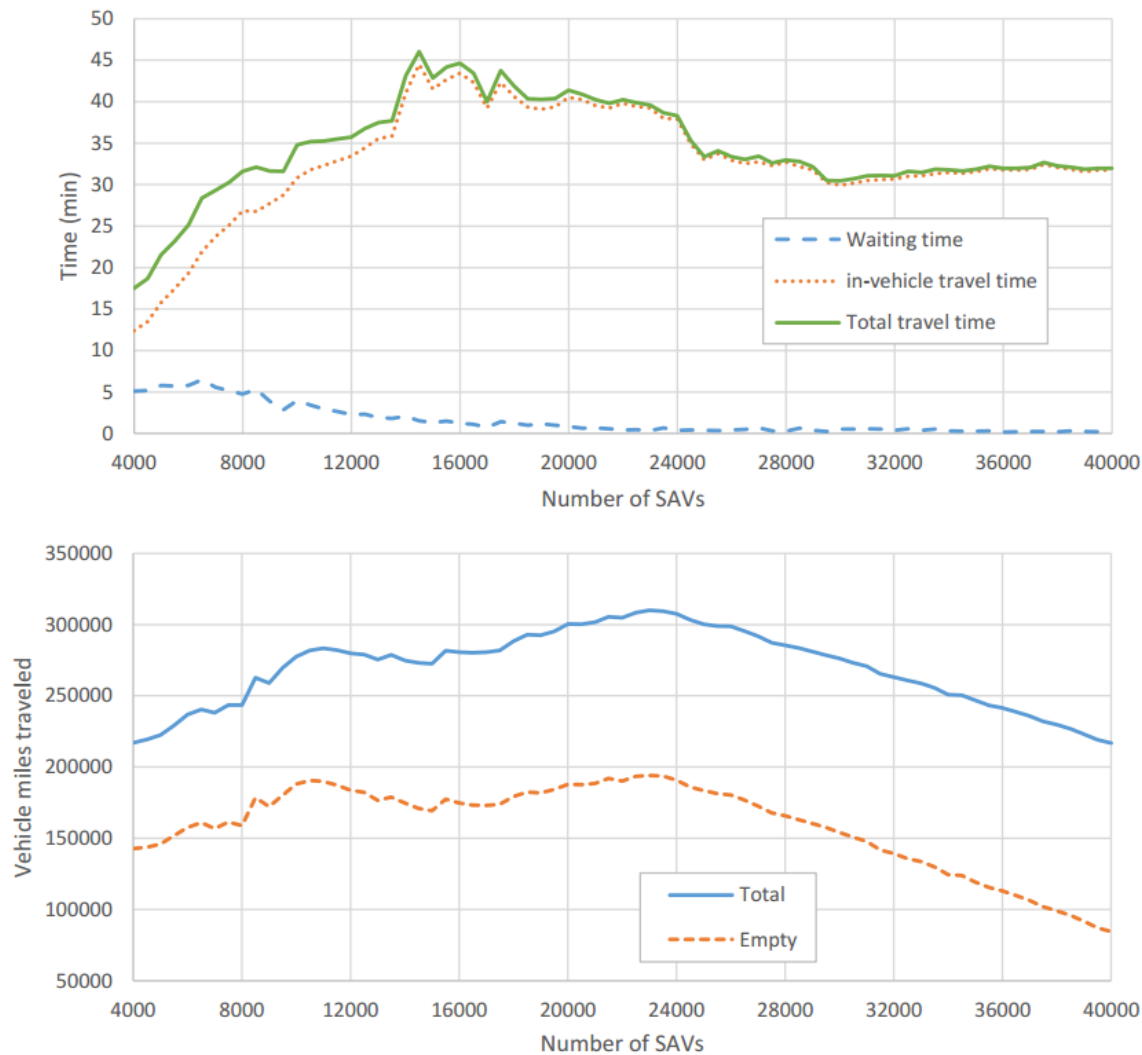
Figure 9.20 Travel Time and VMT for the Preemptive Relocation Scenario

Dynamic Ride-Sharing

Compared with the base and pre-emptive relocation SAV scenarios, dynamic ride-sharing allowed SAVs to provide in-vehicle travel times competitive with personal vehicles. SAV capacity was four passengers, and ϵ was set at 0.4 (Fagnant and Kockelman 2015b). At the minimum scenario of 4000 SAVs, the average in-vehicle travel time was 12.4 minutes and the average waiting time was only 5.1 minutes, as shown in Figure 9.21. For travelers who call a SAV a few minutes before they plan to leave, a 5.1-minute waiting time is easily forgivable. Those 12.4-minute in-vehicle travel times improve over average travel times with personal vehicles and traffic signals and are only around 5 minutes greater than personal vehicles with reservation controls. As the number of SAVs increased, though, travel times also increased until they were comparable with the non-ride-sharing scenario. Waiting times were overall much lower. This was probably because travelers with nearby destinations could share the same SAV, when one arrived. This approach yielded the best results when the fewest SAVs were available: despite increased waiting times, SAV utilization was greater.

Figure 9.21 shows that VMT peaked with around 23,000 SAVs. With only 4000 SAVs, VMT was low because of the low number of SAVs, but dynamic ride-sharing allowed just 4000 SAVs to service 62,836 travelers in the AM peak. Note that the difference between total and empty VMT increases as the number of SAVs increases due to the reduction in average number of passengers carried per SAV. This demonstrates an interesting result: when ride-sharing is possible, having fewer SAVs is sometimes more efficient. Ride-sharing reduces congestion and maximizes the utilization of each SAV because travelers accumulate as they wait for one of the few SAVs to arrive for pick-up.

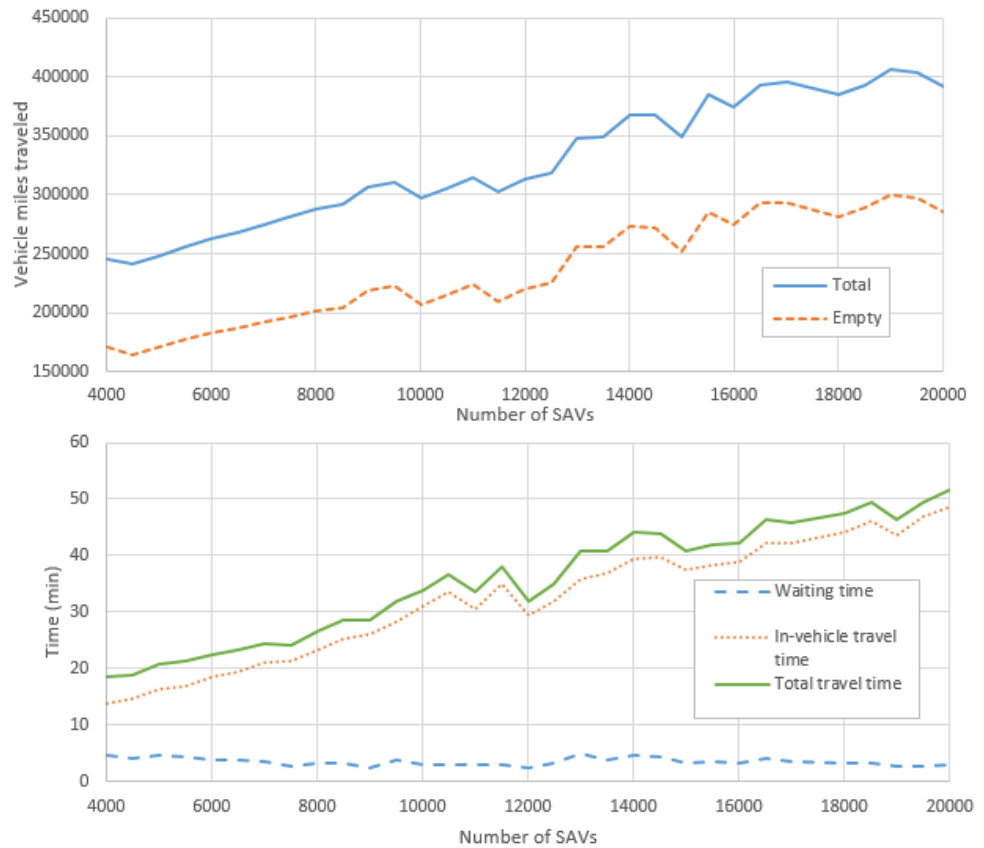
Figure 9.21 Travel Time and VMT for the Dynamic Ride-Sharing Scenario



A fleet of 4000 SAVs corresponds to a 93.6% reduction in the number of vehicles: each SAV services an average of 15.7 travelers. This efficiency is similar to that found in previous studies, such as one SAV servicing 11 travelers (Fagnant and Kockelman 2015b). However, the observed efficiency is at least partially due to the network topology: due to considering only the downtown region, traveler origin/destinations are fairly close together. If a regional network were used, the efficiency would likely decrease.

Preemptive relocation was somewhat detrimental when used with dynamic ride-sharing, as shown in Figure 9.22. When the number of SAVs was below 10,000, preemptive relocation slightly reduced waiting times. At higher numbers of SAVs, though, relocation still had a waiting time of around 3–4 minutes. This probably resulted from high congestion delaying the arrival of relocating vehicles. Beyond 20,000 SAVs, the congestion caused by the additional relocations prevented travelers from reaching their destination. Travel time increased significantly with the number of SAVs, mostly due to increases in in-vehicle travel time from congestion. However, travel time with ride-sharing and relocation increased at a lower rate than travel time with just ride-sharing. In fact, when the number of SAVs was between 4000 or 10,000, preemptive relocation with ride-sharing had slightly lower travel times than ride-sharing alone. However, at higher numbers of SAVs, with ride-sharing available, most SAVs were relocating, resulting in high congestion and worse travel times than in the base case. As the number of SAVs increased, the empty VMT increased as well, resulting in around 100,000 additional miles traveled at 20,000 SAVs when relocation and ride-sharing was used compared to ride-sharing alone (Figure 9.23).

Figure 9.22 Travel Time and VMT for the Dynamic Ride-Sharing and Preemptive Relocation Scenario



CHAPTER 10 ANTICIPATING THE EMISSIONS IMPACTS OF AUTONOMOUS VEHICLES USING THE MOVES MODEL

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10.1 Introduction

In addition to affecting human mobility and safety, connected autonomous vehicles (CAVs) are also expected to impact emissions, air quality, and energy use. Many elements of vehicular and fuel technologies are associated with the energy use and emissions, such as vehicle weights (Greene 2008; Ford 2012; Chapin et al. 2013; MacKenzie et al. 2014), fuel efficiencies and alternative fuels (Chapin et al. 2013; Liu et al. 2015; Reiter and Kockelman 2016), and engine technologies (Paul et al. 2011; Folsom 2012; Bansal et al. 2016; Reiter and Kockelman 2016). CAVs are anticipated to be lighter than existing human-driven vehicles (HVs) (Chapin et al. 2013; Anderson et al. 2014) and powered by alternative fuels or electricity (Chen and Kockelman 2015; Chen et al. 2016) and more efficient engines (Anderson et al. 2014). CAV operational features are also likely to affect the energy used and emissions generated. Anderson et al. (2014) pointed out that CAVs would likely have fewer stop-and-go movements, given the connectivity of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I), resulting in lower levels of fuel consumption and emissions.

Fagnant and Kockelman (2015a) simulated a fleet of shared autonomous vehicles (SAVs) to serve travelers in an idealized small city and estimated that each SAV might replace 11 HVs while increasing total vehicle-miles traveled (VMT)—due to empty-vehicle driving (to reach the next trip-maker). However, a high rate of SAV warm-starts (73% of trips began with a warm engine) and the use of smaller vehicles (as well as a need for fewer parking spaces, and their embodied emissions) led to overall estimates of lower emissions. Fagnant and Kockelman (2015a) estimated that such SAV fleets could deliver an energy savings of 12%, along with a 5.6% reduction in greenhouse gas (GHG) emissions, relative to privately owned and operated HVs. AV platooning can also be expected to be associated with higher fuel efficiency and lower emission rates (Alam et al. 2010; Tsugawa 2014).

Wu et al. (2014) discussed the sustainability benefits of vehicle automation at signalized intersections. Their results indicated 5 to 7% reductions in energy use and GHG emissions, up to 7% reductions in hydrocarbon (HC) emissions, and 15 to 22% reductions in carbon monoxide (CO) emissions. Wadud et al. (2016) expect greater energy savings and emissions reductions at higher levels of vehicle automation. Chen et al. (2016) estimated the energy and emissions benefits from an automated-vehicle-based personal rapid transit system and revealed approximately 30% energy saving and reductions in GHG emissions.

CAV technologies are also expected to improve fuel economy and reduce emissions per mile driven through more automated and optimized driving, thanks to more gradual acceleration and deceleration in driving cycles. A driving cycle is often represented as a vehicle's speed profile versus time. Figure 10.1 presents a driving cycle designed by the Environmental Protection Agency (EPA) to represent highway driving conditions under 60 mph. In using HVs, driving patterns with gradual acceleration and deceleration are often referred to as

“eco-driving” profiles (see, e.g., Anderson et al. 2014; Barth and Boriboonsomsin 2009; Chapin et al. 2013). Barth and Boriboonsomsin (2009) expect approximately 10 to 20% fuel savings and GHG emissions reductions, from humans driving conventional vehicles more thoughtfully, to reduce their energy use. Given the precision of fully automated driving, CAV driving profiles are likely to be much more fuel-efficient or at least smoother than human-controlled eco-driving profiles. Mersky and Samaras (2016) simulated the automated following driving cycles to estimate the changes in energy use and found up to 10% energy savings. This paper estimates the energy and emissions impacts of CAVs, by presuming that CAVs can (and ultimately will be programmed to) deliver smooth driving cycles or engine loading profiles, effectively practicing Eco-Autonomous Driving (EAD).

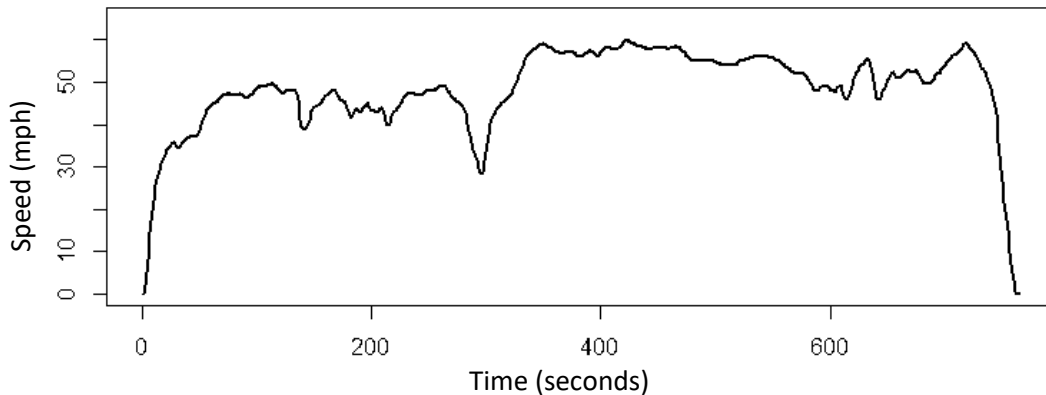


Figure 10.1 An EPA Driving Cycle for Conventional Vehicles on Highway Driving Conditions (EPA 2013)

To simulate the EAD profile, this study employed two types of existing HV driving cycles:

- 3) EPA driving cycles used to test for compliance with Corporate Average Fuel Economy (CAFE) standards for light-duty vehicles (EPA 2012), and
- 4) Austin-specific driving schedules developed by the Texas A&M Transportation Institute (TTI) to reflect local driving patterns of light-duty vehicles (Farzaneh et al. 2014).

The EAD profiles were simulated by smoothing the existing driving cycles, given the anticipation that CAV driving profiles will contain fewer extreme driving events (like hard accelerations, sudden braking, and sharp or quick turns) than HV cycles. Then, this study used the US EPA’s Motor Vehicle Emission Simulator (MOVES) to estimate emission rates (in grams per mile traveled) for various pollutants, including volatile organic compounds (VOC), fine particulate matter (PM_{2.5}), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO₂) and carbon dioxide (CO₂), based on the EAD profiles and HV cycles.

MOVES is the EPA’s regulatory simulator for estimating on-road emissions from conventional vehicles such as passenger cars, buses, and trucks. It is used by planning organizations for project conformity analyses that are required for state implementation plans (SIPs), as well as for environmental analyses that gauge the impacts of potential transport planning decisions (EPA 2014, 2015). The EPA and state environmental agencies have developed a database that provides basic emissions parameters for counties across the U.S. (EPA 2015). Though this database is continually updated to provide the most accurate parameters for a given area, the EPA recommends that local data be developed and inserted into the MOVES simulator to provide the best estimate of on-road emissions at the project area, which Farzaneh et al. (2014) did for several Texas cities.

In this chapter, CAV emissions impacts are limited to differences in basic driving profiles, as elected by independent CAVs driving at the same time in the same locations, with the same traffic control strategies and traffic variations that HVs face. In reality, many other CAV technologies and applications (like cooperative intersection coordination systems, platooning and coordinated adaptive cruise control) should also help save fuel and reduce emissions, but these are not evaluated in this paper. In addition, many factors that may affect the fuel consumption and emissions of vehicles, such as vehicle size and road grade (Boriboonsomsin and Barth 2009) are not discussed here.

10.2 Envisioning Eco-Self-Driving Cycles of Autonomous Vehicles

This section presents the Eco-Self-Driving (ESD) cycles that are envisioned for CAVs based on existing HV driving cycles. The HV driving cycle data used in this task include EPA driving cycles that are used for the Corporate Average Fuel Economy (CAFE) for light-duty vehicles (EPA 2012), and Texas-specific driving schedules (Farzaneh, et al. 2014). ESD cycles are expected to be smoother than HV cycles, given the advances in CAVs as relative to HVs.

Smoothing Method

Many methods can be used to smooth the driving cycles, such as moving average, local polynomial regression, kernel density estimation, and smoothing splines (Simonoff 2012). Most data smoothing efforts are designed to impute missing data points or smooth out noise. In contrast, this study envisions CAV ESD cycles by smoothing the existing HV cycles. There are two main concerns with the smoothed driving cycles:

- CAV ESD profiles should have far fewer extreme driving events—like hard accelerations and sudden braking, as compared to HV cycles. Intelligent and CV-informed vehicles should be able to anticipate several seconds of downstream driving conditions, making timelier decisions and ultimately smoother responses to evolving traffic conditions. In such cases, a higher extent of smoothing (like a wider smoothing window) can be expected.
- CAV movements on road are influenced by other vehicles (when there is no free-flow and HVs are still on road) and the traffic control devices (like intersection signals and signs). Therefore, at the early stage of introducing CAVs on road, the CAV profiles may be somehow similar to HV cycles from a microscopic perspective. In other words, the time-distance diagrams of both CAV (smoothed) and HV (unsmoothed) driving profiles should generally be similar to each other, to ensure that smoothed cycles do not make travelers late for meetings, late to green lights, or unyielding to (and thus colliding with) driveway-entering vehicles and the like. And the extent of smoothing (or level of smoothness) should not be extreme. This assumption implies largely unchanged driving patterns, from a macroscopic perspective. However, CAV technologies are likely to eventually impact such patterns, as adoption and use rates rise; cooperative intersection management and smart CAV routing decisions will shorten travel times, everything else constant, but added VMT may make travel more congested. Such changes in load profiles are not examined here.

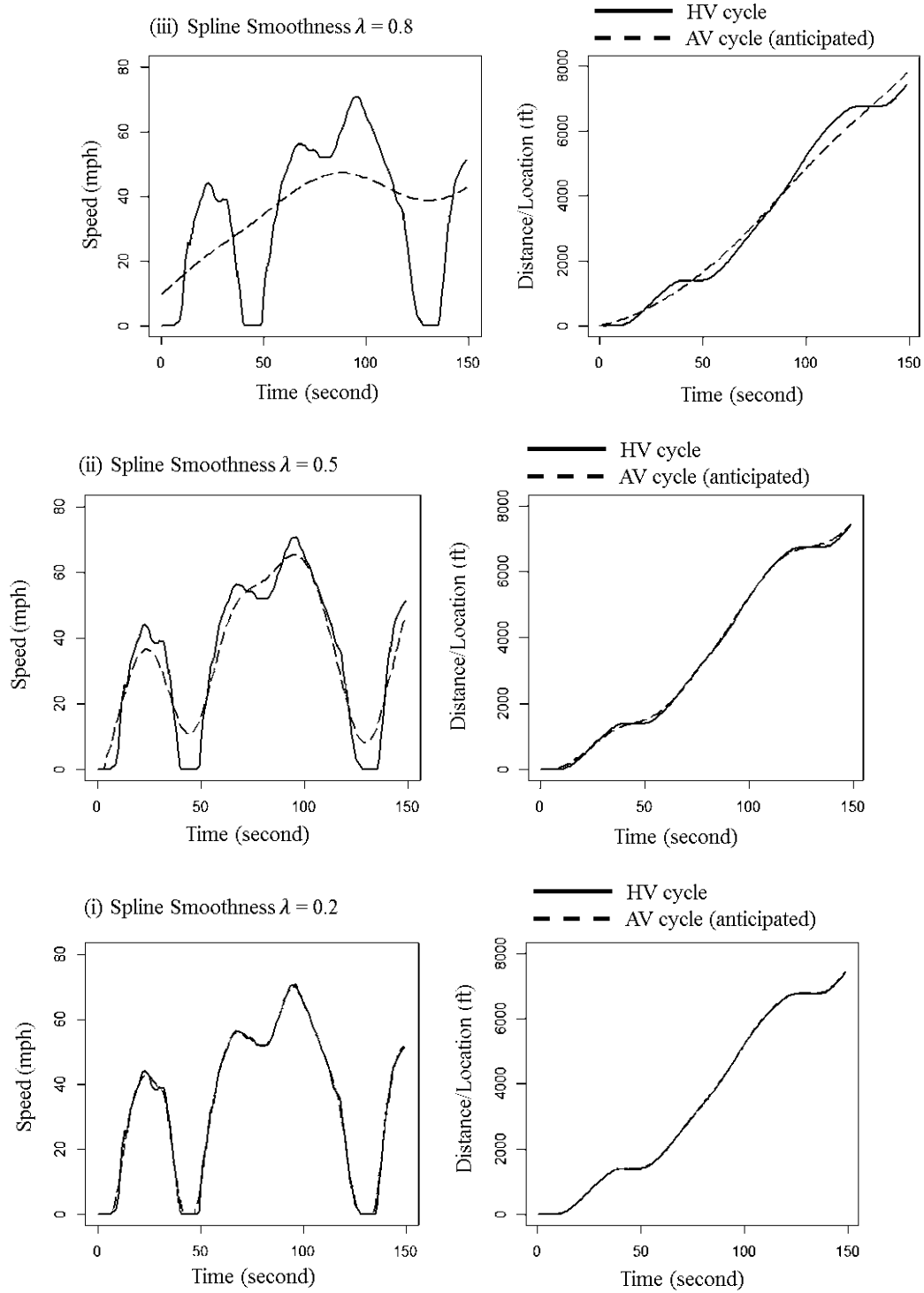
The first concern is about small curvatures of the cycles and the second concern is about the great similarities between smoothed and original cycles (i.e., small mean squared errors or MSE). In order to approximate this “balance” between these two concerns, the method of smoothing spline was employed in this study. The smoothing process is to minimize the objective function:

$$\arg \min_m \frac{1}{n} \sum_{i=1}^n (y_i - m(x_i))^2 + \lambda \int dx (m''(x))^2$$

where, the first term is the mean squared errors (y_i = the speed value of y at i^{th} data point x_i in an original driving cycle, $i = 1, 2, \dots, n$; $m(x_i)$ = the predicted value of m at i^{th} data point x_i in a smoothed driving cycle); $m''(x)$ = the second derivative of m with respect to x , i.e., the curvature of m at x ; λ = the smoothness factor to penalize mean squared errors. As $\lambda \rightarrow +\infty$, the MSE is not a concern and there is only a linear function resulted from the smoothing process. In contrast, as $\lambda \rightarrow 0$, the curvature is negligible and remains the same as un-smoothed. To address both these ideas and the two objectives or complexities listed above, an appropriate smoothness factor λ was chosen to construct smoothing cycles.

To determine the most appropriate smoothness factor, various λ values were tested, as shown in Figure 10.2. The larger smoothness factor $\lambda = 0.8$ is associated with a smoother cycle, compared with smaller smoothness factors, the time-distance diagram of the smoothed cycle significantly deviates from the original cycle.

Figure 10.2 Driving Cycle Example (Smoothed CAV Cycle vs. Original HV Cycle)



To better appreciate the effects of the chosen λ , the distributions of the smoothed and original cycles' accelerations and decelerations were also compared. Figure 10.3 presents the distributions of acceleration/deceleration values before smoothing (when $\lambda=0$) and after the smoothing. For comparison, typical distributions of acceleration/deceleration are shown in the figure as well, indicated by means (solid line) and means plus one standard deviation (dashed lines). The means and standard deviations were calculated for specific speed ranges (with bin width = 0.5 mph) using large-scale trajectory data from the Austin region.

The trajectory data were obtained from the Transportation Secure Data Center (TSDC) of the National Renewable Energy Laboratory (NREL) (TSDC 2014). The data were originally collected in TTI's 2006 Austin/San Antonio GPS-Enhanced Household Travel Surveys. This study extracted 241 hours of second-by-second driving speed records collected from 231 vehicles in Austin, Texas in 2005–2006. (More details about the calculation of distributions of acceleration/deceleration along speeds can be found in Wang et al. 2015. Note that the distributions can vary from one region to another). Figure 10.3 shows how, with a high smoothness factor ($\lambda=0.8$), the accelerations/decelerations are close to zero across speeds. To ensure that AV cycles remain similar to existing HV cycles (in order stop at red lights, and slow when vehicles merge in front of a CAV), this study chose $\lambda=0.22999$ as the smoothing factor, since this value allows most acceleration/deceleration data points to lay within the mean + one standard deviation of the typical distributions in the Austin region. In the study by Wang et al. (2015), the acceleration/deceleration data points were regarded as extreme driving events for falling beyond the mean-value lines plus one standard deviation, reflecting the unpredictable maneuvers of HVs. As CAVs become more common in traffic streams, such unpredictable maneuvers are likely to fall dramatically (thanks to inter-vehicle communications).

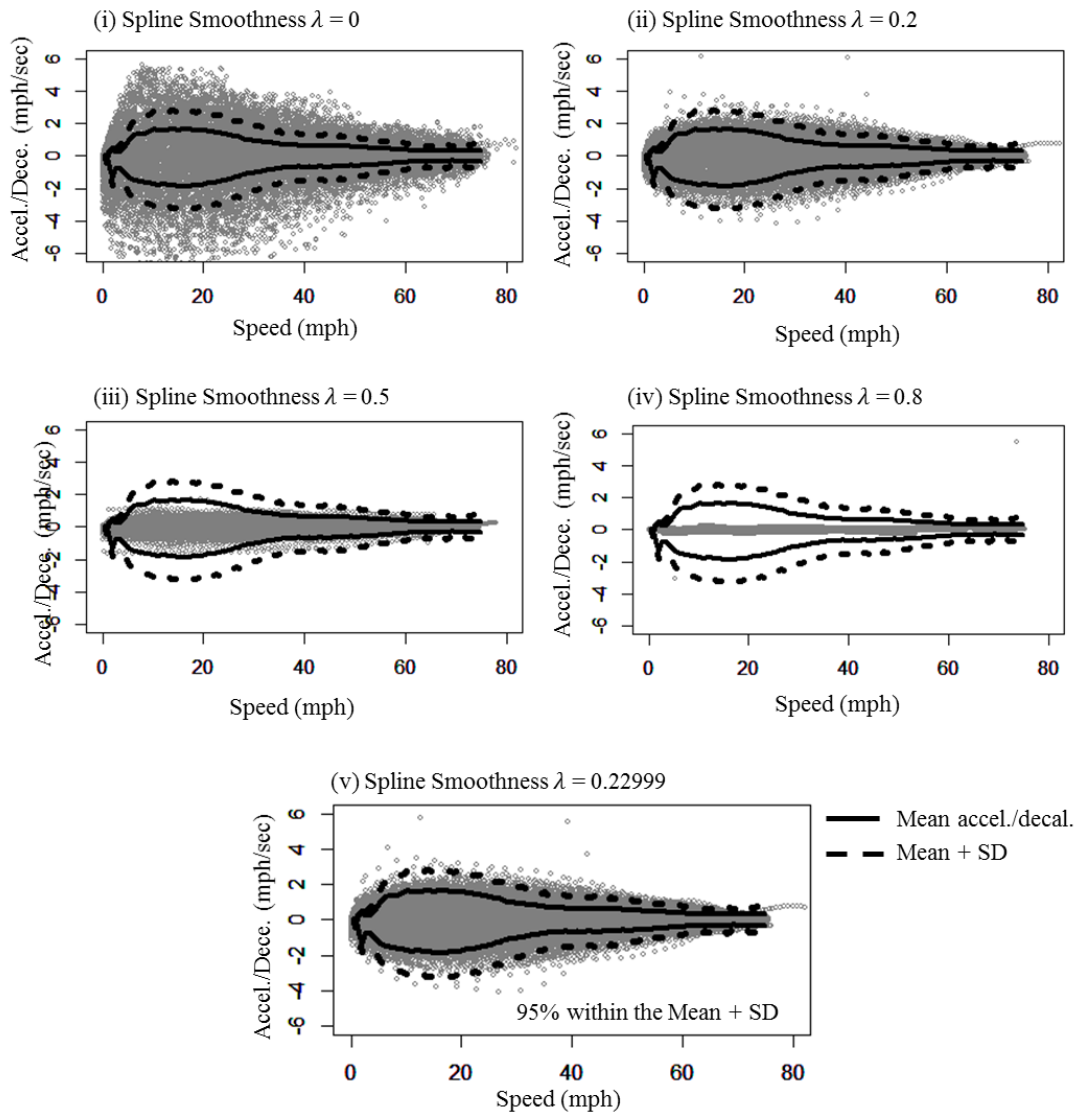


Figure 10.3 Distributions of Acceleration and Decelerations: Before Smoothing and After Smoothing at Different Smoothing Factors

10.3 Envisioned CAV Driving Profiles using EPA Cycles

The EPA has designed various driving cycles to represent a variety of driving conditions, such as highway/city driving, aggressive behavior, and air-conditioner usage. There are five EPA cycles that are usually used for the CAFE for light-duty vehicles (Davis, Diegel, and Boundy 2009 and Berry 2010). This study also used these five cycles to envision the future CAV cycles in various driving contexts. Table 10.1 summarizes basic information about these cycles, and Figure 10.4 presents these cycles in their original time-speed schedule (blue solid line) versus a smoothed time-speed profile (red dashed line). The smoothed cycles are envisioned to be the driving profiles for CAVs operating in the trip conditions listed in Table 10.1.

Table 10.1 EPA Driving Cycles Before (blue solid line) and After (red dashed line) the Smoothing ($\lambda=0.22999$) (EPA 2013)

EPA Cycle	Represented Trip Information	Max. Speed	Avg. Speed	Max. Acceleration	Simulated Distance	Duration	Test Temp
FTP (Federal Test Procedure)	Low speeds in stop-and-go urban traffic	56 mph	21.2 mph	3.3 mph/sec	11 mi.	31.2 min.	68°F–86°F
HWFET (Highway Fuel Economy Driving Schedule)	Free-flow traffic at highway speeds	60 mph	48.3 mph	3.2 mph/sec	10.3 mi.	12.75 min.	68°F–86°F
US06 (Supplemental FT)	Higher speeds; harder acceleration & braking	80 mph	48.4 mph	8.46 mph/sec	8 mi.	9.9 min.	68°F–86°F
SC03 (Supplemental FTP)	A/C use under hot ambient conditions	54.8 mph	21.2 mph	5.1 mph/sec	3.6 mi.	9.9 min.	95°F
UDDS (Urban Dynamometer Driving Schedule)	City test w/ colder outside temp.	56 mph	21.2 mph	3.3 mph/sec	11 mi.	31.2 min.	20°F

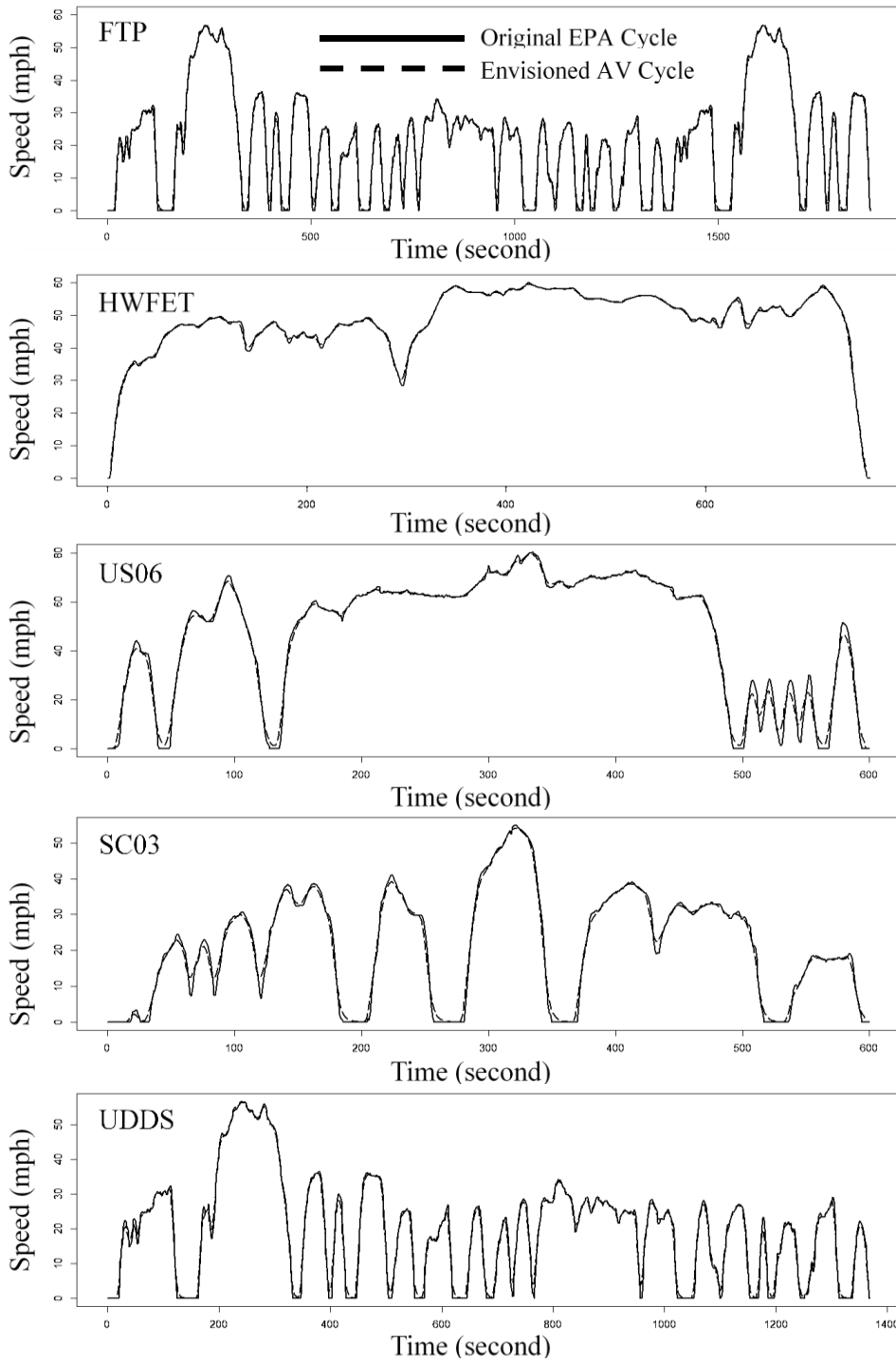


Figure 10.4 EPA Driving Cycles Before (solid line) and After (dashed line) Smoothing

10.4 Envisioned CAV Driving Profiles using Austin Cycles

EPA's cycles represent national representative drive schedules. Using a single set of representative driving cycles for fuel consumption and emissions estimates ensures comparable results across vehicle types, fuel types, manufacturers and many other factors. For this task, the researchers sought Austin-specific driving cycles, extracting them from the Database of Texas-Specific Vehicle Activity Profiles for Use with MOVES (Farzaneh, et al. 2014). Note that these extracted cycles do not represent a complete automobile trip, but rather a specific type of road link (or a road segment). These links may be combined to create a complete cycle. In this task, the analysis is conducted at link level. In future analysis these links may be summed at different weights according to their proportions in the Austin road network.

In total, 36 links were extracted from the database, covering two types of light-duty vehicles (passenger car and light-duty truck), two types of roadways (urban restricted and unrestricted road), and nine link-level average speed bins. Using the smoothing method introduced above, the links' driving cycles were smoothed to envision the driving profiles of CAVs running in the Austin region. Given the large number of links, the original and smoothed driving profiles are not shown in this chapter. Instead, Figure 10.4 presents the distributions of acceleration/deceleration (i) before and (ii) after the smoothing.

10.5 Preparing Data Inputs for MOVES

Configuring MOVES for Emission Estimations

MOVES is the EPA's regulatory simulator for estimating on-road emissions from conventional vehicles, such as passenger cars, buses, and trucks. It is used by planning organizations for project conformity analyses that are required for state implementation plans (SIPs). MOVES is also used to gauge the air quality impacts of potential transport planning decisions. The EPA and other state agencies have developed a database that provides basic emissions parameters for counties across the U.S. Though this database is continually updated to provide the most accurate parameters for a given area, the EPA recommends that local data be developed and inserted into the MOVES simulator to provide the best estimate of on-road emissions at the project area, which is what Farzaneh et al. (2014) did for several Texas regions.

Several studies have employed MOVES to estimate on-road emissions. Instead of using real data to estimate travel times, queue length, and other parameters, microsimulation data can provide the needed MOVES inputs. This method was employed by Xie et al. (2012) to estimate emissions on a freeway segment in Greenville, South Carolina. The researchers used PARAMIC to simulate the freeway operations and outputs were used in MOVES for emissions modeling. Xie et al. modified the fuel table to estimate the environmental benefits of using alternative fuels. Their results showed alternative fuels changed emissions rates as expected, but the scope of their study was limited to one freeway segment.

Another emissions study was performed by Abou-Senna and Radwan (2013). This study employed VisSim to produce driving patterns along a single highway corridor. The researchers wanted to look at how traffic volume, vehicle speed, grade, and temperature affected CO₂ emission rates. The vehicles in their VisSim model were categorized into operating bins based on the vehicle specific power (VSP) of the cars in the microscopic simulation. The magnitude of a car's VSP is used to estimate the severity of the emissions rates of that particular vehicle. Their results produced another example of data transferability between a traffic simulator and MOVES and reconfirmed that increasing factors like grade and traffic volume on a link lead to higher emission rates.

Amirjamshidi and Roorda (2015) also developed simulated driving cycles for the Toronto Waterfront area using a microsimulator. Their simulation program produced sets of micro-trips, which are the periods of driving by a vehicle between two successive idles, and then randomly selected micro-trips to piece together and form drive cycles. The researchers chose to develop drive cycles for light, medium, and heavy-duty trucks in the AM peak. These cycles were inserted into MOVES version 2010b to produce CO₂ emission rates.

Several other studies have used microsimulation programs to develop drive cycles for a particular project area. However, all of these microsimulations have modeled conventional vehicles only. Because of the lack of readily available microsimulation data representing CAV driving behavior, the most optimal and feasible method of predicting CAV emission rates is by statistical smoothing of driving cycles used to model HV driving behavior. This is based on the assumption that CAVs will be optimized in a way in which their

movement will minimize the erratic acceleration behavior associated with higher emission rates. Other studies have not employed this technique to predict CAV emission rates, and this would be an important contribution to HV/CAV planning research.

To run a project-scale analysis in MOVES, the model must be configured with the desired parameters. The MOVES model output is called a RunSpec. The parameters that must be specified are listed below:

- **Scale:** this study employed a project-scale domain. This is generally smaller than a county- or national-scale analysis. This task is based on the EPA driving cycles and the Austin link-based cycles (before and after the smoothing). Therefore, this task is, to be specific, to estimate the emissions on several road segments or combinations of road segments on which the vehicles run in EPA cycles or Austin link-based cycles.
- **Time Span:** because the scale is set at the project level, MOVES allows the RunSpec to simulate only one hour of emissions production at a time. The RunSpec program was processed individually for several different hours to estimate emissions for longer than one hour.
- **Geographic Bounds:** the county where the project is located is selected (Travis County for this analysis).
- **Vehicles/Equipment:** the types of vehicles that emissions will be produced from in the simulation are specified with this parameter. Additionally, the fuels these vehicles use are also specified. For this project, passenger cars and light-duty trucks powered by diesel fuel, ethanol (E-85), and gasoline were considered. Fuel source distribution is consistent with the default values in MOVES.
- **Road Type:** the five available road types to be modeled in MOVES are off-network, rural roads, and urban roads. Urban and rural roads are classified as having either restricted or unrestricted access. Only urban roads were considered in this analysis.
- **Pollutants and Processes:** these are the pollutants and emissions processes being modeled by MOVES. The user selects the combinations of pollutants and the process to model for his or her project. MOVES can model emission of pollutants such as VOC, CO₂, nitrous oxides, hydrocarbons, and particulate matter (PM) with mean diameter of 2.5 μm (PM_{2.5}), and PM with mean diameter of 10 μm (PM₁₀).

Data Inputs for MOVES

After finishing the configuration of the MOVES model, the user enters project-specific data into the Project Data Manager. There are up to 13 inputs that the user can specify to customize the MOVES model for a project. The inputs specified for this project are listed and described below:

- **Links:** the user specifies the road type, length, volume, average speed, and grade of each link being modeled in the project analysis. The road type, length, and average speed for each link considered was provided in the Texas drive cycle database referenced earlier. The grades of all roads were considered as flat. Though this is a very simplistic assumption, analyzing the emissions impacts of smoothing cycles can still be performed effectively because the input parameters remain the same for both unsmoothed and smoother driving cycles. Only urban restricted and urban unrestricted roads were considered in this analysis to minimize MOVES run times. The volume of the link, which is the total traffic volume in one hour, was considered to be 145,000 vehicles for urban restricted roads and 10,000 for all urban unrestricted roads included in the analysis (averaged according to TxDOT highway system statistics). Since link volumes are not readily available in a database for each link on a network, a conservative estimate was used for both urban restricted roads and urban unrestricted roads.
- **Link Source Types:** each link considered must have the vehicle mix specified. Only light vehicles were considered in this analysis due the lack of available data highlighting the actual vehicle mixes in this analysis.
- **Link Drive Schedules:** the speed versus time profiles (drive cycles) extracted from the Texas drive cycle database were used as the model of driving behavior for vehicles in the project area.

- **Age Distribution:** The proportions of cars within age ranges are specified in MOVES. The program includes default proportions for each year, and this study used default values due to the lack of available local information on age distribution.
- **Fuel:** The types of fuels used by vehicles on the network must be specified. Many analyses rely on default fuel databases maintained by MOVES, and this study took the same approach.
- **Off-Network:** the user specifies the start fraction, which is the average fraction of vehicle population that has started during the hour. The extended idle fraction is also specified when trucks are considered. Since only light vehicles were included in this analysis, no extended idle fraction was specified.
- **Meteorology Data:** the average temperature and humidity at a given time and location is provided by MOVES. The EPA provides this information inside of MOVES for each county in the U.S.
- **Truck Hoteling:** if heavy-duty trucks are included in the analysis, the fraction of hours when trucks are idling roadside, or “-hoteling” should be specified. This was not relevant here because only the active operation of light-duty CAVs were simulated.

10.6 CAV Emissions Impacts

This section presents emissions estimates based on smoothed driving cycles (for light-duty CAVs), using MOVES, as compared to original, HV driving schedules. Results using the US EPA’s national driving cycles are presented first, followed by some Austin-specific driving cycle results.

Emission Estimates using EPA Cycles

The emission rates of specific types of pollutants were estimated for light-duty passenger vehicles. The HV emission estimations were based on the original EPA schedules and the CAV emissions were estimated according to the corresponding smoothed EPA schedules.

Figure 10.5 presents the estimates of volatile organic compounds (VOC) emissions. The estimates are generally reasonable. For example, 1) the SC03 cycle with air-conditioning on in high temperature of 95°F and FTP cycle with frequent acceleration and brake events at low speeds lead to the high emission rates in both gasoline and diesel vehicles; and 2) the HWFET cycle representing free-flow freeway traffic is associated with the least emission rates, with other factors held constant. CAV emission levels are expected to be lower than those of HVs. Among both gasoline and diesel passenger vehicles, all five cycles are estimated to have lower VOC emission rates after the spline smoothing. Noticeably, the HWFET cycle is associated with the smallest emissions reductions, perhaps because this cycle does not contain many hard brakes and accelerations. The US06 cycle is linked with greatest emissions reductions (6.25% to 6.65%), as the original US06 cycle contains many rapid acceleration and hard-braking events that may occur only rarely in CAV operations. FTP cycle is associated with the second greatest reductions (4.99% to 5.23%) in VOC emissions.

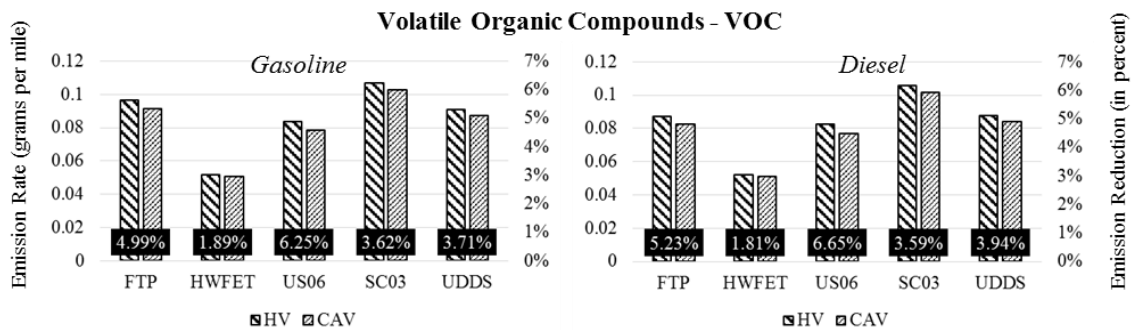


Figure 10.5 Emission Estimates for VOC

Figure 10.6 shows estimated emissions of particulate matters (PM), carbon monoxide (CO), nitrogen oxides (NO_x), and carbon dioxide (CO₂). Variations are found in these emission species. US06 cycle leads to greater emission rates than FTP and HWFET cycles for emissions of PM 2.5 and CO, owing to the hard brakes and accelerations in US06 cycle. UDDS SC03 cycles are found to have the greatest emission rate of PM_{2.5}, and CO, respectively, for gasoline vehicles. The reason may be related to the testing temperature: UDDS was tested at extreme cold temperature, 20°F, and SC03 cycle was to simulate the driving in hot weather, 95°F. For emissions of NO_x, US06 cycle leads to greatest emission rates among both gasoline and diesel vehicles. FTP cycle has relatively great CO₂ emission rates, which may be related to the low-speed driving, and frequent acceleration or brake events.

Regarding the emission reductions from HVs and CAVs, FTP and UDDS cycles seem to have great reductions (> 10%) in emissions of PM 2.5 and NO_x. US06 cycle is expected to have great reductions (around 7%) in emissions of CO. Again, HWFET cycle with least hard brake and acceleration events is related to the smallest reductions across all emission species.

Overall, smoothed EPA cycles were associated with lower emission rates, indicating that CAVs are likely to be more environmentally friendly than HVs. However, these reductions are not guaranteed, and vary according to emission types, fuel types, and driving contexts.

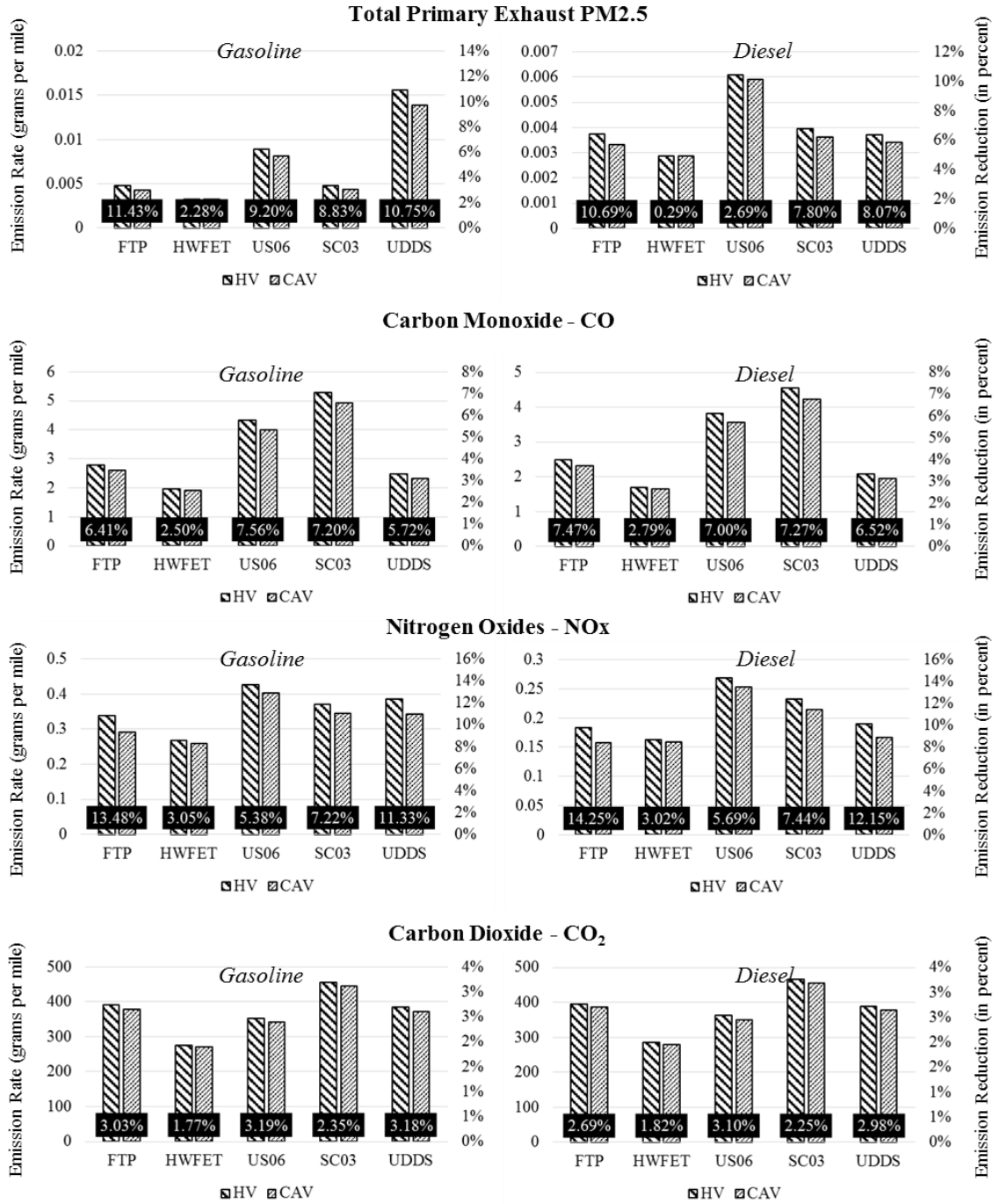


Figure 10.6 Emission Estimates for PM2.5, CO, NOx, and CO2

Emissions Estimates using Austin-area Cycles

The original and smoothed Austin cycles as obtained from TTI researchers (Farzaneh 2014) were entered into the MOVES program to estimate the emissions of current HV fleets and future CAV fleets. To make the results comparable, all configurations and inputs in MOVES except the inputs of driving schedules were

identical for HV and CAV emission estimates. The emissions were estimated in 36 Austin-specific cycles that represent the local driving patterns.

Given the variety of pollutant types, fuel types, vehicle types, various cycles, etc., simple regression models were constructed to present and explain the results. The correlates of emissions reductions for a specific pollutant were explored. The response or dependent variable is the percentage reduction in any specific pollutant species. Explanatory or independent variables (X_1 , X_2 , etc.) include fuel type, vehicle type, temperature, and link-level average speed values. All explanatory variables, except link-level average speed values are indicators ($X = 0$ or 1) variables, and just two ambient temperature conditions (cold, 40°F in January, and warm, 75°F in September) were simulated. Table 10.2 shows the descriptive statistics of variables in the regression models. The models for different pollutants had exactly the same descriptive statistics.

Table 10.2 Summary Statistics of Emissions-Related Variables

<i>(i) Explanatory Variables</i>					
Variable		Mean or Proportion	S.D. or Freq.	Min	Max
Vehicle Type	Passenger Car	50%	216	0	1
	Light-Duty Truck	50%	216	0	1
Fuel Type	Gasoline	33%	144	0	1
	Diesel	33%	144	0	1
	Ethanol	33%	144	0	1
Temperature	Cold	50%	216	0	1
	Hot	50%	216	0	1
Link Mean Speed (mph)		30.18	21	2.5	69.5
Emission Species		Average Drop	S.D.	Min	Max
Volatile Organic Compounds - VOC		10.89%	9.09%	-4.56%	30.77%
Fine Particulate Matter - PM2.5		19.09%	17.31%	-23.81%	59.66%
Carbon Monoxide - CO		13.23%	16.50%	-16.93%	40.04%
Nitrogen Oxides - NOx		15.51%	11.50%	-7.41%	38.63%
Sulfur Dioxide – SO ₂		6.55%	5.45%	-4.12%	16.77%
Carbon Dioxide - CO ₂		6.55%	5.45%	-4.11%	16.76%

Note: all variables except Link Mean Speed and Emission Reduction are indicator variables. No. of observations = 432 for each emission type.

Figure 10.7 presents the distributions of percent reductions (Y) in emissions of VOC, PM2.5, CO, NOx, SO2, and CO2. The positive percentages indicate the emissions reductions from HV to CAV cycles. The magnitudes of percent reductions are generally consistent with the estimates from EPA cycles. In most cases, the estimated emissions decreased during the shift from HV to CAV cycles (i.e., positive percentages). The mean emission reductions are 10.89% for VOC, 19.09% for PM2.5, 13.23% for CO, 15.51% for NOx, and 6.55% for SO2 and CO2.

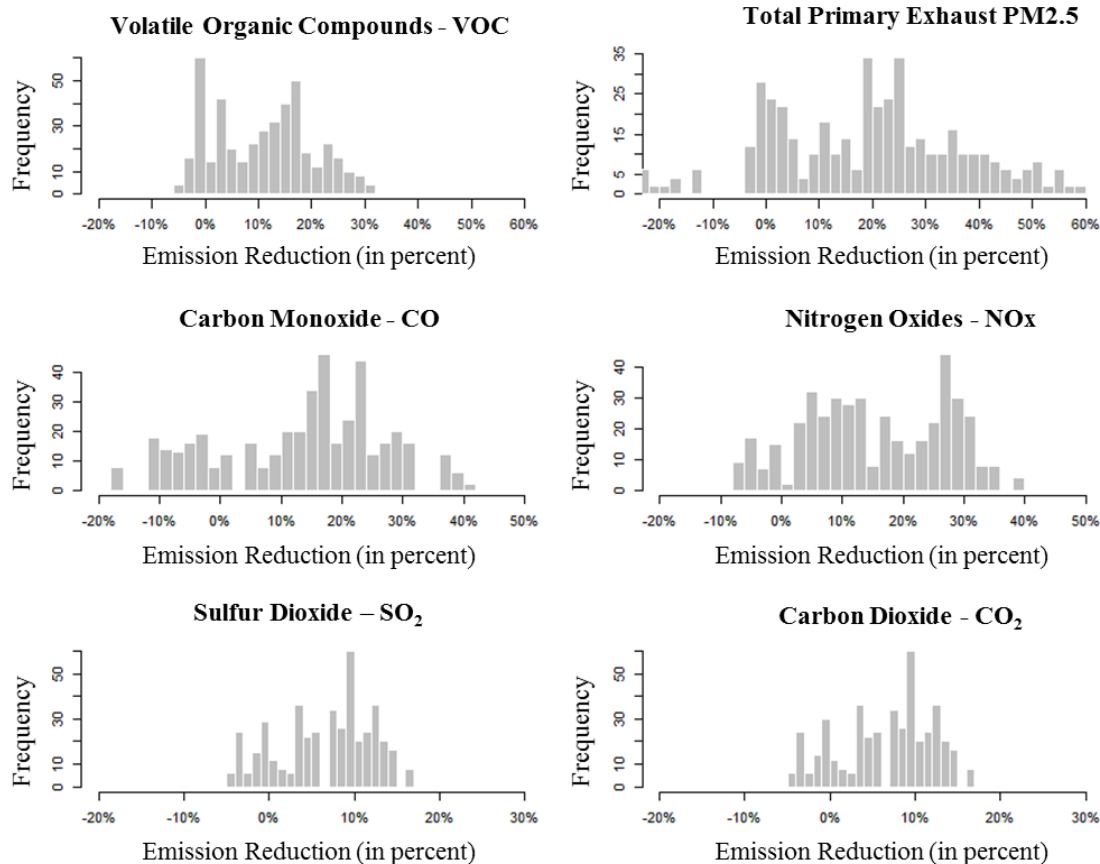


Figure 10.7 Distributions of Emissions Reductions (in percentages) of VOC, PM2.5, CO, NO_x, SO₂, and CO₂

Table 10.3 delivers the regression models, showing the correlates of emission reductions (from HV to CAV EAD cycles) with the factors shown in Figure 10.7. The coefficients refer to the changes in emission reductions (%) from HV to CAV cycles, with one unit of change in explanatory variables, when controlling for other variables. The findings from the models include the following:

- VOC:** Greater reductions in VOC emissions are expected for passenger cars, 1.925 percentage points more than for passenger trucks. Diesel vehicles showed smaller emission reductions, 4.636 percentage points less than vehicles powered by ethanol. Higher average link speeds lead to greater reductions in VOC emissions, while a one-unit increase in speeds results in a reduction in VOC of 0.273 percentage points less.
- PM2.5:** Gasoline vehicle are associated with a greater reduction (4.367 percentage points more) in emissions of PM2.5, and diesel vehicle are linked with a smaller reduction (8.307 percentage points less), as relative to the vehicles powered by ethanol. The road links with higher average speeds are expected to have a greater emission reduction. A one-unit increase (1 mph) in average speed corresponds to a 0.302 percentage point reduction in PM2.5 emissions.
- CO:** Passenger cars are related to greater CO emission reductions (1.655 percentage point more) when moving from HV to CAV cycles, as relative to passenger trucks. Diesel vehicles demonstrated smaller emission reductions, 2.131 percentage points less than vehicles powered by ethanol. Higher average link speeds are expected to result in a greater reduction in CO emissions. The regression shows that a one-unit increase in average link speed results in a 0.505 percentage points greater emission reduction in CO.

- **NOx:** Passenger cars demonstrated greater NOx emission reductions from the HV to CAV cycles, 1.363 percentage points more than passenger trucks. Diesel vehicles showed smaller emission reductions, 4.042 percentage points less than vehicles powered by ethanol. Higher average link speeds are expected to result in a lower reduction in NOx emissions, while a one-unit increase in speeds results in a reduction in NOx of 0.048 percentage points less.
- **SO₂ and CO₂:** These two types of emissions were found to have similar correlates of emission reductions. Only the link average speed has a significant correlation with these emission reductions. Higher link average speeds are expected to result in a lower reduction in SO₂ and CO₂ emissions. A one-unit increase in speeds results in a reduction in SO₂ and CO₂ emissions that are 0.069 percentage points less.

Table 10.3 Regression Results for $Y = \% \text{ Emission Reductions}$, as a Function of Vehicle, Fuel Type, Starting Engine Temperature, and Average Speed

Emission Species	Variable	β	Std Error	P-value	R-Square
Volatile Organic Compounds (VOC)	Constant	2.641 *	5.74	<.0001	0.643
	Passenger Car (base: Passenger Truck)	1.925 *	7.33	<.0001	
	Gasoline (base: Ethanol)	-0.588	-1.58	0.1146	
	Diesel (base: Ethanol)	-4.636 *	-12.47	<.0001	
	Cold (base: Hot)	-0.188	-0.72	0.4737	
	Link Mean Speed (mph)	0.273 *	21.81	<.0001	
Fine Particulate Matter (PM2.5)	Constant	9.983 *	7.87	<.0001	0.253
	Passenger Car (base: Passenger Truck)	-0.862	-1.19	0.2342	
	Gasoline (base: Ethanol)	4.367 *	4.27	<.0001	
	Diesel (base: Ethanol)	-8.307 *	-8.12	<.0001	
	Cold (base: Hot)	0.550	0.76	0.4477	
	Link Mean Speed (mph)	0.302 *	8.75	<.0001	
Carbon Monoxide (CO)	Constant	-2.011 *	-2.95	0.0034	0.646
	Passenger Car (base: Passenger Truck)	1.655 *	4.25	<.0001	
	Gasoline (base: Ethanol)	0.038	0.07	0.9455	
	Diesel (base: Ethanol)	-2.131 *	-3.87	0.0001	
	Cold (base: Hot)	0.080	0.21	0.8373	

Emission Species	Variable	β	Std Error	p-value	R-Square
	Link Mean Speed (mph)	0.505 *	27.20	<.0001	
Nitrogen Oxides (NOx)	Constant	14.054 *	15.21	<.0001	0.103
	Passenger Car (base: Passenger Truck)	1.363 *	2.59	0.0101	
	Gasoline (base: Ethanol)	0.116	0.16	0.8768	
	Diesel (base: Ethanol)	-4.042 *	-5.42	<.0001	
	Cold (base: Hot)	-0.275	-0.52	0.6017	
	Link Mean Speed (mph)	0.048	1.92	0.0555	
Sulfur Dioxide (SO ₂)	Constant	4.480 *	10.09	<.0001	0.076
	Passenger Car (base: Passenger Truck)	-0.392	-1.55	0.1225	
	Gasoline (base: Ethanol)	-0.089	-0.25	0.8043	
	Diesel (base: Ethanol)	0.247	0.69	0.4903	
	Cold (base: Hot)	0.046	0.18	0.8562	
	Link Mean Speed (mph)	0.069 *	5.69	<.0001	
Carbon Dioxide (CO ₂)	Constant	4.479 *	10.10	<.0001	0.076
	Passenger Car (base: Passenger Truck)	-0.391	-1.550	0.1231	
	Gasoline (base: Ethanol)	-0.089	-0.250	0.804	
	Diesel (base: Ethanol)	0.248	0.690	0.4898	
	Cold (base: Hot)	0.046	0.180	0.8562	
	Link Mean Speed (mph)	0.069 *	5.690	<.0001	

Notes: ** = significant at 99% confidence level; * = significant at 95% confidence level.

10.7 Conclusions

This study seeks to anticipate some of the emission impacts of CAVs. CAV driving profiles are envisioned to be smoother than those of HVs, because CAVs are expected to be faster and more precise than human drivers, in terms of reaction times and maneuvering. Human drivers tend to create significant, frequent speed fluctuations (i.e., hard brakes and rapid accelerations) and have relatively long reaction times (e.g., 1.5 seconds). CAV technologies may rarely suffer from such fluctuations, allowing for smoother driving profiles, referred to here as Eco-Autonomous Driving (EAD) cycles. Hard braking and rapid acceleration events are associated with increased emissions, so, by smoothing HVs' existing driving cycles, this work anticipates the emission benefits of CAVs.

National EPA cycles and Austin, Texas cycles were smoothed to obtain EAD emissions estimates using MOVES. Various emission species were considered here, including volatile organic compounds (VOC), fine particulate matter (PM_{2.5}), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO₂), and carbon dioxide (CO₂). Differences in HV versus CAV emissions estimates suggest valuable air quality from CAVs—assuming CAVs are driven no more than HVs would be.

The results from EPA cycles suggest that, in general, if HVs are replaced by AVs, greater emission benefits (up to 14% emission reductions) are anticipated in driving conditions where there are many hard acceleration and braking events, and for drivers with aggressive driving styles. The results from Austin cycles indicate the mean emission reductions are 10.89% for VOC, 19.09% for PM_{2.5}, 13.23% for CO, 15.51% for NO_x, and 6.55% for SO₂ and CO₂. Regression models revealed that passenger cars were found to be associated with lower emission reductions for VOC, PM_{2.5}, CO, and NO_x than passenger trucks. Diesel vehicles are linked with smaller emission reductions for these six types of emissions. The road links with higher average speeds have greater emission reductions for all emission species.

These results are solely based estimates from MOVES models. Other emission modeling tools, such as UC Riverside's Comprehensive Modal Emissions Model (CMEM) (Scora and Barth 2006), may be employed in continuing efforts. At this point, the discussion of emission impacts of AVs is limited to the differences between the anticipated EAD profiles of CAVs and existing HV driving cycles. CAV profiles are envisioned to be smoother than HV cycles as compared to HV cycles. Other CAV-based technologies (like platooning of vehicles and CACC) may also save fuel and reduce emissions further.

CHAPTER 11 APPLICATION OF TRAFFIC MODELS

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11.1 Introduction

Currently, AV, connected vehicle (CV), and CAV technologies are still in the development stage, meaning CAVs are not widespread and are currently too expensive for the average household to afford. However, companies are investing more money into CAV technologies. As these technologies develop further, perceptions and availability of CAVs are poised to change for the better. CAVs have a spate of benefits to offer to the user, other vehicle users, and the environment. These benefits include improved safety, reduced travel times, and reduced roadway emissions. While 100% CAV penetration is unlikely in the near future, the expected increase in the number of CAVs on the roadways is almost certain. Therefore, understanding how different levels of CAV penetration on roadways can affect other commuters and the environment is important.

Since human-driven vehicles (HVs) will still be present on the roadway, existing infrastructure will have to remain so that HVs can continue to travel safely. As a result, the interplay between CAVs and HVs using current infrastructure, such as traffic lights and traditional stop signs, is an important area of interest.

The majority of this chapter is concerned with the interplay between human and autonomous drivers. The following sections outline the test networks and results used to see how travel time are affected by the inclusion of CAVs at different roadway penetrations. In order to adequately explore the effects of mixed use between CAVs and HVs on travel times, multiple types of roadway networks are tested. These networks are also tested under different scenarios such as rush-hour traffic demands or less congested demand levels. Once the particular networks to use and scenarios to model were selected, simulations were performed to assess the impacts of CAVs at different penetration levels. For a discussion of the methodologies, please refer to Chapter 9.

11.2 Test Networks Used for Link-Based Meso-simulation

This section presents the test networks used in the multi-class cell transmission model (CTM) meso-simulation to model the effects of CAVs on congestion and different types of road networks. (CTM is a Godunov approximation to the kinematic wave theory of traffic flow). These networks included two arterial networks, three freeway networks, and one downtown city network. Because these roadways are among the 100 most congested in Texas (TxDOT 2015), they are suitable for observing the effects of CAVs on congestion and traffic levels.

Arterial Networks

Two arterial networks in the city of Austin, Texas are used, including the intersection of Lamar and 38th Street, as well as a strip of Congress Avenue, as shown in Figure 11.1. The first arterial network contains the intersection between the Lamar and 38th Street arterials, as well as five other local road intersections. This network contains 31 links, 17 nodes, and 5 signals with a total demand of 16,284 vehicles over 4 hours in the AM peak. Studying Congress Avenue in Austin was also of interest. This network consists of a total of 25 signals in the network, 216 links, and 122 nodes with a total demand of 64,667 vehicles in a 4-hour period. These arterial networks employ fixed-time signals for controlling flow along the entire corridor.

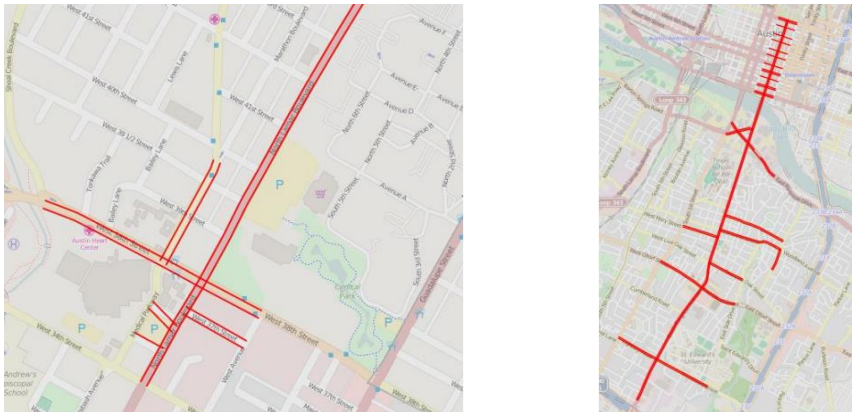


Figure 11.1 Lamar and 38th Street and Congress Avenue Networks (from left to right)

Freeway Networks

The three total freeway networks are shown in Figure 11.2. The first freeway network is the I-35 corridor in the Austin region, which includes 220 links and 220 nodes with a total demand of 128,051 vehicles within a 4-hour span. (Due to the length, the on- and off-ramps are difficult to see in the image.) All intersections are off-ramps or on-ramps. The I-35 network is by far the most congested of the three freeway networks and one of the most congested freeways in all of Texas, especially in the Austin region. Simulations were also performed on the US-290 network in the Austin region, consisting of 97 links, 62 nodes, 5 intersection signals,

and with a total demand of 11,098 vehicles within 4 hours. US-290 is one of the busiest arterials in the Austin area and a major east-west corridor. Finally, Texas State Highway Loop 1 (MoPac) Expressway was studied in the Austin region because of its role as a major north-south corridor in the city. This network contains 45 links, 36 nodes, and 4 intersection signals with a total demand of 27,787 vehicles within 4 hours. On this network, there is a mixture of merging and diverging ramps and signals, which allows for intersection comparisons. The MoPac network was also chosen due to the large number of signals around the freeway. All freeway networks are also among the 100 most congested roads in Texas (TxDOT 2015). Average travel times on this network encompass the entire network, meaning that the slower movement at the few intersections of the MoPac and US-290 networks are taken into account.



Figure 11.2 I 35, Hwy 290, and MoPac Networks (from left to right)

City Networks

The last network chosen was the Austin downtown network; the largest network tested, it could show us effects of tile-based reservations (TBR) and CAVs as they apply to an entire downtown structure. Downtown Austin differs from the previous networks in that there are many route choices available. To simulate these networks, CTM was used, which discretizes links into space-time cells to approximate the partial differential equations of the kinematic wave theory. Based on these three parameters, and assuming instantaneous acceleration, speeds and therefore travel times can be estimated for each vehicle. We used the method of successive averages to solve dynamic traffic assignment (DTA) in order to obtain user equilibrium routes and travel times for the vehicles. All scenarios were solved to a 2% gap, which was defined as the ratio of average excess cost to total system travel time. This gap was deemed sufficient to return realistic results. Any decrease in the gap would incur larger amounts of computation time that would not alter the results significantly. Route choice admits issues such as the Braess and Daganzo paradoxes (1968, 1998), in which capacity improvements induce selfish route choice that increase travel times for all vehicles. The downtown network also contains both freeway and arterial links, with a section of IH 35 on the east side, a grid structure, and several major arterials.

11.3 Effects of Autonomous Vehicles on Networks

This section presents results of the DTA simulation to analyze the effects of different proportions of CAVs on a network with HVs. In addition, simulations were run with 100% CAVs using a TBR system on chosen test networks to see if there were travel time improvements in comparison with those of typical traffic signals. The results were analyzed by comparing travel times in vehicles per minute as well as the total travel time (TSTT) of all vehicles in the network. The two main objectives of these simulations were to measure the effects on congestion of increasing the proportion of CAVs to HVs and implementing a TBR system instead of a traditional signal system with 100% CAVs.

In most simulations, perception reaction times of 0.5 second (0.5s) and 1 second (1s) were assumed for CAVs and HVs respectively. However, these times can be seen as something to be achieved in the future by CAVs. Since CAV technology is still an emerging field and has not yet achieved widespread acceptance, companies

tend to be hesitant to implement the newest technology, keeping the reaction times higher than what might be observed in subsequent years. Reaction times of one and two seconds for CAVs and HVs respectively is currently a more accurate and more achievable goal due to public perceptions and technology limitations. While the research here is primarily concerned with an advanced look into the future where CAVs are the norm, several simulations were run using these one and two second reaction times, including on the following networks. After running simulations at these reaction times, observations demonstrated that the simulations using longer perception reaction times showed the same trends as simulations performed with shorter perception reaction times. For most of the simulations, nearly the same travel times were generated. For these reasons, only four networks (I-35, MoPac, Lamar and 38th, and Congress) were simulated using the reaction times of CAVs and HVs. The purpose of these simulations is to analyze effects of different reaction times, and to observe changes in road capacity. Changes to these reaction times can reduce following headways and the rate at which queues form behind bottlenecks, thus altering flow and capacity. Our capacities for HVs have been directly taken from models calibrated for VISTA, a CTM-based DTA software used by the Network Modeling Center.

Effects of Autonomous Vehicles on Arterial Networks

The travel time results for arterial networks are shown in Figure 11.3. The general trend for the arterial networks is that the use of the first-come-first-serve (FCFS) TBR protocol reduced travel times. Although reservations helped most of the considered arterial networks, such as Congress Avenue, the reservations increased travel times for Lamar and 38th Street when subject to high demands. The lower 0.5 second reaction time for CAVs, compared to the 1 second reaction time for HVs, decreased travel times for every network tested. The one second and two second reaction times also decreased travel times for every network tested and followed similar trends for traditional signal systems with CAVs. However, the slower perception reaction times decreased travel times under the TBR system to a greater extent than when the faster 0.5 seconds and 1 second reaction times were employed. This is primarily because one and two second reaction times result in a greater benefit from CAVs relative to HVs, compared with 0.5 second and 1 second reaction times. As the proportion of CAVs in the network increased, the observed travel times decreased. Reduced reaction times were more beneficial in some scenarios than in others, but all scenarios saw a net benefit. Simulations of each network were conducted using a moderate 85% demand and by changing the proportion of CAVs, ranging from 0% to 100%.

In the Lamar and 38th Street network, the reservation protocol significantly decreased travel times for a 50% demand simulation as compared to traffic signals at 50% demand; however, once the demand was increased to 75%, reservations began increasing travel times relative to signals. This is most likely due to the close proximity of the local road intersections. On local road-arterial intersections, the FCFS reservations could grant greater capacity to the local road than would traffic signals. Because these intersections are so close together, reservations likely induced queue spillback on the arterial with the larger capacity. The longer travel times might also be linked to reservations removing signal progression on 38th Street. During high congestion, FCFS reservations tended to be less optimized than signals for the local road-arterial intersections. On the other hand, during low demand, intersection saturation was sufficiently low for reservations to reduce delays and travel times.

The Lamar and 38th Street network responded well to an increase in the proportion of CAVs with dramatic decreases in travel times, as a result of the shorter CAV reaction times. At 85% demand and at 25% CAVs, the TSTT was reduced by 50%, and when all vehicles were CAVs, the TSTT was reduced by 87%. Each demand proportion was then simulated with only CAVs. As demand increased, the improvements from reduced reaction times also increased. At 50% demand, reduced reaction times decreased travel times by 44%, whereas at 100% demand, reduced reaction times decreased travel times by 93%. The effect of greater capacity improved as demand increased, because as demand increased, the network became more limited by intersection capacity. At low congestion (50% demand), signal delays hurt travel times because reservations made significant improvements. At higher congestion, intersection capacity was the major limitation, and therefore reduced reaction times were of greater benefit.

Congress Avenue responded well to the introduction of reservations, showing decreases in travel times at all demand scenarios. These improvements are due to the large number of streets intersecting Congress Avenue,

each with a signal not timed for progression. The switch to reservations therefore reduced the intersection delay. However, the switch to reservations could result in greater demand on this arterial in the future.

CAVs also improved travel times and congestion due to reduced reaction times. At 85% demand, using reaction times of 0.5 seconds and 1 second for CAVs and HVs respectively, even a 25% proportion of CAVs on roads decreased travel times by almost 60%. This increased to almost 70% when all vehicles were CAVs. As with Lamar and 38th Street, as demand increased, the improvements from CAV reaction times also increased. For example, at 50% demand, 100% CAVs decreased travel time by about 10%, but at 100% demand, using all CAVs reduced the travel time by nearly 82%. The reduced reaction times did not improve travel times as much as the reservation protocol however, except for in the 100% demand scenario. This indicates that at lower demands, travel time was primarily increased by signal delay—but was still improved by CAV reaction times.

Overall, these results consistently show significant improvements at all demand scenarios as a result of reduced reaction times of CAVs. Reducing the reaction time to 0.5 seconds nearly doubles road and intersection capacity. However, the effects of reservations were mixed. At low congestion, traffic signal delays had a greater impact on travel time, and in these scenarios reservations performed relatively better. Reservations also improved when signals were not timed for progression (although this may be detrimental to the overall system). However, as seen on Lamar and 38th Street, during high demand, reservations performed more poorly than signals, particularly around local road-arterial intersections.

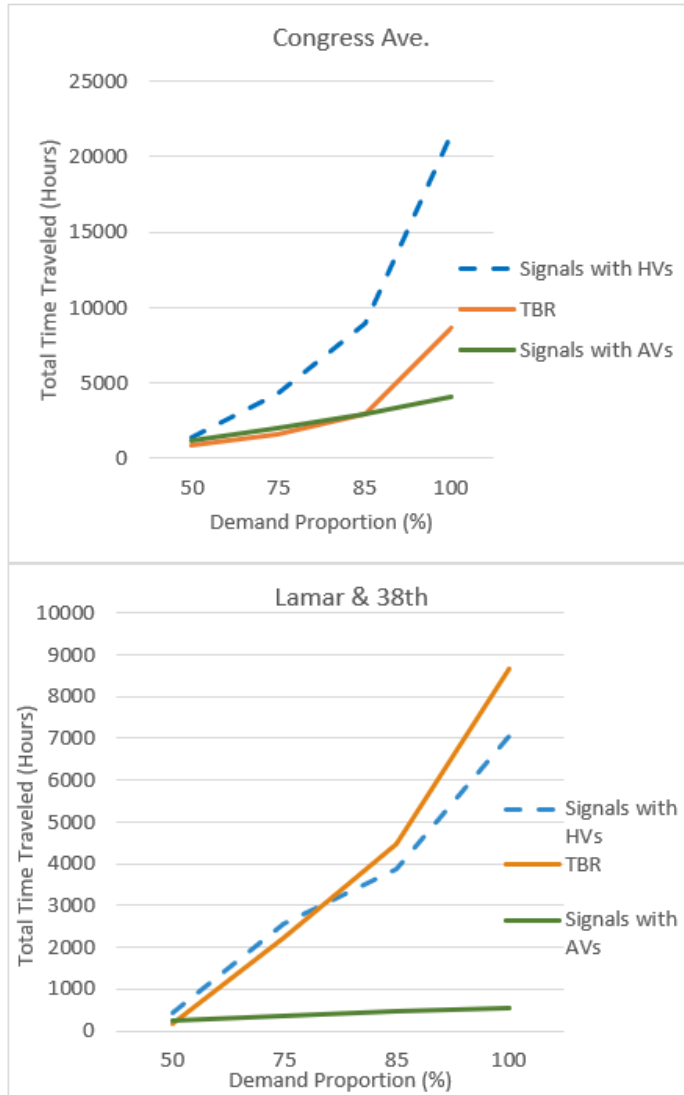


Figure 11.3 Arterial Network Travel Time Results for Lamar & 38th, and Congress Ave.

Effects of Autonomous Vehicles on Freeway Networks

Results for the freeway networks are presented in Figure 11.4. Although there were some observed improvements in travel times for the US-290 network using reservations, the improvements were modest. On the other hand, observing the I-35 and MoPac networks, reservations made travel times worse for all demand scenarios. Most of the access on US-290 is controlled by signals without progression, which explains the improvements observed when reservations were used there. Reservations seem to have worked more effectively with arterial networks, probably because freeway on- and off-ramps do not have signal delays. Therefore, the potential for improvement from reservations is smaller on freeways.

Overall, greater capacity from CAVs' reduced reaction times improved travel times in all freeway networks tested, with better improvements at higher demands. Reduced reaction times improved travel times by almost 72% at 100% demand on I-35. On US-290 and I-35, as with the arterial networks, the improvement from CAVs' shorter reaction times increased as demand increased. This is because freeways are primarily capacity restricted and the faster reaction times increase this capacity. On MoPac, reaction times had a smaller impact, but the network overall appeared to be less congested.

Links and nodes were chosen to study how reservations affected travel times at critical intersections or spans on the freeways, such as high demand on- or off-ramps. For these specific links, average link travel times were compared between 120 and 135 minutes into the simulation at the peak of the congestion. Simulations were also performed to compare HVs, CAVs with signals, and different CAV proportions with signals at 85% demand, which resulted in moderate congestion. In the I-35 network, very few changes in travel times for the critical groups of links were observed from the different intersection controls, which is to be expected since no intersections were in this network.

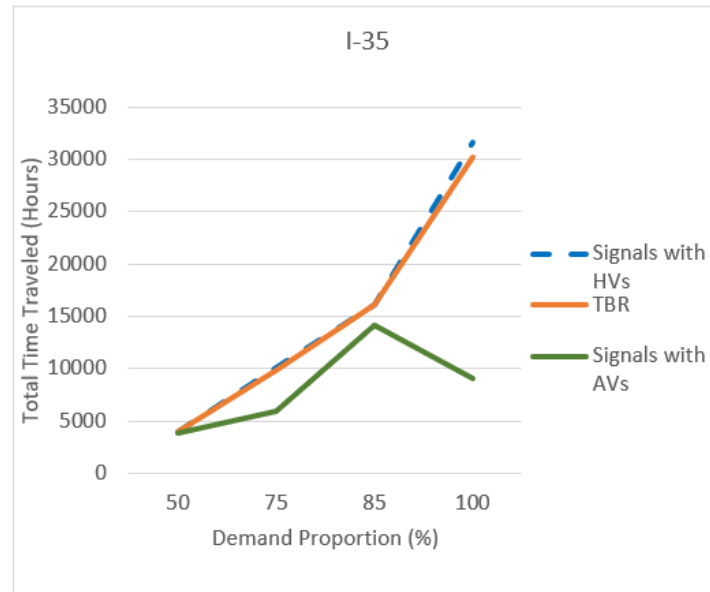


Figure 11.4 Freeway Network Travel Time Results for I-35

The differences appear greater in the US-290 corridor, with more overall improvements in critical groupings of links near intersections. Interestingly, the largest improvements in travel times from using reservations instead of traffic signals occurred at queues for right turns onto the freeway. A possible explanation for this result is that making a right turn conflicts with less traffic than going straight or making a left turn. Although signals often combine right-turn and straight movements, reservations could combine turning movements in more flexible ways. Although larger improvements in travel times occurred at the observed right turns, improvements at left turns were also observed. Because US-290 has signals intermittently spaced throughout the model's span on arterials crossing the expressway, vehicles are frequently stopping at lights, causing signal delays, which can increase as the demand increases. Using the reservation system, the flow of traffic is stopped less frequently, if at all, reducing congestion along the freeway. Also, in the US-290 network, analyzing the effects of reduced reaction times showed that improvements to travel times were made due to the reaction times and their respective capacity increases, but these improvements were less than those experienced due to reservations. It is also important to note that the use of one second and two second reaction times rather than 0.5 second and 1 second reaction times for the CAVs and HVs respectively did not affect travel times or any trends seen in the original reaction time simulations for any networks. In most cases, using reservations instead of signals doubled the improvements resulting from using CAVs. On US-290, reservations appear to have a positive effect on traffic flow and congestion in networks (freeway and arterial) that use signals to control intersections. Figures 11.5 and 11.6 depict the results for MoPac and US-290.

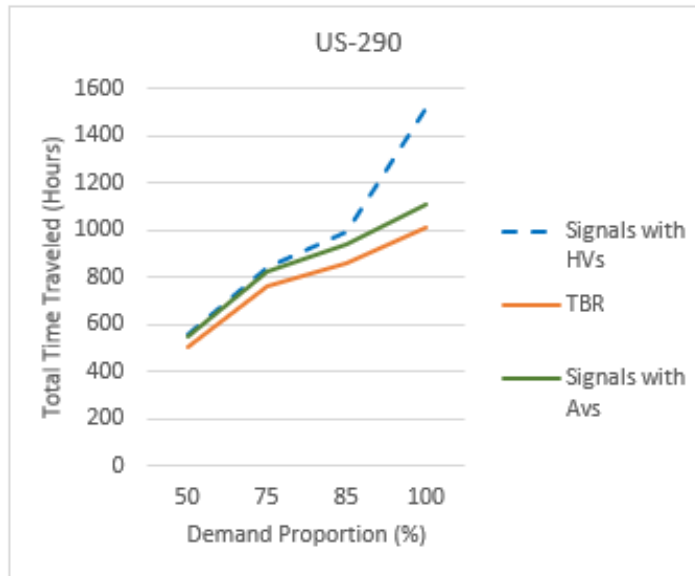


Figure 11.5 Freeway Network Travel Time Results for MoPac

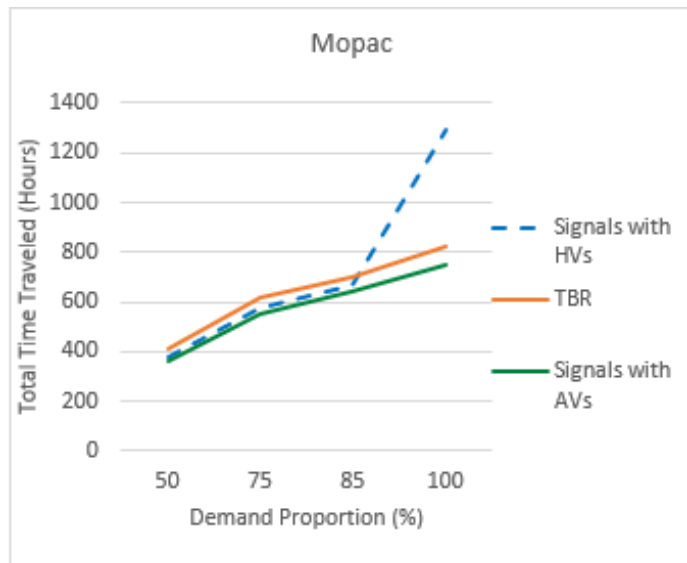


Figure 11.6 Freeway Network Travel Time Results for US-290

Effects of Autonomous Vehicles on City Networks

For the downtown network of Austin (Figure 11.7), simulations were run at 100% demand for different proportions of CAVs in a traditional signal system. Additionally, the downtown Austin network was run with the TBR system at 100% CAVs, as shown in Table 11.1. Downtown Austin differs from the previous networks in that many route choices are available.

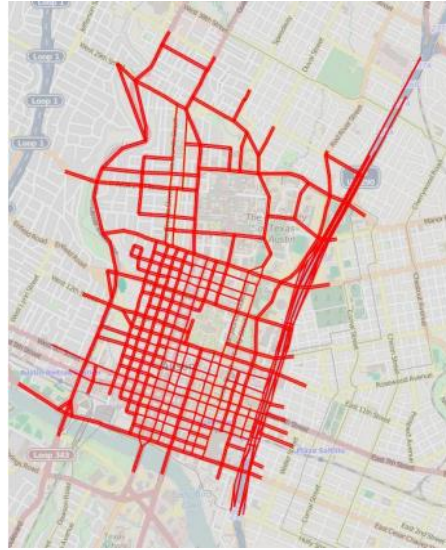


Figure 11.7 *Downtown Austin Network*

Reservations greatly helped travel times and congestion in the downtown network, cutting travel times by an additional 55% at 100% demand. When combined with reduced reaction times, the total reduction in travel time was 78%. Reservations were highly effective in downtown Austin—more effective than in the freeway or arterial networks, even under high congestion. In downtown Austin, most intersections are controlled by signals with significant potential for improvement from reservations. Although many intersections are close together, congested intersections might be avoided by dynamic user equilibrium route choice decisions, avoiding the issues seen with reservations in Lamar & 38th Street. The increased capacity from 100% CAVs also contributed to much less congestion, reducing travel times by around 51%.

Table 11.1 Downtown Austin City Network Travel Time Results

Downtown Austin				
Network System	Demand	Proportion of CAVs	TSTT (hr)	Min/veh
Signals	100%	0	18040.2	17.23
Signals with CAV's	100%	0.25	13371.4	12.77
Signals with CAV's	100%	0.5	11522.3	11
Signals with CAV's	100%	0.75	9905.1	9.46
Signals with CAV's	100%	1	8824.7	8.43
TBR Reservation System	100%	1	3984.3	3.8

11.4 Summary of Work

In order to achieve the above objectives with regards to AIM, the research focused on two main sub-objectives:

- SemiAIM protocol:** SemiAIM is an enhanced version of the AIM protocol. As opposed to the AIM protocol, the SemiAIM protocol can correspond with semi-CAVs and HVs as well as full CAVs. Figure 11.8 summarizes the interaction model of the SemiAIM protocol between human drivers, driver agents (with CAV or semi-CAV capabilities), and the Intersection Manager (IM). Inclusion that the vehicle has a single button to signal the driver agent to ask for a reservation is required. After the human driver presses the button, the driver agent will automatically send a request message to the IM on behalf of the human driver. It is also important that there is a clear Okay indicator (such as a green light) installed in the car that indicates when the request has been confirmed. After seeing the okay signal, the driver would have to actively pass control to the driver agent, again by pressing a single button. This way the driver will not be surprised by any sudden autonomous actions of the vehicle. The driver's involvement in this procedure depends on the level of autonomous capabilities installed in the car. SemiAIM requires the human driver to perform only relatively simple driving maneuvers such as holding the steering wheel at a certain angle or driving as if under a traffic signal. These tasks are much simpler than other maneuvers such as lane changing and passing other vehicles, and thus should not be taxing to experienced human drivers.
- SemiAIM simulator:** In order to experiment with the SemiAIM protocol, a SemiAIM simulator was devised. Based on the AIM simulator, SemiAIM is able to simulate semi-CAVs and human drivers as well as full-CAVs. Some experiments to test the efficiency of the SemiAIM protocol have been run using the SemiAIM simulator. These showed that (as expected) as the percentage of cars with autonomous capabilities increases, then each vehicle suffers less delays. Figure 11.8 presents the average delay per car while crossing the intersection (y-axis) against the ratio of CAVs/HVs (x-axis) for different types of autonomous capabilities. Traffic level was fixed at 360 vehicles/lane/hour.

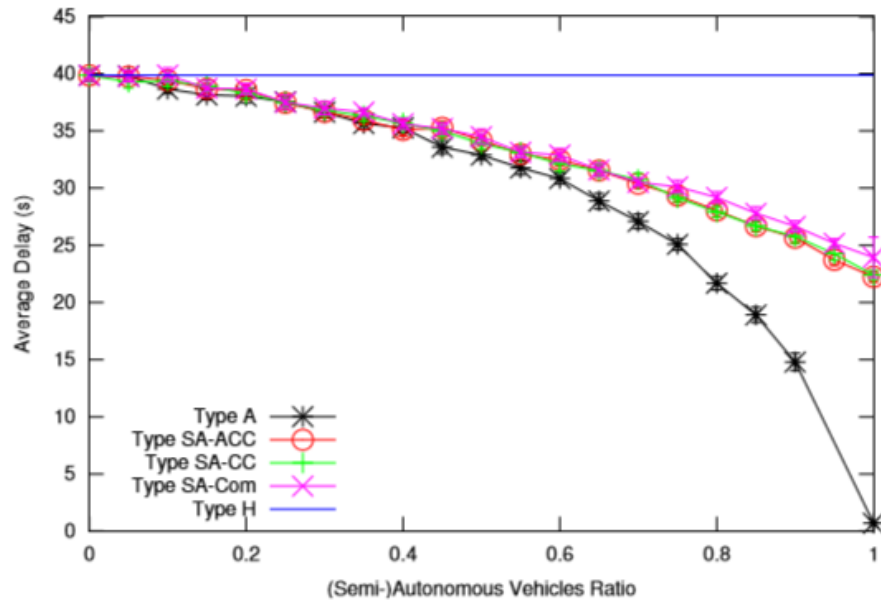
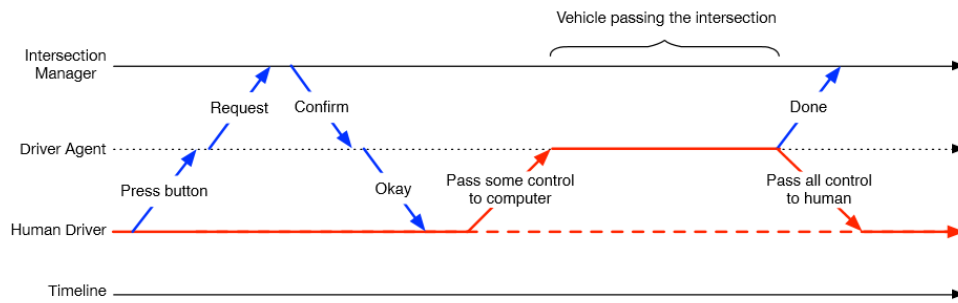


Figure 11.8 Average Delay vs. Different Ratio of Autonomous/Human Drivers at Traffic Level of 360 Vehicles/Lane/Hour



CHAPTER 12 IMPLEMENTATION OF DYNAMIC MICRO-TOLLING

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12.1 Introduction

This chapter introduces a novel tolling scheme denoted Δ -tolling. Δ -tolling approximates the marginal cost of each link using only two variables (current travel time and free-flow travel time) and one parameter. Due to its simplicity, Δ -tolling is fast to compute, adaptive to current traffic, and accurate. This section proves that, under some assumptions, Δ -tolling results in tolls that are equivalent to the marginal cost, and it demonstrates that Δ -tolling can lead to near-optimal performance in practice.

12.2 Motivation and Problem Definition

This section defines the notion of *user equilibrium* (UE) and *system optimum* (SO). Applying tolls is then introduced as a mechanism that allows UE and SO to coincide. The *marginal cost toll* (MCT) policy is then presented, followed by some mesoscopic traffic models that approximate it. Discussions on some of the drawbacks of such meso-models are presented, which provide the motivation for the current study.

Computing User Equilibrium

Consider a directed network $G = (V, E)$, where V and E are the set of nodes and links respectively. Suppose that the demand (flow rates) between every pair of nodes is known. In this chapter the travel time, t_e , on a link $e \in E$ is a function of its flow (x_e) and is represented using a non-decreasing function $t_e(x_e)$ (also called

volume delay or link-performance functions). In practice, the Bureau of Public Roads (BPR) function $t_e(x_e) = T_e(1 + \alpha(\frac{x_e}{C_e})^\beta)$ is commonly used as the delay function, where T_e is the free-flow travel time and C_e is the capacity of link e . Finally, α and β are parameters whose default values are 0.15 and 4, respectively.

When agents choose routes selfishly, a state of equilibrium, called *user equilibrium* (UE) (Wardrop 1952), is reached in which all used routes between an origin-destination (OD) pair have equal and minimal travel time. The link flow rates corresponding to this state can be obtained by solving a non-linear convex program that minimizes the Beckmann potential function ($\sum_{e \in E} \int_0^{x_e} t_e(x_e) dx$) (Beckmann et al. 1956). This objective ensures that the KKT (Karush-Kuhn-Tucker) conditions (Kuhn and Tucker 1951; Karush 1939) of the convex program correspond to Wardrop's UE principle (Wardrop 1952). The constraints of the optimization problem include non-negativity and flow conservation constraints. This model, also known as the *traffic assignment problem* (see Patriksson [1994] for a thorough overview), has been widely studied because of the mathematically appealing properties associated with convex programming.

Computing System Optimum

The System Optimum (SO) problem is the most conducive outcome produced by a set of programs. It can be formulated using a set of constraints similar to those used for computing UE but replacing the objective function with $\sum_{e \in E} x_e t_e(x_e)$. As mentioned before, all agents do not experience equal and minimal travel times at the SO state, which incentivizes agents to switch routes. Instead, if an optimal tolling policy is applied, the flows resulting from a UE assignment in which agents minimize the generalized cost (time + toll) coincides with the SO solution. MCT (Pigou 1920; Beckmann et al. 1956; Braess 1968) is one such policy, where each agent is charged a toll that is equal to the increase in travel time he or she inflicts on all other agents. Unfortunately, knowing in advance the marginal impact of an agent on traffic is infeasible in practice.

Approximating Marginal Cost Tolls

The focus of this chapter is presenting methods that approximate marginal costs. Most of these methods assume that demand on each link is constant. In such cases MCT can be formally defined as follows: given a link (e) and flow (x_e), the toll applied to e equals the change in travel time caused by an infinitesimal flow ($\frac{dt_e(x_e)}{dx_e}$) multiplied by the number of agents currently on this link (x_e).

A number of researchers have attempted to develop macro-models that approximate MCT for a given system (Yang et al. 2004; Han and Yang 2009). However, a major drawback of such macro-models is that they are static and do not capture the time-varying nature of traffic. They also assume that the delay on each link is a function of its flow and hence neglect effects of intersections and traffic shocks. Although there has been some research on congestion pricing using finer traffic flow models, most of the existing models either assume complete knowledge of demand distribution over time (Wie and Tobin 1998; Joksimovic et al. 2005) or are restricted to finding tolls on freeways in which travelers choose only between parallel tolled and free general-purpose lanes (Gardner et al. 2013, 2015; Yin and Lou 2009). This limitation motivates us to employ a simulation framework to simulate traffic in a more realistic manner, evaluate the performance of existing macro-models, and develop new methods to determine optimal tolls while adapting to unknown and changing demand.

12.3 Simulation

In order to evaluate the effectiveness of different tolling models on traffic flow optimization, a modified version of the AIM microsimulator (Dresner and Stone 2008) was chosen.

Autonomous Intersection Manager Simulator

AIM provides a multi-agent framework for simulating CAVs on a road network grid; it presents a realistic traffic flow model that allows experimenting with adaptive tolling. The AIM simulator uses two types of agents: intersection managers (one per intersection) and driver agents (one per vehicle). Intersection managers are responsible for directing the vehicles through the intersections, while the driver agents are responsible for

controlling the vehicles to which they are assigned. To improve the throughput and efficiency of the system, the driver agents “call ahead” to the intersection manager and request a path reservation (space-time sequence) within the intersection. The intersection manager then determines whether or not this request can be met. If the intersection manager approves a driver agent’s request, the driver agent must follow the assigned path through the intersection. On the other hand, if the intersection manager rejects a driver agent’s request, the driver agent may not pass through the intersection but may attempt to request a new reservation.

At every intersection, the driver agent navigator runs an A^* search (Hart et al. 1968) to determine the shortest path leading to the destination of the vehicle associated with it. The navigator then directs the driver agent to drive via the shortest route. This behavior ensures that each vehicle acts greedily with respect to minimizing travel time. Next, the required enhancements to the standard AIM simulator (Dresner and Stone 2008) necessary to simulate realistic tolling experiments are outlined.

12.4 Enhancements to the AIM Simulator

In order to evaluate adaptive tolling using AIM, the following modifications were required:

- **Link toll:** each link (e) in the road network is associated with a toll, $toll_e$, which can adapt in real time according to traffic conditions.
- **Link travel time:** each link stores (1) an estimated travel time, t_e , that is based on real-time observed flow speed, and (2) an estimated free-flow travel time, T_e , that is based on the link’s length divided by its speed limit.
- **Route selection:** when a car has several routes leading to its destination, the driver agent chooses the route ($r = e_1, e_2, \dots, e_3$) that minimizes $\sum_{e \in r} t_e \times VOT + toll_e$, where VOT is the monetary *value of time*.
- **Value of Time:** each driver agent is associated with a randomly generated VOT that is drawn from a normal distribution. Monetary units are chosen such that the mean value is 1 per second and assume a standard deviation of 0.2. VOT represents the value (in cents for instance) of one second for the driver. A driver with $VOT = x$ is willing to pay up to x in order to reduce travel time by 1 second.

Macroscopic Model

This research uses a macroscopic model to approximate MCT. This model is used to solve convex programs using Algorithm B (Dial 2006). Algorithm B is a bush-based/origin-based algorithm, which exploits the fact that, at equilibrium, all used routes carrying demand from a particular origin must belong to an acyclic subgraph in which each destination can be reached from the origin (such a subgraph is also called a bush). At each iteration, the algorithm maintains a collection of bushes (one for each origin), shifts agents within a bush to minimize their generalized costs, and adds or removes links in a bush until equilibrium is reached. Closeness to equilibrium is measured using *average excess cost*, which represents the average of the difference between each agent’s generalized cost and the least cost path at the current flow solution. In the experiments presented in this chapter, the algorithm was terminated when the average excess cost of the flow solution dropped below a tolerance level of 10^{-13} .

Example Road-Network

Figure 12.1 illustrates an exemplar road network demonstrating the impact of tolls that adapt to traffic demand. The speed limit across all roads is 25 meters per second. Each horizontal road is 142 meters long, and each vertical road is 192 meters long. A scenario was examined in which agents enter the network from a single source, the top road (incoming arrow), and leave the network from one of two destinations (outgoing arrows): D1 or D2. All roads are composed of two lanes per direction and assumed to have infinite capacity¹¹⁴ except the two vertical roads in the middle of the network (congestible links #1 and #2), which possess only one lane

¹¹⁴The capacity on roads with two lanes is higher than the rate in which agents are spawned. Hence, we consider such roads as having infinite capacity.

(capacity = 1,908 agents per hour). An agent entering the system and heading towards D1 (or symmetrically D2) has two possible routes to choose from: a short route (668 m) or a long route (964 m). Each agent chooses one of the two routes according to the distance, traffic conditions, and tolls associated with it. This road network represents a special case where if most agents are heading to D1 (or symmetrically D2) then link #1 (#2) should be tolled, while link #2 (#1) should not. Define z (or symmetrically, $1 - z$) to be the proportion of agents heading to D1 (D2). The incoming traffic rate was set to 2160 agents per lane per hour.

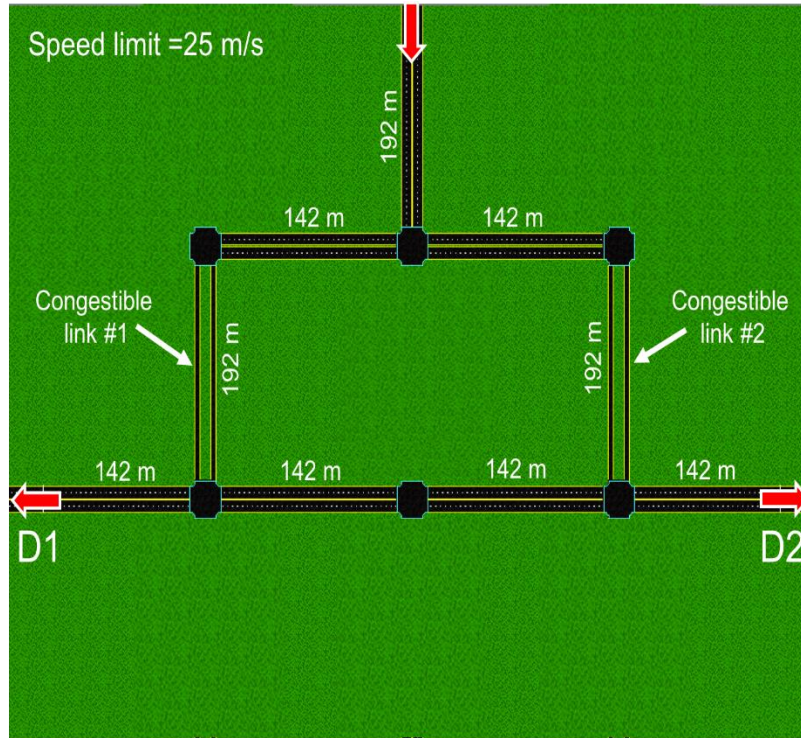


Figure 12.1 Example Road Network within the AIM Simulator

Empirical Evaluation: Macroscopic Model

One of the main contributions of this chapter is an empirical demonstration that setting tolls based on macro-models MCT approximations can lead to suboptimal results when evaluated in a more realistic microsimulator. This section presents these empirical results, which motivate our new tolling scheme as presented in the next section. The experimental results obtained from the adapted AIM simulator are reported using the road network described in the previous section (depicted in Figure 12.1). The percentage of cars going to D1 (D2) is defined to be z ($1-z$). The incoming traffic rate was set to 2160 cars per lane per hour.

Table 12.1 presents these results. The left side of the table shows the empirical optimal and macro-model predicted toll values (imposed on link #2) for different z values. The right side shows average travel times when no tolls, static tolls, optimal tolls, macro-model tolls, and Δ -tolls are applied as calculated by the AIM simulator. The asterisk (*) indicates statistical significance over no tolls (using unpaired t-test with $p_{value} = 0.05$).

Table 12.1 Toll Values and Travel Times

z	Toll Values		Average Travel Time (seconds)				
	Optimal	Macro Model	No Toll	Static Toll	Optimal Toll	Macro Toll	Δ -Toll
0.0	15	14.8	46.0	47.6	40.9*	40.3*	40.5*
0.1	10	14.8	43.2	45.1	39.1*	39.3*	39.0*
0.2	10	14.8	38.4	40.8	35.8*	38.4	36.9*

0.3	10	14.8	34.3	35.1	33.8	37.7	33.1*
0.4	0	14.8	31.7	32.4	31.7	36.8	31.4
0.5	5	-5.3	30.8	31.2	30.8	30.9	30.9
0.6	5	-14.8	31.1	31.5	31.1	34.7	31.6
0.7	-5	-14.8	32.2	32.2	32.2	35.2	32.8
0.8	-10	-14.8	37.0	34.1*	34.1*	36.2	35.8*
0.9	-10	-14.8	40.7	36.2*	36.2*	36.8*	36.5*
1.0	-15	-14.8	43.1	39.0*	38.5*	38.1*	38.7*

Computing the Optimal Tolls

The toll values that optimize average travel time for each $z \in \{0.0, 0.1, 0.2, \dots, 1\}$ were computed by brute force. Consider tolling only congestible link #2. Tolling links that are not susceptible to congestion is unnecessary, as there is no congestion externality associated with travel on these links. Moreover, there is no reason to toll both congestible links simultaneously (#1 and #2) since any of the two possible routes (leading from source to Di) includes exactly one of these links. A negative toll value for link #2 is symmetrical to a positive toll on link #1. There is a distinction between the optimal adaptive toll and the optimal static toll. The optimal adaptive toll is the toll value that minimizes travel time for a given z value. The optimal static toll is the toll value that minimizes travel time over all z values (assuming equal weighting of the z values, i.e., all z values have the same probability), found to be -10 in this example. While it might seem like the optimal static toll should be zero, asymmetries in the model arising from differences between left and right turns affect junction delays and skew the optimal static toll to one side.

Optimal adaptive tolls for each z value are presented in Table 12.2. Notice that as the z value increases, the optimal toll steadily decreases. Intuitively, when all agents go to one destination ($z = 0$ or $z = 1$), more of them choose the longer route to achieve the optimal system flow, thus requiring a more extreme toll. When $z \approx 0.5$, a zero toll is optimal since agents that choose their longer route will only make congestion worse for agents going to the other destination. As a result, enforcing tolls for $0.2 < z < 0.8$ did not result in a significant improvement over enforcing no tolls.

Evaluating Optimal Tolls using a Macro-Model

Toll values calculated by the macro-model are also presented in Table 12.2, as well as average travel time under different tolling policies. Though the macro-model obtains near optimal results for the extreme z values and $z = 0.5$, it is sub-optimal for intermediate values. One explanation for this phenomenon is that the stylized congestion models assume that delays on a link are a function solely of flow on that link, ignoring interactions between links at intersections. For the extreme z values this assumption is more reasonable because almost all agents on congestible links are heading in the same direction. However, for the intermediate values (excluding 0.5), the agents on the congestible links encounter traffic on the bottom horizontal link (by cars taking the longer route), causing changes in the capacity of the congestible links that cannot be captured by a stylized model. These results lead us to the following conclusions:

- Tolls can reduce average travel time by up to 11% compared to applying no tolls (see $z = 0$).
- Static tolls might have a negative effect in some cases (see $z < 0.6$).
- The macro-model fails to achieve SO, in some cases reaching up to 10% suboptimality (see $z = 0.3$).

Both static and adaptive macro-model based tolls (a) result in suboptimal performance and (b) require that the demand over all OD pairs is known and fixed. As a result, neither is applicable to real-world traffic. Thus, there is a need for a new tolling scheme that is dynamic, adaptive, and results in near-optimal traffic flow.

12.5 Delta-tolling Technique (Δ -tolling)

This section introduces the main technical contribution of this research, a new tolling scheme called “delta tolling” (Δ -tolling). Unlike macroscopic models, Δ -tolling is adaptive to unknown and changing link

capacities and demands. First, Δ -tolling is defined and then proven, under mild assumptions, to be equivalent to MCT.

Δ -tolling is defined over a directed network $G = (V, E)$ (a road network, for example) with a set of current flow values (traffic volume, for example). The output of Δ -tolling is a set of toll values, with one toll value per link. Let t_e denote the current flow time on link $e \in E$. Recall that T_e denotes the free-flow travel time and $toll_e$ denotes the toll value assigned to link e . For each link (e), Δ -tolling assigns a toll equivalent to the difference between the current flow time (t_e) and the free-flow time (T_e) multiplied by a parameter (β). More formally: $\Delta\text{-toll}_e = \beta(t_e - T_e)$. As a rule of thumb, β should be correlated to the mean VOT. High β values result in high toll values, which are needed to influence agents with high VOT. Calculating $\Delta\text{-toll}_e$ requires a constant amount of time. As a result, the complexity of computing tolls for an entire network is $\theta(E)$.

In Box 1, proof is given that Δ -tolling is equivalent to MCT under some conditions. This is a desirable property, since MCT results in SO (see Section 12.2). The assumptions under which the above statement holds are:

- The delay on each link is expressed by the BPR volume delay function, $t_e(x_e) = T_e(1 + \alpha(\frac{x_e}{c_e})^\beta)$.
- Changes in demand are negligible between the time an agent plans its route and the time it executes it.

Lemma 1 Under the above assumptions, the tolls computed by Δ -tolling are equivalent to the MCT.

Proof: We express the BPR volume delay function as:

$$(1) t_e(x_e) = T_e + ax_e^\beta$$

$$\text{where } a = T_e \frac{\alpha}{c_e^\beta}$$

MCT, under the above assumption 2, is defined as the derivative of the delay function

$(\frac{dt_e(x_e)}{dx_e})$ multiplied by the current flow (x_e). So:

$$(2) MCT_e = x_e \frac{dt_e(x_e)}{dx_e} = x_e(\beta ax_e^{\beta-1}) = \beta ax_e^\beta = \beta(T_e + ax_e^\beta - T_e)$$

Combining (1) and (2):

Figure 12.2 Box 1

The main theoretical differences between Δ -tolling and macroscopic models are summarized in Figure 12.2. In the next section the differences in performance are studied using the adapted AIM simulator.

Table 12.2 Model Tolling The Different Parameters, Variables, and Properties of Δ -tolling and Macro-

	Macro-model	Δ -tolling
Parameters	Required	
α	yes	no
β	yes	yes

Variables	Required	
Demands	yes	no
C_e	yes	no
T_e	yes	yes
t_e	no	yes
Properties	Satisfied	
Adaptive	no	yes
MCT	yes	yes

Note: MCT refers to approximating the marginal cost.

Although the assumptions made in this section might not hold in all possible traffic networks, experimental results show that in realistic simulations, Δ -tolling improves traffic flow and may achieve near optimal flow.

Empirical Evaluation of Delta-Tolling

This section analyzes the performance of Δ -tolling on a representative road network. Findings are then generalized and shown to hold for randomly generated networks. Initially, the system performance when using Δ -tolling on the example road network (presented in Figure 12.2) was examined. Table 12.1 also presents the average travel time for Δ -tolling. Unlike the macro-model, Δ -tolling achieves performance that is similar to the optimal. The toll values for Δ -tolling are not reported as they are dynamically changing across the simulation.

Next, simulations were run to engender results for larger networks. In such networks finding the optimal tolls in a brute force manner is infeasible.¹¹⁵ For the following experiments, grid networks of size 3×3 are used. These grids include nine intersections (see Figure 12.3 for an example). Agents enter at the same rate of 300 agents per hour from any incoming lane (a road with three lanes, for example, spawns 900 agents per hour). Each agent entering the system is assigned one of two possible exit roads with equal probability (0.5). Each agent is also assigned two alternative exits. Exiting via an alternative exit imposes a predefined, randomly generated, delay.¹¹⁶ Alternative exits are justified because in many real-life scenarios several routes, usually of different lengths, may lead an agent to its destination. For example, while a driver exiting Manhattan and heading to Queens will prefer to use the Queens Midtown Tunnel, the driver can suffer some delay and instead exit from Ed Koch Queensboro Bridge or suffer a severe delay while exiting via Williamsburg Bridge. Following this logic, the simulated network is viewed as part of a larger road network in which agents may use paths outside of the network to reach their final destination.

In the representative road network, each agent is assigned one of two destinations (**D1**, **D2**). **A1** and **A2** denote alternative destinations for **D1** and **D2** respectively. The time penalty associated with each alternative destination is given in parenthesis.

¹¹⁵Examining different combinations of toll assignment to all links in the system leads to an exponential blowup.

¹¹⁶When each agent is assigned only one possible exit, distributing traffic becomes impossible in many cases. For such scenarios, imposing tolls did not have a positive effect in our experiments.

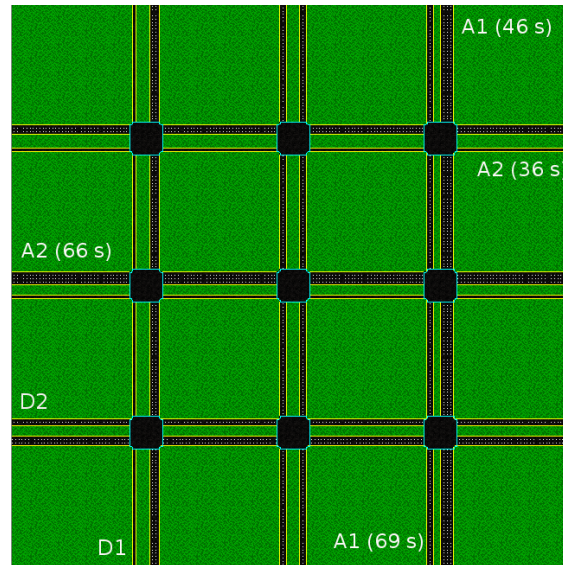


Figure 12.3 A Representative Road Network

Some roads in the simulated network are more congestible than others, i.e., the number of lanes varies. The number of lanes for each road was randomly selected as either 1, 2, 3, or 4. Simulations were run for 5000 seconds for each reported setting.¹¹⁷ In the following experiments, an upper bound on toll values was set equal to.¹¹⁸ The upper bound is set for two reasons: (1) avoiding overcharging in links with temporary heavy congestion; (2) avoiding oscillation in congestion caused by overpricing. Applying no cap on toll values resulted in up to 5% reduced utility. There are three different measurements to report:

- **Time:** the average travel time.
- **Utility:** the average utility (in cents). Where utility is defined for each agent as its travel time multiplied by its VOT plus the summation of tolls paid by it.
- **Standardized Utility (SU):** toll revenue may be redistributed back to the drivers in the form of road improvements or tax reductions. *Refund* is the sum of collected tolls divided by the number of agents that exited the system. SU is defined as average utility minus refund.

Representative Road Network

The purpose of our first experiment is to determine how different β values affect system performance. A single randomly generated instance of a 3×3 road network (depicted in Figure 12.2) was used for these simulations. Average travel time, utility, and SU for different β values are presented in Figure 12.3. Notice that $\beta = 0$ represent the case where no tolls are used.

¹¹⁷When running the simulator, in order to allow the system to balance, we excluded data from the first 500 seconds.

¹¹⁸The output from the macro-model contained no toll greater than 25. Hence, we deduced that greater tolls won't have a positive affect and we set the cap accordingly.

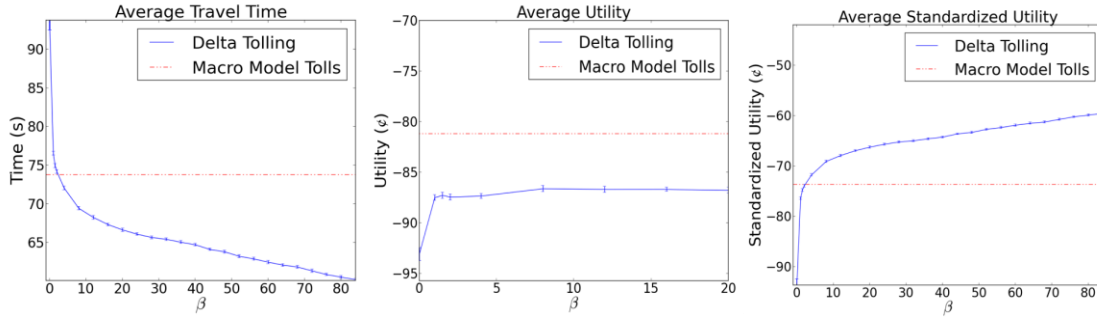


Figure 12.4 Average Travel Time, Utility, and SU as a Function of β for the Representative Road Network

Setting $\beta = 80$ gives an improvement of 35.0% in average travel time over no tolls. Setting $\beta = 80$ also gives an improvement of 35.0% for SU over no tolls. β values greater than 80 result in average travel times that are not significantly worse or better. Increasing β (up to 80) results in higher toll values that better distribute congestion. However, higher tolls also negatively impact utility as drivers are forced to pay more. Utility is maximized with $\beta = 8$, which gives a 7.0% improvement over no tolls. Performance for setting tolls that are computed by the macro-model is shown as a dashed (red) line across the result graphs. Δ -tolling outperforms macro-model tolling for $\beta \geq 4$ by up to 18% in both average travel time and SU. On the other hand, macro-model tolling exceeds by 6.3% when utility is considered. The main reason for the macro-model’s advantage with respect to utility is that Δ -tolling imposes higher toll values. Δ -tolling (with $\beta = 8$) collected a total of \$1,921 while macro-model tolling collected only \$825. Unfortunately, higher tolls are required to better distribute congestion and optimize system performance. On the other hand, SU is a more relevant measurement for performance comparison between the models. In real road networks, tolls are most often used to fund road maintenance, effectively redistributing the money collected back to the public. When SU is considered, delta tolling significantly outperforms the macro-model in all but very low β . Moreover, macro-model tolling relies on static traffic conditions, and so unlike Δ -tolling, it is not applicable to real-life, dynamic road networks.

Evaluating Optimal Tolls using a Macro-Model

In order to validate that the results obtained from a single randomized instance are representative, multiple simulations of the same experiment were run using 50 different randomized road networks. Each of these networks is a 3×3 grid, similar to the representative road network, but the exit roads, alternative exits, alternative exits’ delay, and number of lanes per road are randomized. Table 12.3 shows results for three representative β values (8, 20, 80) compared to no tolling. $\beta = 8$ and $\beta = 80$ were chosen since they maximized performance with respect to utility and travel time/SU. $\beta = 20$ represents a good balance between utility and travel time.

The advantage of Δ -tolling is that it is responsive to changes in network topology. For the general case, Δ -tolling achieves an improvement over no tolling of 29.2%, 9.3%, and 30.3% in Time, Utility, and SU respectively.

Table 12.3 Average Travel Time, Utility, and SU for β Values 8, 20, 80

β	Time	Utility	SU
0.0	69.9	-70.0	-70.0
8.0	51.4*	-63.5	-51.1*
20.0	50.3*	-67.0	-49.8*

80.0	49.5*	-76.6	-48.8*
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Note: These β values represent a trade-off between the three metrics.

*Denotes a statistically significant improvement over no tolling (using a paired t-test with p-value=0.05).

12.6 Conclusions

This chapter considers applying tolls to road networks in order to direct the route choice of self-interested agents towards a system optimal. The notion of such a tolling scheme is becoming more practical as cars are becoming increasingly autonomous and the computational effort required to evaluate several alternative routes is becoming more feasible.

This chapter envelops two main contributions. First, using a traffic microsimulator (AIM), the empirical evidence suggests that stylized macroscopic traffic models are unable to approximate optimal tolls accurately. Given this finding and the fact that such models require full knowledge of demand and supply and assume that these remain fixed, the research team concluded that using such models to set tolls in real-life road networks is impractical. This conclusion leads to the second contribution, the presentation and evaluation of a new tolling scheme, denoted Δ -tolling. Theoretical and empirical evidence shows that Δ -tolling results in near-optimal system performance while being adaptive to traffic conditions and computationally feasible.

CHAPTER 13 DESIGN AND IMPLEMENTATION OF A SHARED AUTONOMOUS VEHICLE SYSTEM IN AUSTIN, TEXAS

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13.1 Introduction

Implementation of shared, self-driving vehicles may completely alter society's experience of transit. One socially-equitable implementation of fully-autonomous self-driving vehicles (AVs) is a shared (SAV) fleet system, which will provide sustainable and cost-effective transit for communities. The ability to allow for expanded mobility and environmental benefits was part of the impetus to provide a forward-looking perspective into the geometrical renderings of this future transit option. Dynamic ride sharing (DRS) is the use of chained trips, which will allow for varied level of service depending upon patron preferences, providing an increased system capacity while rewarding patrons for ride sharing.

The designs developed here integrate a DRS-SAV fleet into the Austin, Texas setting with the assumption that fully operable SAV technology is market-ready. The fleet system builds upon Kornhauser's (2013) DRS-SAV simulations in New Jersey, which contained hub centers where SAVs would function to serve patrons. Jorge and Correia's (2013) notion of one-way transit options bolstered the idea of the ride-sharing program. Ride-sharing, which has its benefits if implemented in more mass, led to a 40% reduction in cumulative trip length if ridesharing had more systematic influence (Resta, Santi et al 2014). Additionally, DRS outperforms non-ridesharing systems in multiple performance measures, including environmental (Zhang and Guhatharkurta 2015a). These four different station locations (explained schematically later in this paper), provide service to special trip generators, along with door-to-door service. Benefits from promoting transit systems, ride-sharing, reduction of individual car-ownership, and the enhanced safety of these vehicles allow the City of Austin to grow within the existing roadway infrastructure. Each AV is assumed to replace 14 traditional vehicles from the network (Zhang and Guhathakurta 2015a). This proposal provides an insight into the future of transit systems within the urban setting, paving the way for cities to implement this type of technology. With a base fee of a dollar per person and a dollar for each mile traveled, the transit system rivals comparable alternatives as displayed in Table 13.1.

Table 13.1 Cost Comparison for Similar Transportation Alternatives in Austin

User Cost of Different Shared Vehicle Systems from Austin Bergstrom Airport to Downtown's Seaholm Station Area (11.2 miles)	
Uber	\$26
Lyft	\$33
Car2Go	\$14
Yellow Cab	\$31
Proposed SAV System	\$13

13.2 Framework for the Transit System

An AV is defined as a car that can “perceive its environment, decide what route to take to its destination, and drive it” (Yeomans 2014). There are different levels of autonomy, varying by the amount of driver assistance needed to operate the car. Current market technology includes adaptive cruise control, self-parking capabilities, and “pilot-assist” technology for congested conditions (Kessler et al 2015). This assumption of market-ready level 4 technology is used here for design and system functionality, which is critical for determining how the car operates within the roadway network and the role of those inside.

At the fully-autonomous stage, the car would be able to navigate itself in known and unknown situations. Vehicle control systems that automatically brake and accelerate provide much more efficient reaction times than an average driver (Preliminary Statement of Policy Concerning Automated Vehicles). Because of the eventual removal of human decision making on the roadways, AV technology will have the capabilities to decrease headways between vehicles, thereby drastically increasing the roadway capacity without having to add additional infrastructure. According to the Environmental Protection Agency in 2010, the value of life was estimated at around \$9.1 million (Appelbaum 2011). Every year on the road, 93% of traffic accidents are due to human mistake, which cause 1.3 million deaths and 50 million injuries worldwide (Yeomans 2014). Therefore, implementing cars that can fully drive themselves would have the potential to decrease collision rates and increase human productivity since everyone sitting in the vehicle will be a passenger capable of performing activities other than driving (Litman 2015). Many major companies like Mercedes-Benz, GM, and Google have already developed working AV prototypes. More recently, vehicles already equipped with sensors may be able to receive software updates to enable level 2 or 3 autonomy, as seen with the recent Tesla software updates to allow for autonomous features such as autopark, autosteer, auto-lane change, traffic-aware cruise control, and side collision warning (Teslamotors.com).

Currently, autonomous technology, excluding vehicle cost (note that some technology cannot be retroactively inserted), costs around \$20,000-\$80,000 which is much higher than most travelers are willing to pay (Litman 2013). Cost, along with the legal system and regulations, are the top three barriers to autonomous vehicle usage (Southwest Research Institute 2015).

System Technology Relating to the Network

The outlined boundaries of the Austin network are illustrated in Figure 13.1, encompassing 90 square miles. The system boundaries were determined by incorporating the most densely populated areas. This varies from the AV fleet system modeled by Fagnant and Kockelman (2014), which utilized a 12x 24 mile-bounded network. However, their simulation data serves here as a base measure for principles of vehicle relocation, person-trips to be served per SAV per day SAV and daily VMT per SAV. System-wide modeling is not used here, with individual vehicles loading individual network links and responding to specific customer calls on SAVs.

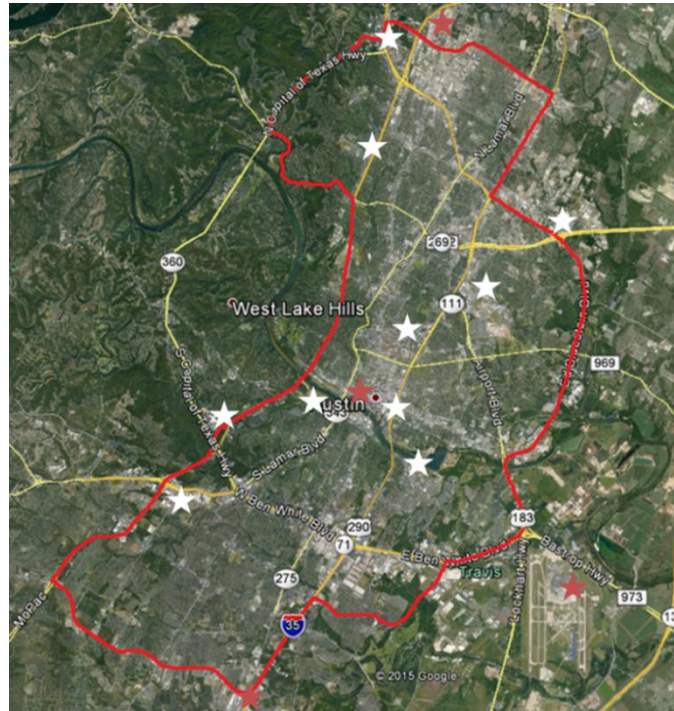


Figure 13.1 Project Limits with Station Locations (Source: Google Earth)

Figure 13.1 shows all station locations. Station placement was determined through a look at Austin's top travel corridors, population and jobs density maps, and reasonably equitable distribution of stations across the region, to help limit vehicle redistribution costs. Figure 1's red-star locations are top stations, with high demand and high levels of service frequency expected. These major stations differ from the white-star queuing areas; which are more common and allow for quicker alighting times at a reduced cost for the system operator. These system attributes are part of the parameters that would be geo-coded by a fleet operator in order to determine permissible drop-off areas in high density and high traffic areas. System design and operations decisions should also account for periods of peak demand (like the morning rush-hours), when more ride-sharing opportunities will exist. All of the data described above can be used in system-management software that will function and interact with patrons, similar to any transportation network company.

User Attributes

Understanding the system's users and how they will interact with the team's proposed product will help provide adequate and desirable amenities. Per assumptions, the basis of charging the passenger \$1.00 per mile of a non-shared trip (with the potential for that cost to decrease with sharing), the affordability of the product should not dissuade a significant percentage of travelers (Fagnant 2015). The DRS-SAV system rivals many other transit systems in the Austin area, as seen in Table 13.1, due to the elimination of driver costs. The costs related to this system and factors of sensitivity related to the variability of the costs of this product will be discussed in further detail in the cost analysis.

Barriers to public participation in this transit alternative are access to smartphones and one's psychological acceptance to cede control of the vehicle. However, this system can incorporate a wider array of patrons through personalization and a reflection of this personalization in the cost of the service. Examples of this personalization can range from the users preferred and maximum wait times, as well as increased levels of service (e.g., as in the use of tolled express lanes). Having the user interact with a mobile application will allow for data collection and suggestions regarding amenities for future stations, and will be helpful in creating shared knowledge and integration of new technologies.

Ridesharing Methodology

A typical ride will consist of the following: a traveler arrives at the station, and his or her willingness to share the ride will dictate where he or she is placed in the network's service queue. A third of U.S. ridesharing occurs between the hours of 7-8 AM and 5:30-7:30 PM (Zhang and Guharkakurta 2015a). If a ride request occurs during these peak times of day, increased ride-sharing or system overuse may occur, which would then mean all rides must be shared, to the greatest extent possible, to protect fleet seat capacity, and avoid not meeting traveler requests. Depending upon the time of day and the station, different vehicle relocation strategies as well as rider-distribution strategies will be utilized. One benefit of self-driving technology is the ability to provide door-to-door service. The transit system promotes ridesharing with stations in attractive destinations, but an added door-to-door service charge could be a way to further promote public-transit-type operations. Door-to-door service will be discouraged in high-density areas where alighting can be disruptive of traffic flows and/or dangerous to pedestrians. For a lower charge, patrons can be dropped off in designated areas, such as hotel valet parking areas, business driveways and hospital drop-off areas. Optimization techniques will reduce total service time even when additional stops are needed to accommodate more passengers (Fagnant 2015). Such techniques effectively increase the "true average vehicle occupancy" while minimizing average user wait times.

13.3 Design Overview

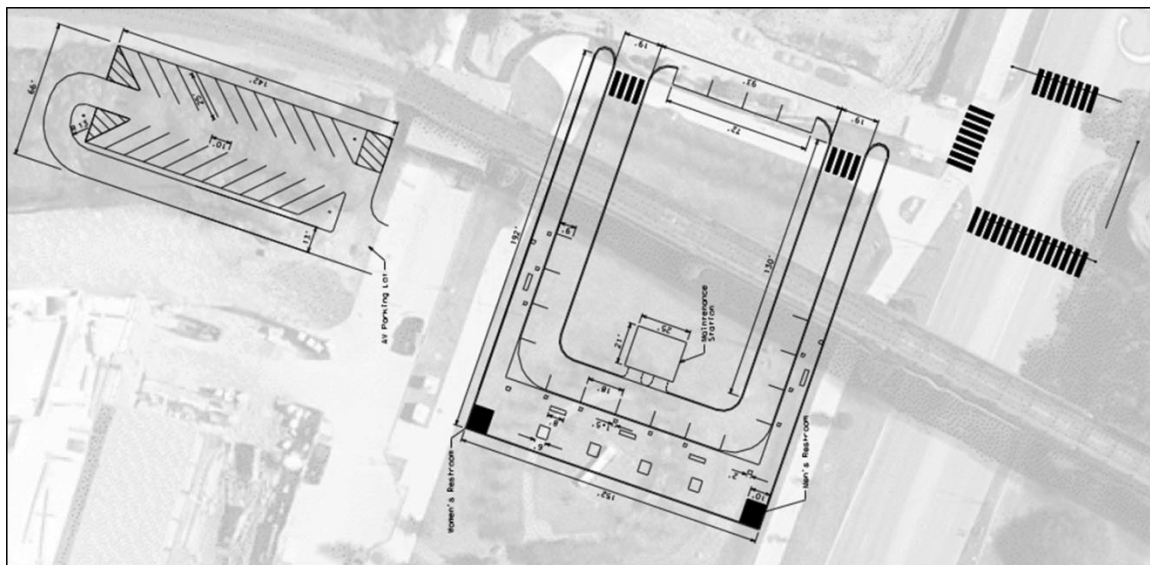
The proposed designs of these stations are backed by research, standards regarding transit systems, and an understanding of the amenities needed for the patrons and for the vehicles themselves. The design of each station has its own uniqueness in capacity, land-use, and clientele. Each of the four schematic drawings below was constructed using MicroStation and Google Earth. Figure 13.2 displays the location of the main station center in the downtown region, where new mixed-use projects will be attracting permanent residents who may prefer the freedom associated with not owning a vehicle.



Figure 13.2 DRS-SAV Station, Seaholm District (CBD Mixed-Use Setting)

DRS-SAV Station Attributes and Locations

DRS-SAV station attributes consider the people being served by that station as well as each station's surroundings. Station locations were determined based on the attractiveness of the surrounding businesses and relative areas. It is important to understand the surrounding businesses and land-uses to ensure that proper amenities are provided, such as having enough pick-up and drop-off spots. For example, many commuters may want to use a high-density area that is peripheral of the central business district (CBD) (which will serve peak-hour travelers) and park their vehicle within close proximity of the station. More densely packed areas that can serve a variety of passengers will need multi-modal access, promoting transit use and reducing the amount of personally owned vehicles, as well as additional infrastructure to support patrons. Selected locations will also require charging stations if EVs are pursued, which will be situated where vehicles are queued for significant time periods or stored overnight. The following four stations which were selected and evaluated in the project analysis correspond to a housed vehicle fleet of 400 AVs. This fleet size rivals competitors such as Yellow Cab Austin (461 permits), but the SAV-DRS system outperforms Yellow Cab Austin with regards to average passengers per month (342,000 vs. 276,738 respectively) (Derr, 2014).

*Figure 13.3 DRS-SAV Station Design at Seaholm Site, Plan View (CBD Mixed-Use Setting)*

CBD Mixed-Use Design

Mixed land use in a CBD proves an attractive transit destination for many people, suggesting a strong demand and need for SAV stations. With a focus on a high level-of-service and quick alighting times, the pedestrian area is segregated from SAV traffic. As seen in Figure 13.3, pedestrian amenities are centered towards the northwest of the station, conveniently situated across from apartments as well as bike and car-sharing programs. Due to the high anticipated traffic at this station, additional pedestrian amenities were provided such as restrooms and shaded waiting areas to provide comfort to patrons who may choose to wait for a shared-vehicle. Allowing for pedestrians to comfortably wait without impeding additional SAVs from entering the system mimics the design of many taxi areas for airport facilities. These SAV storage areas use diagonal parking to maximize the space and to allow for easy electric-vehicle (SAEV) charging access. City of Austin parking standards require 17'6" x 9' space minima (www.municode.com), but SAVs do not need to accommodate human access while parked, and many can be of compact or mini size; so their parking space standards can be reduced, in addition to eliminating striping and its maintenance. A benefit of this system is its ability to utilize presently unwanted or unused space, as shown in Figure 3, which incorporates the land below a heavy-rail line just west of Austin's CBD.

The Seaholm redevelopment project, a major mixed use area in the Austin CBD, poses as an exciting backdrop for a major metropolitan SAV station. The City of Austin owns a significant amount of property in this area; and, with the addition of a brand new public library, the city will be looking for different modes of transit to accommodate a growing amount of residents living in the area. The Seaholm station is the most capable station to hold a large fraction of the fleet system, given the projected density of the area, spurred by significant private investment as well as the current accessibility of land underneath the railway. The capacity of this fleet station is 31 vehicles (about 8% of the fleet analyzed here). The design incorporates three different components: an AV charging and storage area, a pick-up/drop-off area, and a waiting area complete with patron amenities.

Airport Alighting Design and Application

The following airport alighting design has considerable transferability to any major transit hub that would currently service taxis or rentals cars. Due to the similarities of the two systems, space may be able to be bought from existing infrastructure. Given the fixed drop-off locations in airports and the ease of implementation in terms of vehicle programming, this technology could also be seen as a way to transport people between terminals. Additional similarities to rental vehicle systems include the incorporation of a mixed-fleet (e.g., SUVs and hybrid electric vehicles), which can appeal to commuters outside of the major metropolitan region. The airport is a location of high demand in the Austin region, producing and attracting more daily trips than almost any other location in the region (Jin 2015). The need for public transit at this location is amplified due to the fact that users attempt to avoid costly parking fees by leaving their personal vehicles at home. These factors make the airport very appealing for one of the four major stations.

The airport, being a unique piece of infrastructure, offers a major challenge, one with huge benefits if the design can encourage a portion of the 10.7 million of people that use the Austin Bergstrom International Airport annually (<https://austintexas.gov>). This design displays 20 parking spaces (offered to 5% of total 400 fleet vehicle system), which serves as an initial number to be scaled up longer-term. The Airport DRS-SAV station will be highly visible as potential customers leave the airport and its proximity to the airport's exits allows for easy access by DRS-SAV users. Speed of service will remain competitive with taxis due to a well positioned garage exit ramp that can be reached from the Airport DRS-SAV station.

High Commercial Traffic Applications

A potentially successful application of this system can be found in repurposing additional car park space for transit stations, providing use for impervious cover that may be underutilized. Attracting more patrons to these commercial areas would benefit neighboring retailers with increased traffic from a diverse group of people who may not otherwise have access to these areas. Applications regarding SAVs in high commercial areas have already seen implementation in Milton Keynes, expanding their test fleet to over 40 vehicles at the end of the calendar year (Gordon-Bloomfield 2015). SAV investment options suggest that densely developed commercial and retail areas, as well as self-contained environments (like university campuses, airports, and hospital campuses) are good initial candidates for SAV services. This relates to the broader idea of taking these car-friendly commercial areas and applying mixed-land use in coordination with a SAV fleet system to help reduce personal automobile usage. Very few materials were put into the roughly 200' x 85' area that was designated for this SAV fleet station. The 10-foot-wide raised pedestrian median provides SAVs with two designated routes on either side of the structure, which can house 14 AVs. Additional SAV parking is located in a nearby parking garage which will accommodate an additional 20 vehicles. Furthermore, benches, charging stations, and covered areas are all made available on the 140' x 10' median (Figure 13.4). Since the proposed design is to use already existing concrete slab and striping, the design's difficulty will be greatly reduced. This commercial applicability is continued at Southpark Meadows, south of Austin's CBD, providing as a potential transit station for commuters coming from San Antonio.

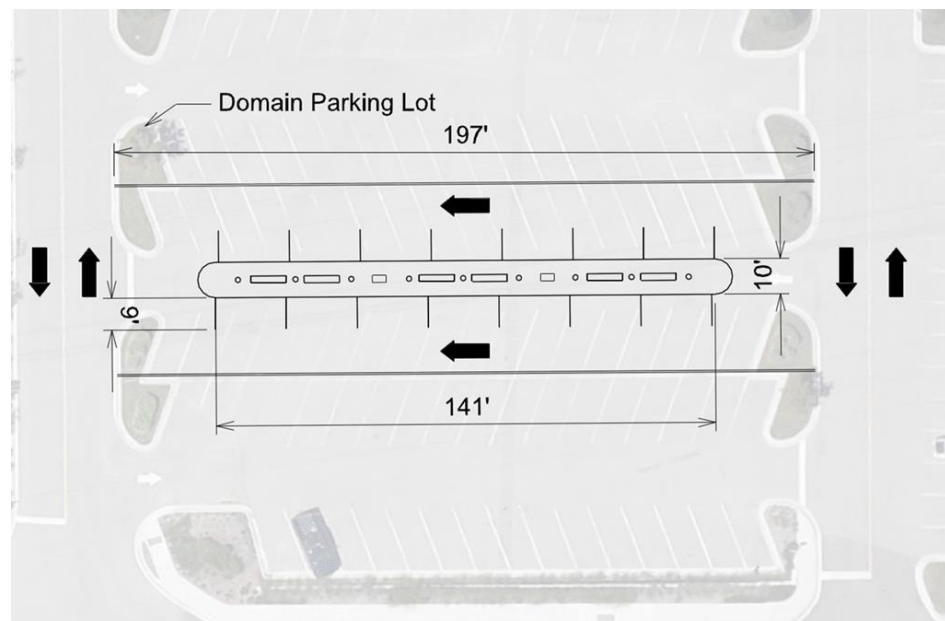


Figure 13.4 Domain Site's DRS-SAV Station Design (Mixed-Use Shopping Center)

Queuing Areas Attributes and Locations

Aside from the areas listed above for AV stations, the following areas were deemed attractive locations for rapid queuing areas. When considering the average wait time for a DRS-SAV system was less than two minutes, this further justifies these cost-effective queuing stations (Zhang 2015a). These areas were chosen for queuing because although they do not have the land capable of supporting an entire station and do not need significant amenities, they still have the demand to support fleet usage. Similar to a bus pick-up stop, the station will provide customers with the bare-essentials in terms of amenities while allowing for quick pick-ups in high-density areas with a significant amount of turnover. The locations of these smaller facilities are dictated primarily on the trip volumes in that area and its ride-sharing attributes. Due to the limited number of queue spots, origin and departure time for the patron can vary but arrival-departure layover time for each vehicle will be relatively short, especially if there is a high demand at the station which would require additional queue space. The last two preliminary designs are standard designs for queuing areas that may be scattered about Austin. The first design is positioned along Rainey Street, a popular neighborhood-bar area near the Austin Convention Center. The second is located in Zilker Park, home to Austin City Limits Music Festival as well as other events. These designs can be translated with ease to other areas of the city, providing a streamlined system to cut down on design costs while providing a recognizable queue area for patrons.

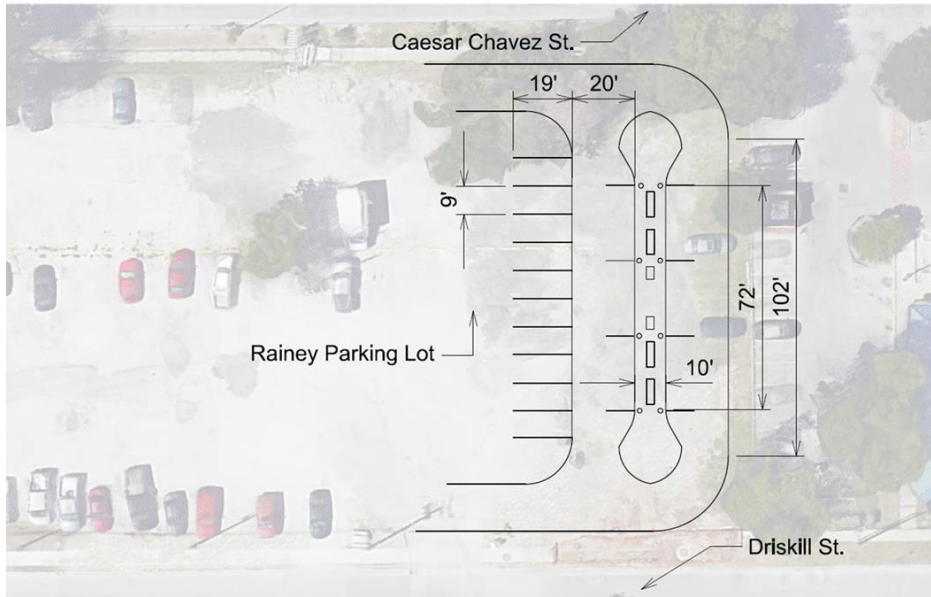


Figure 13.5 Queuing Station for High Vehicle Turnover (Local Parking Lot)

The Rainey queuing area mimics the design of the Domain location in that it provides a single entry and exit point with a raised median separating two lanes of SAV thru traffic (Figure 13.5). In total, the land area covers roughly 8,425 square feet. This area contains a ten foot bulb-in median curb with benches, and a covered area. The total median length is around 102 feet. Other design specifications include curbs on either side to allow for steady flow of traffic through the DRS-SAV pick-up/drop-off area which can house six AVs (three on either side). Additional considerations relating to the segregation of SAV with human operated vehicles will help to avoid delays associated with confused drivers potentially utilizing the system analysis.

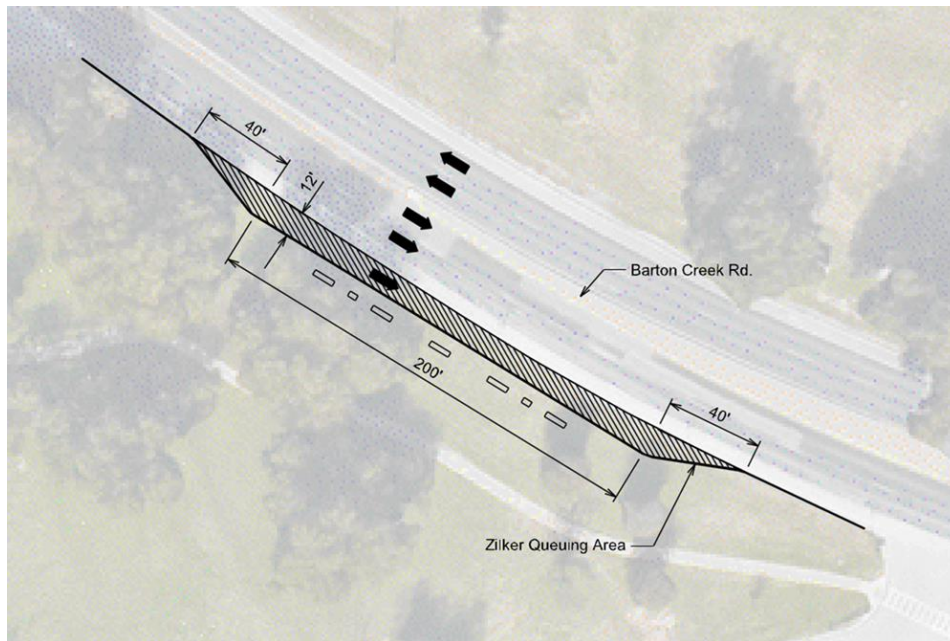


Figure 13.6 Zilker Park Queuing Station Design (Roadside Site)

This design will be implemented in four other locations scattered throughout Austin: Arboretum mall, Mueller neighborhood, Barton Creek Square, and Sunset Valley queuing areas. Areas that already enjoy good transit access are valuable for SAV stations to function as a last-mile travel provider, if warranted or preferred by

travelers. The additional four designs are to follow the Rainey Street design above with small variances due to site characteristics. See Table 13.2 for additional queuing area information.

The Zilker queuing area is the last given design option for high-patron turnover. This is the most basic design given its specific focus on high turnover. Figure 13.6 shows the designated queuing areas meant for AVs. The project area specifications include a 12' wide, 200' long parking accessibility zone and a total square footage of around 2,700 square feet for the area of the project. This design, if relevant to the preferred alternative, will be implemented in four other locations scattered throughout Austin: University of Texas, Tuscany Business Park, Riverside, and Far West queuing areas.

Table 13.2 Queuing Area Overview

Name	Location	Capacity (# AVs)	Cost Estimate (\$)	Special Features
Rainey Street	Downtown near Sixth Street & the Warehouse District	15	\$4,366,400	Proximity to Trip Attractors such as the Convention Center, Town Lake, & bar-districts
Arboretum	US 183 South & Great Hills Trail near the North Capital of Texas Highway	10	\$1,802,500	Mixed-use area with housing, offices, shops & restaurants as well as transit stops & pre-existing transit park & ride centers
Mueller	Central Austin east of I-35	15	\$1,803,500	Mixed-use redevelopment where alternative modes of transit are encouraged by the community
Barton Creek Square	Intersection of Loop 1 & Capital of Texas Highway	15	\$1,803,500	Close Proximity to highways as well as commercial areas
Sunset Valley	South of downtown at the intersection of Mopac & SH-71	15	\$1,803,500	Small rural resident community which allows access to the hill country, a prime trip attractor & heavily commuted corridor into the CBD
Zilker Park	South Austin east of Mopac	10	\$655,500	Access to trip attractors such as Town Lake, Barton Springs & a multitude of events that occur in this area (Austin City Limits Festival, The annual Trail of Lights)
Far West	South of US 183, North of 2222, West of Mopac	10	\$655,500	Mixed-use with a high density of student population, often without access to a vehicle

Tuscany Business Park	Northeast central Austin at intersection of Highway 290 & US 183	10	\$655,500	Serves an area of east Austin that has a recent influx of tech companies as well as access to tolled facilities which could support a park & ride for commuters out of the system
University of Texas	Central Austin, next to I-35	15	\$655,500	350 acre main campus, with 51,000 students, 24,000 faculty & staff
Riverside	Along Lady Bird Lake, east of I-35	10	\$655,500	Major housing area as well as access to music venues & close proximity to a major interstate

13.4 Vehicle Specifications

Electric vs. Gas Powered

Two major variables were experimented with when choosing the alternatives: number of locations and vehicle energy source. EVs were chosen for the AV fleet in alternatives 2 and 4. These vehicles are relatively inexpensive to fuel and comparatively minimize polluting their surroundings with noise and emissions. EVs offer a move away from gasoline usage which decreases dependence on foreign markets for energy. EVs are often associated with “range anxiety” but this is assuaged through advances and technology and EVs have significant amount of chargeable breaks when applied in a shared environment (Zhang et al 2015a).

13.5 Project Alternatives Evaluation

The alternatives that include station and queuing areas, in addition to an increased vehicle fleet size (800 SAVS), offer the highest levels-of-service to the Austin network by providing a variety of locations and a larger AV fleet of 800 vehicles. These alternatives will be capable of accommodating more users than their counterparts (stations only with 400 vehicles, and a variance of gas and EV powered vehicles). However, the added queuing locations increase initial project cost and may not warrant the additional infrastructure initially.

Using the assumptions found in a similar study (Fagnant 2015), an average trip length of six miles was chosen for these alternatives with unoccupied vehicle miles travelled (VMT) accounting for 8% of this distance. The average trip length for alternatives with the additional infrastructure was adjusted to ten miles with unoccupied VMT also increasing to 20% of AV travel (due to increased location spacing). These adjustments account for the difference in average radii needed (around each location) to cover the entire network. Increased infrastructure may lead to shorter trips and less unoccupied VMT, if priced favorably to encourage system use in a transit-like setting and emphasis on ride sharing. Each of the alternatives offer benefits in the form of decreased hourly value of travel time from \$16.30 (Fagnant, 2014) to \$5.00 due to passengers’ ability to use their travel time productively or leisurely. These alternatives will also encourage ridesharing (achieving an average of 1.3 people per vehicle) and reduce the number of crashes.

13.6 Preferred Alternative and Project Analysis

This project was designed for a ten-year period, enabling a testing period suitable for studying how well the AV system will function in the Austin traffic environment. Emphasis was placed on the B/C ratio in this evaluation as it offers a better summary of project impacts. Monetizing the parameters to give an economists’ perspective on the system was critical in defining the benefits this system produces when adopted full scale. Table 13.3 shows the benefit of using an AV in terms of the traveler’s value of travel time.

Table 13.3 *Alternative 2 Sensitivity Analysis*

Value of Travel Time		
Number of Vehicles (NoV) =	200	AVs
Person Trips Per Day (PTPD) =	28.5	trips
Vehicle Trips Per Day (VTPD) =	21.9	trips
Average Trip Length (ATL) =	10.0	miles
Daily Miles Traveled per Vehicle (DMT) =	219.2	miles
AV Yearly Miles Traveled (YMT) =	16,014,808	miles
Occupied Yearly Miles Traveled (OYMT) =	13,345,673	miles
AV VOTT =	5.0	\$/hr
Non AV VOTT =	16.3	\$/hr
Difference =	11.3	\$/hr
Average Vehicle Speed (AVS) =	26.0	mph
Occupied Yearly Travel Time (OYTT) =	513,295	hours
VOTT Yearly Savings =	5,800,235	\$
Unmanned Miles Traveled =	2,669,135	miles/year

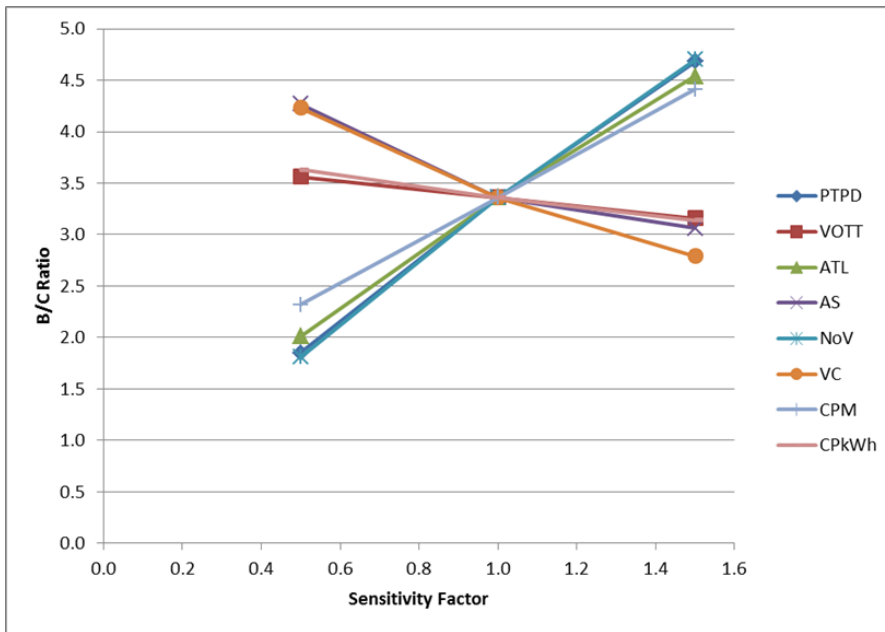


Figure 13.7 400 EVs Utilizing 4 Stations: Sensitivity Analysis

The alternative using EVs with 4 station hub centers utilizing 400 EVs had the highest B/C ratio of 4.42, corresponding with an IRR of 103%. This selection reasoned with the fact that additional construction and maintenance of a larger fleet system with queuing areas outweigh the benefits of having a larger network. The higher fuel costs associated with gas-powered vehicles shifted the selection in favor of an EV fleet. Two additional benefits of utilizing electric vehicles are reduced dependence on foreign markets and long term sustainability.

The sensitivity analysis performed (illustrated in Figure 13.7 with corresponding data in Table 13.4) reveals important relationships. Number of vehicles, person-trips-per-day, average trip length, and cost per-mile proved to be the parameters with the most significant impact on B/C Ratio. Therefore, the accuracy of certain assumptions made in this report could have significant impacts on the system’s success. The sensitivity analysis provides knowledge that can be used to make informed decisions regarding adjustments and their likely effects on the system.

Table 13.4 Alternative 2 Sensitivity Analysis

Sensitivity Analysis				
Variable	Value	Sensitivity Factor	B/C	IRR (%)
Person Trips Per Day	14.25	0.5	1.85	24
	28.5	1.0	3.36	58
	42.75	1.5	4.68	90
Value of Travel Time (\$/hr)	2.5	0.5	3.56	62
	5	1.0	3.36	58
	7.5	1.5	3.16	54
Average Trip Length (mi)	5	0.5	2.01	28
	10	1.0	3.36	58
	15	1.5	4.54	87
Average Speed (mph)	13	0.5	4.27	76
	26	1.0	3.36	58
	39	1.5	3.06	52
Number of Vehicles	300	0.5	1.81	23
	600	1.0	3.36	58
	900	1.5	4.70	90
Vehicle Cost (\$)	30,000	0.5	4.23	72
	60,000	1.0	3.36	58
	90,000	1.5	2.79	48
Cost Per Mile (\$)	0.5	0.5	2.32	36
	1	1.0	3.36	58
	1.5	1.5	4.41	79
Cost Per kWh (\$)	0.075	0.5	3.63	60
	0.15	1.0	3.36	58
	0.225	1.5	3.14	57

Due to this unique endeavor, starting small may make initial financial sense, but system-wide adoption and the need for increased mobility may see exponential affects and high demand.

13.7 Further System Enhancements

The proposed enhancements offer a variety of differing options and amenities, which can meet a multitude of patron preferences. Dealing with fleet options, a multiplicity of vehicles would allow for a variety of customers, providing differing levels of service. With the use of a fuel-efficient hybrid fleet, patrons could travel between cities (i.e. Austin-Dallas) and skip the hassle often associated with flying. Short-term car rentals at the periphery stations could allow for increased service, but additional consideration will focus on increased unmanned vehicle time and increased collaboration to find cost-efficient ways to return the vehicle once the one-way destination has been served. The data from Zhang (2015a) may suggest fewer patron amenities at stations, with the average wait time with a 700 vehicle fleet only at 1.7 minutes. This data lends itself to borrowing space in unused parking lots and only the need to provide signage to notify patrons on where to wait. This minimalistic approach can serve underutilized areas for a fraction of the calculated station cost. Project simulation to complement and possibly validate results of others' simulation would be useful to pursue, as an extension of this research. Further emphasis should be added to encourage and build systems in place for disable patrons and older individuals who may not have access to smart phones.

13.8 Altering Our Urban Environments: Ripple Effects of an SAV-DRS System

SAVs and DRS may transform the automotive industry, much like Henry Ford's Model T. Urban areas have the ability to become even more land efficient by opening doors to new opportunities with their extra space. Zhang's (2015a) base simulation called for over 90 percent in parking reductions, with only a small market penetration of the vehicles on the roadway. All in all, this would amount to drastically planned urban environments, allowing for more density and the opportunities for cities to revitalize their CBD area.

Many cities could then shift their focus on how to provide infrastructure to suit these reduced transit needs and could further enhance the SAV system. Parking for these vehicles would be more efficient and cost effective as the cars can be packed in together, eliminating pedestrian traffic (Zhang and Guhathakurta 2015a). Many of the cities in the US created their planned areas based on the automobile and the predicted reductions due to SAVs could change our urban environment. Will tolled roads alter their infrastructure to attract these

vehicles to increase throughput on their roadways? Could property values near these roadways increase if signage is eliminated, congestion is prevented, and roadway capacity increases? Will our roads be able to transform from thoroughfares for AVs during morning and afternoon peak to pedestrian friendly areas during the lunch hour? Urbanites also could be looking at the pavement for innovation and reap the benefits among the asphalt areas which can be modified for business or environmental benefits.

13.9 Conclusions

Automobiles previously had no concerns systematically but, will soon provide increased usable area for our roadways. SAVs operate more often than traditional personally owned vehicles, and by serving trip generators, allow for increased trip-chaining as well as utilizing active transit. Land-use and parking infrastructure are some of the areas with which SAVs have the ability to transform and eliminate, respectively. The design elements regarding this SAV system highlight vehicle amenities as well as station amenities. This 400 vehicle fleet system serves as an indication of this system's financial possibilities, producing a benefit/cost ratio of 4.42. Through a basic cost evaluation and monetized systematic benefits, a pilot electric-vehicle fleet system will serve 11,400 people per day and each SAV has the potential to eliminate 14 vehicles of the roadway network. Further vehicle incorporation should be the next step in noticing an increasing amount of benefits given to vehicles that can communicate between each other and outperform their human counterpart in operating a vehicle.

CHAPTER 14 MAKING THE MOST OF CURB SPACES IN A WORLD OF SHARED AUTONOMOUS VEHICLES

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14.1 Introduction

The rapid urbanization and the desire for the urban lifestyle throughout age groups have highlighted the need to provide a higher quality of life. Urban residents and their quality of life depend upon thoughtful urban planning and a transportation system to mobilize its citizens. Growing urban populations want streets to serve not only as corridors for the conveyance of people, goods, and services, but also as playgrounds and public spaces. Ideally, city streets are safe, sustainable, resilient, multi-modal, and economically beneficial, all while accommodating travelers. In response to these unprecedented demands, cities around the world are attempting innovative solutions through technology, automation and a shifting emphasis on active transit amenities.

Mobility is a key factor in urban quality of life and connected and autonomous vehicles (CAVs) have the potential to upend our current transportation system. CAVs are predicted to be one of the greatest technological advances in daily traffic service, with a promising future of safer and more convenient transportation (Fagnant and Kockelman 2015a, Schoettle and Sivak 2014a). CAVs are now within reach and may soon become a daily mode of transport for hundreds of millions of people (Bansal and Kockelman 2016). Many major companies, like Google, Toyota, Nissan, and Audi, are developing and testing their own autonomous vehicle (AV) prototypes (Anderson et al. 2014). Past transport transformations, like Henry Ford's mass-produced Model T, helped shape our modern-day traffic systems. Our existing urban traffic systems are now being called into question, in terms of whether they can optimally support the needs and aspirations of a world increasingly dependent on more automated vehicles and traffic management systems.

Vehicle ownership costs and the freedom that SAVs offer travelers may lead to rapid adoption of shared autonomous vehicles (SAVs). SAVs, also known as autonomous taxis or aTaxis (Kornhauser et al. 2013), offer short-term, on-demand rentals with self-driving capabilities, enabling members to call up distant SAVs using mobile phone applications, rather than searching for and walking long distances to an available vehicle. SAVs may overcome the limitations of current car-sharing programs, such as vehicle availability, due to their ability to offer door-to-door service as well as effective connectivity to exist transit facilities. Therefore, one might expect the early integration of SAVs to cater to the shift in urban living where vehicle ownership is the most expensive and cumbersome. Martin and Shaheen (2011) estimate that 9 to 13 vehicles may be replaced for every non-automated shared vehicle. Burns et al. (2013) found that in mid-sized urban and suburban settings, each shared vehicle could replace 6.7 privately owned vehicles. Spieser et al. (2014) modeled a fleet of shared self-driving vehicles in Singapore in the absence of any private vehicles, and it found that each shared vehicle can replace three privately owned vehicles and serve 12.3 households.

Douglas (2015) uses Kornhauser et al.'s (2013) base model proposal to size an SAV fleet for a 5-mile by 5-mile subset of the New Jersey model and found that at least 550 SAVs would be needed to serve the trip demand with reasonable wait times. The International Transport Forum (2015) applied SAVs to serve Lisbon, Portugal, and found that with ride-sharing enabled, each SAV could be expected to replace approximately 10 privately owned vehicles while inducing about 6% more vehicle-miles travelled (VMT) than the city's

baseline. Without ride-sharing in Lisbon, each SAV was expected to replace about six privately owned vehicles, but deliver 44% more VMT, which could easily gridlock that city. Fagnant and Kockelman's (2015a) 10 by 10 mile simulations of relatively short trip-making patterns indicated that each SAV may be able to replace 11 conventional, privately owned vehicles, while generating up to 10% more VMT. When the simulation was extended to a 12 by 24-mile case study of Austin (Fagnant 2015), with relatively low market penetration (just 1.3% of all person-trips in early test scenarios), each SAV was estimated to be able to replace nine conventional vehicles while generating about 8% more VMT (due to unoccupied travel. Chen et al. (2016) utilized 2009 NHTS trip distance and time-of-day distributions indicate that fleet size is sensitive to battery recharge time and vehicle range, with each 80-mile range SAEV replacing 3.7 privately owned vehicles and each 200-mile range SAEV replacing 5.5 privately owned vehicles, under Level II (240-volt AC) charging. With Level III 480-volt DC fast-charging infrastructure in place, these ratios rise to 5.4 vehicles for the 80-mile range SAEV and 6.8 vehicles for the 200-mile range SAEV.

In the forefront of these changes is a need to re-evaluate current parking provision. Its supply and demand will define new parking baselines alongside AV technologies. Parking analyses require data on existing conditions and how estimations of future demands will respond to the provisions available. Parking is not cheap, and it is estimated to represent 15% of the total rental costs in central Seattle (Thompson 2016). Cities like Boston have increased parking charges, in order to promote greater use of multi-modal, public transit trip-making (Arnott et al. 2006). Current parking studies have indicated that some current pricing schemes incentivize automobile travel and do not accurately internalize the external costs of parking in the downtown area. Despite this perceived parking shortage in some downtown areas, US parking spaces outnumber the number of vehicles by a factor of four (Thompson 2016).

Parking seems to be in abundance, as evidenced by the staggering number of parking spots in the US, but the location of the supply does not always meet the demand within proximity, causing high parking costs and increased traffic associated with locating vacant parking. The impetus of high parking fees and the advent of autonomous vehicles lead Fagnant and Kockelman (2015a) to estimate a savings of \$250 in parking costs for each new autonomous vehicle in the market, primarily through reallocating parking space from Central Business District (CBD) locations to more remote areas utilized in conjunction with ride-sharing. Zhang et al. (2015a) estimated the potential impact of SAVs systems on urban parking demands under different system operational scenarios with the help of an agent-based simulation model. The simulation results indicate the potential for a 90% reduction of parking demand for clients who adopt the system, at a low market penetration rate of 2%. Hayes (2011) suggested that AVs can economize parking garages because they can park inches from each other, since there is no need to open the car doors, assuming that the passengers will be dropped off before the AVs enter the parking facility. New mobile applications can serve individuals who participate in dynamic ride-sharing services by matching the nearest vehicle with the route that matches the users' preferences. Such a matching system will serve several passengers at the same time by linking trips that have origins and destinations close to each other. Once the vehicle occupancy rate is improved, a greater reduction in parking demand can be achieved.

Previous studies examined parking provision and policies (e.g., Brooke et al., 2014; Habib et al., 2012; van Ommeren et al., 2012), but theoretical studies on parking provisions and networks are rare. Bifulco (1993) introduced several parking types, fees and average walking times to a static traffic assignment model to evaluate the efficacy of regulatory parking policies in a general urban network. Arnott and Rowse (1999) assumed travelers' choice of parking lot is uniformly distributed on the ring-road, and thereafter derived the expected parking time, driving time and cruising distance for the available parking search. Calthrop and Proost (2006) presented a spatially homogeneous model characterizing the steady-state equilibrium of on- and off-street parking, in which the search cost for on-street parking balances the higher fee associated with off-street parking, but did not consider traffic congestion, per se. Chester et al. (2010) developed five parking space inventory scenarios and estimated the environmental consequences from a range of 105 million and 2 billion parking spaces in the US. Chester et al. (2015) then estimated how parking has grown in Los Angeles County (CA) from 1900 to 2010 and how parking infrastructure evolves, affects urban form, and relates to changes in automobile travel using building and roadway growth models.

This work relates to the investigation of the parking provisions in downtown Austin, which will be shortly followed by the downtown Austin Alliances commissioned study. A basic spatial distribution for the

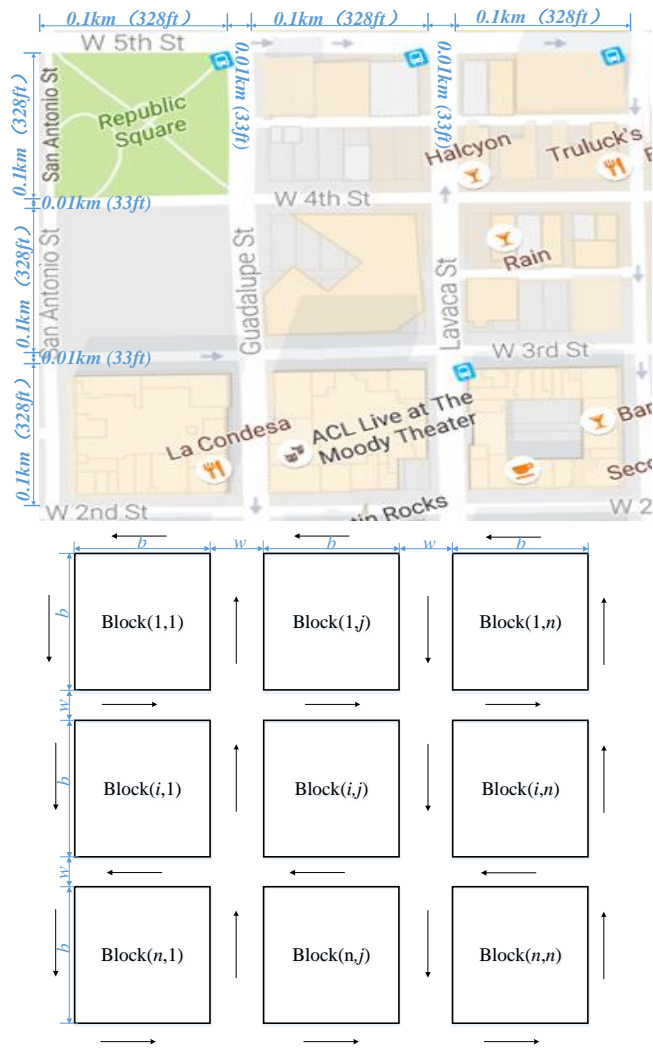
environmental impact analysis of CAVs is postulated. This estimation model builds off additional works mentioned as well as incorporating CAV technologies to repurpose parking amenities and capture the effect on traffic and commuting patterns. In summary, the contributions of this paper include:

- The first analysis on real-time dynamic sharing of parking spaces in downtown Austin. A basic spatial distribution for an environmental impact analysis of CAVs is formulated within the paper.
- An estimation model, which updates the parking provision to avoid affecting traffic and commute time. The re-configuration of the curb parking provision will greatly impact the already packed traffic in the urban core, which is an inevitable problem during the transition period from private-cars to shared-vehicles.
- Extensive research which validates that re-planning parking spaces improves both comfort and convenience of life downtown through the implementation of SAVs.
- The value of curb parking for other utilitarian uses should encourage city officials to begin discussions about how to utilize emerging infrastructure to allow for dynamic changes.

14.2 Spatial Model Analysis

The following illustrates a spatially symmetric road network structure of Austin's downtown area and will highlight the benefits seen as urban environments expand. Essential assumptions of this model are made, such that all transit has enabled CAV technology and all parking is on-street. All trips are the same; they entail driving a fixed distance over downtown streets directly to a destination, followed immediately by having the vehicle park if a vacant parking spot is available, and otherwise searching until a vacancy is found. The demand for trips is inversely related to the full trip price, which includes time and capital costs. Downtown corridors and the adjacent parking provisions rely upon adjacent land-uses, street width, and the proportion of the curbside allocated to parking. Vehicular travel and the proportion of vehicles in transit searching for parking makeup a significant proportion of the travelling public in downtown areas when analyzing parking availability and turnover. Within the model, the drop-off and pick-up of citizens from vehicles present the biggest opportunity to improve traffic, as cars cruising for parking greatly slow down traffic. Traffic equilibrium conditions are also affected by policy decisions, including management and design pricing and the designated use of curbside parking.

Spatial symmetry is assumed to simplify the analysis according to the survey of the blocks and road network. There are $n \times n$ blocks in the network, numbered as $\{Block(1,1), Block(1,2), \dots, Block(i,j), \dots, Block(n,n)\}$ and illustrated in Figure 14.1(b). Blocks are square with sides of length b , streets are of width W , and those blocks are connected to the automobile network by four roadway links. The capacity parking of each block is expressed as the total of the maximum possible number of on-street parking spaces per roadway link. The paper ignores the complications that arise from the indivisibility of lanes.



(a) Investigation of blocks and roads (b) Geometric model from road network

Figure 14.1 Geometric model of road network in downtown Austin.

Suppose each $Block(i,j)$ has a capacity of P_{ij} spaces and its parking fee is f_{ij} , and the time horizon is discretized into T time periods, $\{1, 2, \dots, T\}$. Then the $f_{ij}(t)$ and $P_{ij}(t)$ represents respectively the dynamic parking fee and the number of effectively occupied spaces in $Block(i,j)$ at time t . Obviously, $P_{ij}(t) \leq P_{ij}$, here, and $\forall i \in \{1, 2, \dots, n\}, \forall j \in \{1, 2, \dots, n\}, \forall t \in \{1, 2, \dots, T\}$. If travelers departing from the same origin and using the same block choose the same roadway route, then, Figure 14.1(a) can be transformed into the graph shown in Figure 14.2.

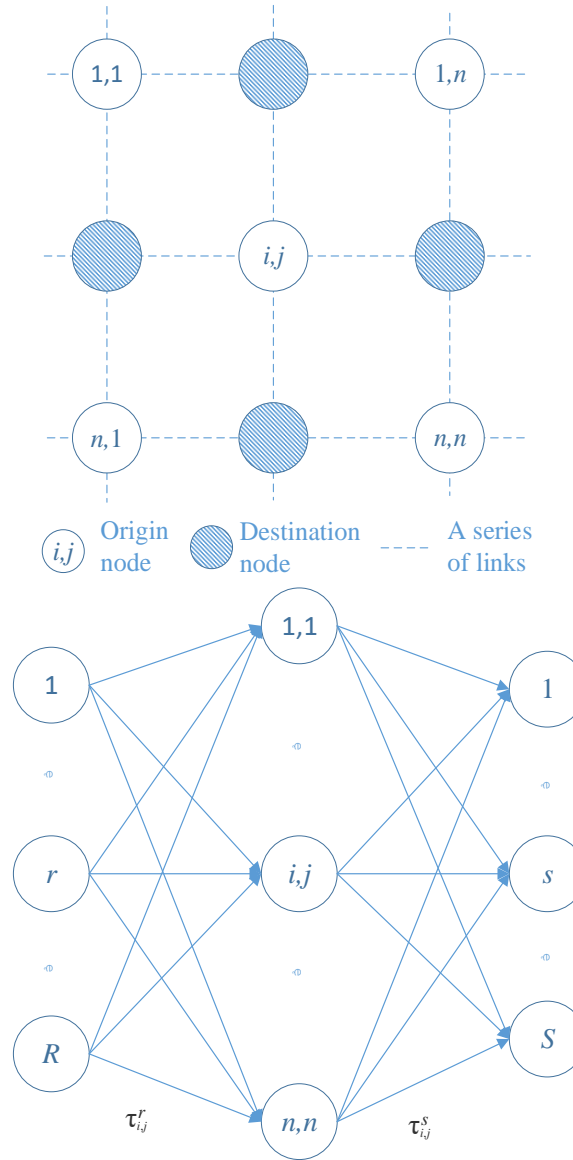


Figure 14.2 A general roadway network

Figure 14.2 is a representation of an average trip, if each traveler departs from an origin, chooses a block to park, and then walks to the destination. As shown in Figure 14.2, there are $|R|$ origin nodes and $|S|$ destination nodes in the road network, where R and S are the set of origin nodes and destination nodes, respectively. Here $\lambda_{ij}^{rs}(t)$ is defined as the traffic demand departing the origin r at time t heading for destination s and choosing the parking $Block(i,j)$, $\forall r \in R, \forall s \in S, \forall i \in \{1, 2, \dots, n\}, \forall t \in \{1, 2, \dots, T\}$. The composite travel time τ_{ij}^{rs} denote the sum of the time from his origin r to $Block(i,j)$ and the walking time to the destination node s . Thus,

$$\tau_{ij}^{rs} = \tau_{ij}^r + \tau_{ij}^s \tag{14-1}$$

The real-time occupancy information helps travelers choose the parking location that yields the lowest travel cost in real time, which ensures a stabilized traffic flow pattern. The current parking space is occupied by travelers whose arrival time to the parking $Block(i,j)$ is prior to t . The real-time effective occupancy is exactly the cumulative arrival rate to the $Block(i,j)$. The lot arrival rate Φ has the closed form by following the definition of the traffic demand directly,

$$p_{ij}(t) = \sum_r \sum_s \sum_{m=\tau_{ij}^r+1}^t \lambda_{ij}^{rs}(m - \tau_{ij}^r) \tag{14-2}$$

$$\lambda_{ij}(t) = p_{ij}(t) - p_{ij}(t-1) = \sum_r \sum_s \lambda_{ij}^{rs}(t - \tau_{ij}^r) \quad (14-3)$$

The charged parking fees are generally not considered (mainly are system optimal price schemes) in the total cruising time. The total system cost (TSC) is the travelers' total composite travel time. The minimal total cost of the optimization parking pricing is calculated by the following optimization equation,

$$\widehat{min}TSC = \alpha \sum_{r \in R} \sum_{s \in S} \sum_{i=1}^n \sum_{j=1}^n \sum_{t=1}^T (\tau_{ij}^r + \tau_{ij}^s) \lambda_{ij}^{rs}(t) \quad (14-4)$$

Where, a denotes the time average of the traveler population. If let $d_{i,j}^{rs} = \tau_{i,j}^r + \tau_{i,j}^s$, then

$$\widehat{min}TSC = \alpha \sum_{r \in R} \sum_{s \in S} \sum_{i=1}^n \sum_{j=1}^n \sum_{t=1}^T d_{i,j}^{rs} \lambda_{ij}^{rs}(t) \quad (14-5)$$

$$\sum_{i=1}^n \sum_{j=1}^n \lambda_{ij}^{rs} = \sum_{t=1}^T \lambda^{rs}(t), \forall r, s \quad (14-6)$$

$$\sum_{i=1}^n \sum_{j=1}^n \lambda_{ij}^{rs}(t) = \lambda^{rs}(t), \forall t, r, s \quad (14-7)$$

$$p_{ij} = \sum_{r \in R} \sum_{s \in S} \sum_{t=1}^T \lambda_{ij}^{rs}(t), \forall i, j, r, s, t \quad p_{ij} \leq P_{ij}, \lambda_{ij}^{rs}(t) \quad (14-8)$$

The $Block(i,j)$ -based parking pricing scheme $\{P_{i,j}(t)\}$ should satisfy that $\forall t \in \{1, 2, \dots, T\}$, travelers choose from $Block(i,j)$ to $Block(x,y)$ $\forall i, j, x, y \in \{1, 2, \dots, n\}$, for the parking. If the rs is a pair of between $Block(i,j)$ and $Block(x,y)$, and there exists $\tau_{ij}^{rs} > 0, \tau_{xy}^{rs} > 0$, then the pair rs of OD is a go-return route.

$$p_{ij}(t + \tau_{ij}^r) - p_{xy}(t + \tau_{xy}^r) = a(d_{ij}^{rs} - d_{xy}^{rs}) \quad (14-9)$$

where, $p_{ij}(t + \tau_{ij}^r)$ means the real-time occupancy at the arrival time $t + \tau_{ij}^r$. Consider the differentiate both sides with respect to t ,

$$p_{ij}^*(t + \tau_{ij}^r) - p_{ij}^*(t + \tau_{ij}^r - 1) = p_{xy}^*(t + \tau_{xy}^r) - p_{xy}^*(t + \tau_{xy}^r - 1) \quad (14-10)$$

where p_{ij}^* denotes the optimal solution, the result shows that the optimal price change is negative relativity with own real-time occupancy. This is because the travelers' parking choice could change according the provision of parking information and the parking price, which may serve as an effective way for traffic manage and control. The parking price and the occupancy information should be balance out and work jointly for the best system performance.

14.3 Renewal of Parking Spaces

Emerging CAVs will grow out of a need to correct modern city car-sharing inefficiencies. The connected and autonomous ride-sharing service will create more-efficient travelling options for the public, saving time and money, while reducing the amount of traffic and burden on the environment. The research conducted strategically reorganizes the existing parking provision, aiming at reducing the need for land occupancy, which has significant potential to improve urban life.

Currently, some major cities have started to convert formerly automobile-only spaces into multi-use spaces for public services, e.g., parklets (areas that include amenities for pedestrians), a bike lane, a bus-only travel lane, a general-purpose traffic lane, extended sidewalks, multi-bus waiting areas, shared-car parking, electric vehicle (EV) battery charging, and truck loading zones. Major redesign of parking spaces requires a variety of considerations since not all streets are appropriate for specific rearrangements, if at all. Some of the ideal land use considerations include traffic flow, parking provision, minimized air pollution, existing pedestrian activity, commercial, high-density building and mixed-use areas. Other considerations include prioritizing parking spaces in rights-of-way, curb parking with low amounts of open space, high open space congestion and environmental transportation demographics. Google Maps and ArcGIS were used in this paper to illustrate one possible way of identifying curb-parking suitable for this study. Additional streets may benefit from the replication of this method or may transform the criteria to account for different local conditions. For full details on this methodology, consult of the following researches.

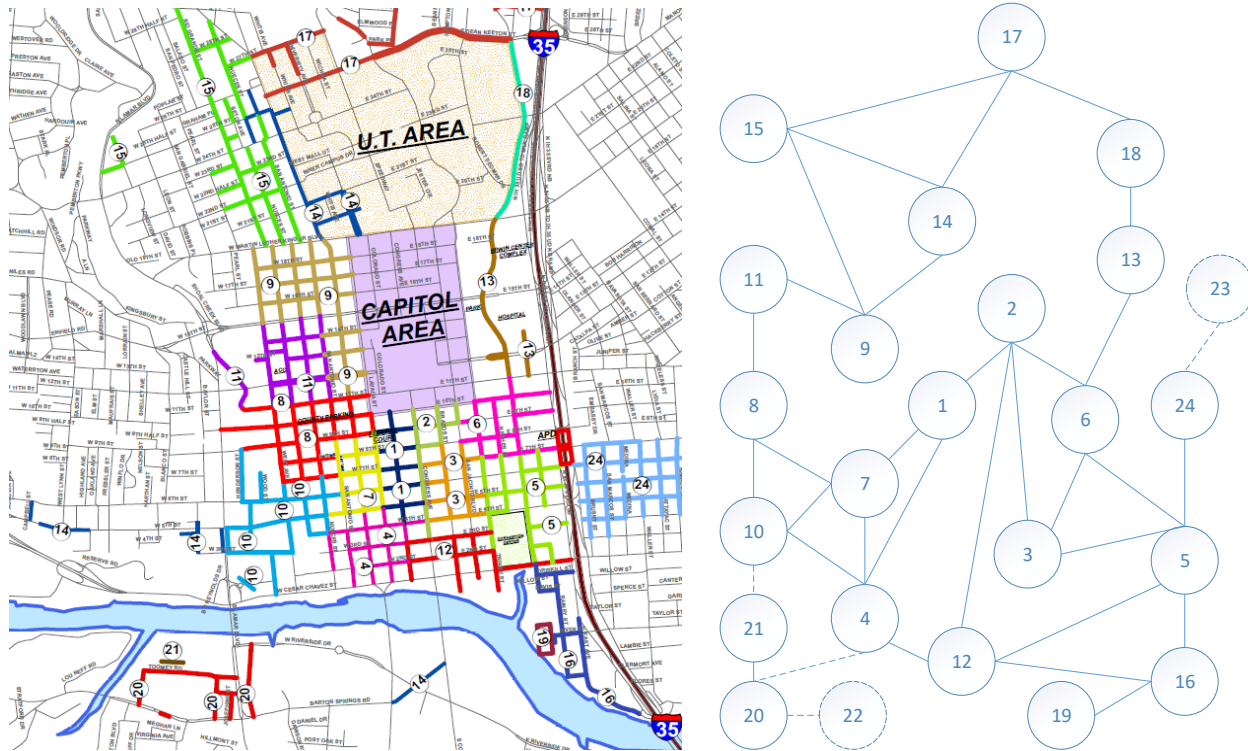
- One quarter mile (a 5-minute walk) is considered to be the maximum that most people would be willing to walk to reach a destination. Beyond this distance, people often bike, drive, take public transportation, or decide not to go to that destination (Nichols 2009).
- The re-plan of parking space prioritized commercial and high-density environments, followed by public service and non-profit institutions, and lastly residential.
- Shared parking will be utilized primarily for adjacent trip attractors and neighboring commercial applications. Therefore, geocoding desirable commercial businesses (restaurants and bars, bookstores, theaters and music venues) and keeping the potential parking locations nearby (within 100 feet) are priorities (ASLA 2011).
- Most residences are within a quarter mile walking distance of current parking provisions. In addition, there is a great deal of variety in population density and size of available public space when considering the parking reductions due to the emergence of SAVs technologies. Therefore, open space congestion was used (population density combined with open space acreage) as a metric.
- Environmental justice is a consideration in many areas of research, and currently no municipality other than New York City has made it a priority when implementing parklets. Ethnic minorities and those below the federal poverty line are historically disadvantaged populations in terms of open space, and therefore, areas with a majority-minority population (>50%) and those with higher levels of poverty are prioritized (Sister 2009).

Keeping parklets and bike lanes more than 300 meters away from highways is a priority (Brugge 2007), as active transit amenities should not be preferred nearby high-speed vehicular facilities.

Re-planning a successful parking provision for a CBD area requires a variety of considerations, as not all streets are appropriate for land use transformation planning. Certain streets and businesses have a higher propensity than others to support a modified parking provision. Along those streets, and despite certain throughput situations, specific blocks may warrant alternative uses, depending upon adjacent land types and means of transportation to reach nearby destinations. The results of the GIS analysis may be used as a basis for discussion with city planners, businesses and residents to supplement parklet location decision-making.

14.4 Case Study

A GIS suitability analysis is used here to demonstrate the above method. The downtown-parking provision data were collected from City of Austin files, and suggest significant potential for repurposing and reuse of existing spaces. There are 24 major parking zones located in downtown Austin. The locations of the parking blocks and the traffic analysis zones (TAZ) are shown in Figure 14.3.



(a) Spatial distribution maps of parking provision (b) Connected state of parking blocks

Figure 14.3 Extraction model based on the parking provision.

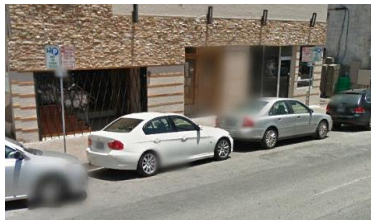
Suppose all parking spaces are available for commuters or visitors, and all of parking are set to charge \$5 per hour. The driving time and walking time is approximated based on the distance measured in Google Maps. In addition, the time horizon for this analysis is 7:00am - 11:00am. Here, an initial subset of 100,000 person-trips was randomly selected to imitate a natural 24-hour cycle of travel. The capacities of the blocks are shown in Table 14.1.

Table 14.1 Total Parking Spaces (Source: Austin Transportation Department, 2016)

Blocks	Meter Spaces	Paystation Spaces	Total Paystations	Total Curb Spaces
1	23	197	31	220
2	29	146	25	175
3	46	232	33	278
4	14	207	25	221
5	54	270	37	324
6	42	385	47	427
7	17	248	36	265
8	56	488	71	544
9	75	399	59	474
10	51	343	48	394
11	43	349	52	392
12	34	126	19	160
13	12	87	15	99
14	39	216	36	255

15	29	463	60	492
16	16	217	24	233
17	23	459	53	482
18	0	37	6	37
19	0	127	4	127
20	16	161	21	177
21	0	195	11	195
22	0	0	30	0
23	0	71	10	71
24	15	812	89	827

Such computations offer planners a conceptual framework for recognizing on-street parking provision and the rearrangement of parking spaces under shared-fleet conditions. After a thorough investigation of Austin’s downtown blocks and road structure, as illustrated in Figure 14.3, the block spacing, $b + w$, is found to be 110 metres (361 ft); the road width, W , is 10 metres (33 ft); and parking spaces typically measure 2.76 metres (913.1 ft) wide by 6.1 metres (20 ft) long, on average, with allowance made for crosswalks (2.45 metres or 8 ft) at the ends of all blocks. As shown in Figure 14.3, there are three types of parking used along downtown Austin’s curbs: parallel parking (the most common design), inclined parking, and bay parking. These three types can contain up to 15, 22, and 10 cars respectively, in a single, average block. Curbside parking on both sides of each block suggests 30, 44, and 20 cars can be parked per block under the three parking designs, respectively.



(a) Parallel parking

(b) Inclined parking

(c) Bay parking

Figure 14.4 Three types of parking in downtown Austin.

The next thing to consider is the amount of roadway surface available for parking space allocation when shared parking is provided for residents, visitors, and businesses. Figure 14.4 presents the current spatial layout of curb parking spaces in downtown area. A study by Fagnant and Kockelman (2015b) indicated that one SAV may be able to replace up to 9 conventional vehicles in the core of a region like Austin, suggesting that the need for any kind of parking spaces may eventually fall by 89%, if all those currently driving shift to SAVs. If one applies this percentage to just curb spots (as listed in Table 14.1), this liberates 6426 parking spaces, or 0.042 square miles (roughly 4% of the core downtown’s 1.0 square mile land area), which can be re-purposed for an extra lane of traffic, parklets, bike use, and other public facilities. With this decrease in parking demand, the rational reuse of parking spaces will become an important part of more sustainable transportation system designs.



Figure 14.5 Parking provision in downtown Austin.

Note: blue for parklets, red for shared parking, purple for extra general traffic lane, green for bicycle lane, and yellow as road axis

This pair of equations involves several parameters, whose values may be assumed as follows: the in-transit travel distance, $t = 2.0$ miles, an approximation of the hourly pay rate downtown, α is set to \$23 per hour, and parking is provided on just one side of every block (as opposed to both sides). The terminal occupancies are shown in Table 14.2.

Table 14.2 Terminal occupancies of the TAZs

TAZ	1	2	3	4	5	6	7	8	9	10	11	12
Capacity	220	175	278	221	324	427	265	544	474	11	392	160
Spots	197	146	232	207	270	385	248	488	399	5	349	126
Percentage	90 %	83 %	83%	94%	83%	90%	94%	90%	84%	45%	89%	79%
TAZ	13	14	15	16	17	18	19	20	21	22	23	24
Capacity	99	255	492	233	482	37	127	177	195	0	71	827
Spots	87	216	463	217	459	37	127	161	195	0	71	812

Percentage	88 %	85 %	94%	93%	95%	100%	100%	91%	100%	0%	100 %	98%
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As part of the future urban development, a new parking provision plan and classification method is proposed here, to redefine and prioritize travel modes for each street (e.g., pedestrian and/or bicycle, transit and/or private cars). This plan can be implemented on the basis of existing street designs, land uses, and transportation system operations details, and can be updated as specific projects are funded and community input is obtained.

Existing curbside parking spaces can be completely or partly re-designed in a variety of ways, based on different needs and aspirations. For example, delivery trucks and bus stops can be moved around corners, in many cases, to create an entirely new bike lane or traffic lanes, using spaces in between truck stops for parklets, bike storage, or shared-car and SAV storage. The objective is to improve access to, and mobility within, the downtown core, while creating a more balanced and dynamic shared-parking system that supports economic growth and land use intensification, while fostering a high-quality pedestrian environment and more sustainable travel choices. The optimal solution is shown in Figure 14.5. It is easily verified that there do not exist any two O-D pairs that use more than one parking block during the entire time horizon.



Figure 14.6 Repurposing downtown parking spaces in Austin

This study seeks to anticipate how much curbside parking may be freed up by the use of self-driving shared vehicle fleets. A shift to fleets of shared and self-driving vehicles may improve quality of life for downtown users and visitors by facilitating all modes of transport; they may open up land for more meaningful uses in this highly desirable and busy downtown setting. After conferring with design professionals, local businesses, residents, downtown workers, government officials, and other stakeholders, models of implementation can emerge.

As downtown land space becomes more expensive, vehicles become more automated, shared-fleets become more common, and existing parking areas become smaller and less needed, it is important to rethink and redo parking provision. Since off-street, structured parking is more difficult to redesign (due to sloped floor plans and low ceilings, for example), and cannot support actual travel, curbside slots represent a city’s top opportunity for re-design. A variety of options along each existing corridor should be considered. Instead of

single-purpose parking spaces, the emergence of shared and dynamic automobile and bicycle parking facilities, transit and SAV stops, parklets, and extended sidewalks becomes a possibility.

14.5 Further Enhancements in the Urban Space

With congestion paralyzing many corridors at peak times of day and self-driving (and thus self-parking) cars around the corner, current curb parking spaces may be repurposed to promote a higher quality of life for the community. Parklets are one example reuse, which is already providing valuable amenities in certain settings (Koue 2012). Cities have also partnered with businesses like Zipcar to implement infrastructure improvements, thereby increasing the efficiency of current downtown transport systems. A closer look at poorly utilized public parking spaces in various CBDs has resulted in new uses and better parking management (like demand-response parking prices and sensors in San Francisco).

In addition to promoting underutilized spaces through tactical urbanism (Pfeifer 2013), coordinating and incentivizing public transit among other, relatively sustainable and active modes of travel, must also be considered. The City of Austin has recently devoted lanes of travel for its bus rapid-transit system routes. Coordination between public and private ride- and vehicle-sharing systems will allow for more sustainable communities, healthier travelers, and more effective land uses.

The freeing of public land via curbside parking reductions offers an exciting opportunity to promote more sustainable modes and land uses along various corridors. For example, in Austin, Texas, the local transit authority, Capital Metro, has invested in improved bus facilities for a variety of bus routes along Guadalupe Street. To further promote multi-modal travel and transit service levels, the current parking spaces along the downtown section of this corridor can be converted into several services that aid public transit. These amenities include an extension of the existing bus lane and/or sidewalks, increased bike and car share locations, in concert with queuing spots for buses to prevent traffic buildup during vehicle alighting.

In general, curbside parking redesign decisions and the travel mode or land use applications they favor, will depend on many factors, corridor by corridor and block by block. Those factors include the following:

- Adjacent land uses and their parking needs
- Access to major corridors (both substitutes and complements, in trip-making)
- Access to other parking lots
- Existing travel modes along the corridor
- Presence of big trip attractors and generators (e.g., convention centers and major theatres)
- Refuge for pedestrians and bicyclists
- Current daily traffic counts versus projected traffic counts

The following corridor case studies offer downtown Austin examples of how such factors can be used to determine curbside parking's new use:

- **San Antonio Street:** The average daily traffic (ADT) is 2,730-2,830 vehicles per day on this bike corridor. This corridor runs from downtown to west campus, and consists of low traffic, tree-lined neighborhood streets. The current corridor has a bike route in place and could be suitable for additional bike traffic. Additional emphasis on this mode of transit would enable other corridors to focus on high-capacity transit options. Meanwhile, this street still serves local traffic effectively and presents an aesthetically pleasing area for pedestrians and active transit users.
- **Lamar Street:** With an ADT of 32,670-38,480 vehicles per day, this would be an ideal SAV preferred corridor. This corridor connects areas of Austin that have been developing rapidly, and the same can be said for the growing transit opportunities along this corridor. Due to the limiting ROW constraints, this corridor would be suitable to encourage high occupancy SAVs to improve and

economize the existing infrastructure and serve the multitude of communities adjacent to Lamar Street.

- **Congress Avenue:** Since Congress Avenue has a mid-range ADT of 7,340-23,260, it would be ideal for a hybrid of amenities for all modes. Congress Avenue has a wide number of bay parking spots that have already been converted to parklets where additional pedestrian amenities are needed. Currently, bicycle traffic is mixed in with vehicular traffic, decreasing potential throughput capacity. During city-wide events and most weekends, large events are planned near the paramount theatre, and a dynamic setting to accommodate the stresses of additional pedestrians in the adjacent area should be considered. Additional downtown developments that do not provide parking amenities for their patrons have be planned; therefore, shared amenities and transit should be considered around this new development.
- **San Jacinto Boulevard:** With an ADT of 4,230-5,980, this area is ideal for multi-modal transit. San Jacinto Boulevard connects a major university to a growing medical center, and has high amounts of student traffic on foot, and on buses and bikes. With the additional roadway space and more centralized parking, more feeder buses should be considered to serve commuters to the university who may park further away. Additionally, to promote active transit and to provide a friendlier environment for the multitude of events and football games in the area, increased pedestrian and cyclist shade and refuge would help to promote these environmentally friendly forms of transit. Current vehicular access is restricted at most areas of San Jacinto, so it is not recommended to encourage additional vehicular traffic.
- **Brazos and Colorado Street:** Brazos Street, with an ADT of 2,880-3,840, and Colorado Street, with an ADT of,780-4,530, are best suited for implementation of a shared-parking environment. This corridor is designed to provide shared parking amenities for downtown destinations. This redesigned space allows for quick queuing and alighting times, and space for carpooling and queueing for these vehicles. The current street configuration promotes active transit with newly created pedestrian space, and this shared parking environment is already enabled with current bike-sharing infrastructure. Additional pedestrian space can be created with this shared parking environment to relieve some of the urban stresses related to additional density. Neighboring streets with pedicab access should be considered for a pedicab queuing area as well. These streets have a high amount of off-street parking, and vehicular traffic should be preferred for these corridors.

14.6 Conclusions

Self-driving technologies may make SAVs a highly competitive mode alternative for many, most, or nearly all person-trips. Around the world, car-sharing is becoming a viable alternative to privately owned vehicles, which helps reduce parking requirements in settings that offer storage for shared fleets. A basic spatial distribution for the environmental impact of SAVs is postulated, liberating curb-parking for other uses. If one SAV can replace nine conventional vehicles, it seems reasonable to expect that 90% or more of Austin's current downtown curb spaces may be easily liberated (especially since off-street parking can be more challenging to repurpose). That space constitutes about 27 acres of land (or 4.2% of the total land) in Austin's 1.0 square mile downtown, would could be re-purposed for other public uses. This paper provides a variety of suggestions for repurposing land along major corridors, including ensuring the provision of truck delivery spots and transit stops, adding bike lanes, extending sidewalks, and providing more general-purpose traffic lanes to facilitate various forms of travel and leisure along north-south routes.

The goal of this research is to improve access to, and mobility within, a downtown core, creating a more balanced and dynamic shared-vehicle and shared-parking system that supports regional and local growth and densification, while fostering a high quality of life for all those destined to, or residing in, the downtown area. As part of any city's long-term planning efforts, a new parking provision plan that recognizes SAVs' potential impacts should emerge. As in this paper, such plans may do well to redefine each street's objectives and priorities (e.g., pedestrian, bicycle, transit and vehicular), to support more active modes, more meaningful land use, and safer and more efficient transport.

Parking provision is a principal factor in shaping the form and character of downtowns everywhere. Although a major goal of many cities is to create sustainable, pedestrian-oriented downtown districts, the lack of many well-connected, frequent, and popular transit routes and transit-supportive land use patterns across Austin requires that adequate levels of automobile parking continue to be provided in this particular case study until there are more viable alternatives. SAVs may be the breakthrough that cities like Austin seek, though their overall impacts (on travel distances, location choices, and traffic congestion) remain to be seen.

CHAPTER 15 PREPARING DATA FOR MODELING DISAGGREGATED TRAVEL MODES: A TOOL OF TAKING ADVANTAGES OF EXISTING TRAVEL MODELS AND OPEN SOURCE DATA

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15.1 Introduction

Observation of travel patterns is evolving in many aspects, including new strategies for existing “tools” (like smartphones for calling transportation network companies’ vehicles) and emerging innovations (like connected and self-driving or “autonomous” vehicles, CAVs). Many evolving and emerging travel patterns merit application of advanced modeling techniques for vehicle tracking, traffic forecasting, and evaluations of transportation policies and projects.

Car-sharing is transforming the way people travel, live and socialize (Cohen et al., 2016). Advanced communication technologies including the internet and smartphones provide a platform that allows individuals to be part of car-sharing, such as booking a car online at home or requesting a ride on the roadside. Including Uber, Car2go, Lyft, Zipcar, Hertz and Enterprise, there were more than 35 major car-sharing industrial participants/competitors in North America that managed or operated more than 25 thousand shared vehicles as on July 2015 (Martin and Shaheen 2016). The global car-sharing market was over \$126 million in 2015, and Global Market Insights (2017) predicts a 35% annual growth rate in carsharing through 2024. Car-sharing offers mobility to travelers without the burden of owning a vehicle and the car-sharing services are more flexible than transit (Liu and Kockelman, 2017). In addition to the personal benefits of travel-cost (including vehicle ownership and parking) savings, car-sharing offers benefits to society. Shared vehicles require fewer parking spaces (both on-street and off-street), since these vehicles are shared across multiple households and are more often in use. Car-sharing can also lower traffic congestion, energy use, and emissions, since car-sharing users are generally unlikely to own or buy a car and shared cars tend to be more efficient than the average household vehicle (Martin and Shaheen 2016, Chen and Kockelman 2016). Emerging transportation tools such as connected and autonomous vehicles (CAVs) will further facilitate the growth of the car-sharing market. Existing car-sharing services either require a driver in the vehicle to pick-up/drop-off customers (e.g., Uber) or need the customer to make a trip to access the service at car-sharing stations (e.g., Car2go CAVs can drive themselves to pick-up/drop-off locations requested by customers).

Currently, most in-use state and regional travel models are “four-step” trip-based (NCHRP, 2012) and the information captured in these models is often aggregated at the level of traffic analysis zones (TAZs). There is little disaggregated information about demographic data such as gender, age, household size, car ownership, employment status, household income, and other personal attributes that are likely to influence individuals’ travel decisions. New travel modes require the modeling of individual trips (rather than aggregated trips between TAZs) at great spatial and temporal details. For example, the car-sharing system needs a model to capture how a service may connect two individual trips, such as modeling the shared car’s travel between the present customer’s drop-off location and next one’s pick-up location. If two trips are connected in the same TAZ, the four-step travel model is unable to capture such car-sharing modes. Therefore, people are seeking advanced travel modeling approaches; and activity-based modeling (ABM) is considered one of the most promising approaches. ABM is based on the principle that travel demand/trips are derived from activities that people plan to perform daily. As compared with the widely-used trip-based travel modeling, the activity-based

approach is more sensitive to person-specific behavioral attributes (e.g. age, gender, value of time, and willingness-to-pay), capturing how individuals allocate their time for activities and travel though the day (Castiglione et al., 2015). The ABM approach is tour-based, capturing trips made by the same person during the course of a day and within the same tour. A tour is a chain of trips made by the same person to conduct activities throughout the day and typically a tour starts and ends at the same place. Trip-based models replicate the TAZ-aggregated decisions, only considering trip characteristics (e.g., trip distance, speed, duration and cost, and mode availability), while the activity-based approach simulates individual decisions that account for characteristic of both trips and activities (activity duration, and value of conducting an activity). Therefore, ABM appears to be able to capture car-sharing behaviors and answering questions regarding car-sharing operational strategies (e.g., evaluating car-sharing services or estimating the demand given one proposed car-sharing policies).

In recent years, powerful computation tools have been developed to help transportation modelers to simulate the transportation systems at microscopic levels. For example, POLARIS (<http://polaris.es.anl.gov/>) and MATSim (<https://www.matsim.org/>) are two masterpieces of activity-based demand modeling that have been extensively used to model travel decisions at the level of individual travelers, including car-sharing behavior (Liu et al., 2017; Javanmardi et al., 2018)

The properties of ABM present a challenge to transportation planning practitioners, since the modeling input information must also be at the disaggregated personal-level. ABM is a data-hungry approach that requires detailed input information about individuals instead of TAZs in trip-based model. For example, in a trip-based model, the origin-destination (OD) matrix is the key travel demand input in the procedure of traffic assignment; the OD matrix contains the number of trips between TAZs. In ABM, the travel demand is derived from the motivation of performing activities. Every individual has a unique tour (travel demand input in ABM) made up of chained trips and activities. In order to prepare the ABM travel demand input data, one may think of conducting a comprehensive travel survey that asks every person in a modeling region about their activity diary (key information should include the times, locations and types of activities). However, it sounds financially infeasible to conduct such a survey and ask every person about where and when they perform their daily activities and how they make to the next activity from last one.

Previous practices offer great insights in preparing data for ABM applications. For example, the ARC's (Atlanta Regional Commission, 2012) Activity-Based Travel Model created synthetic persons and households based on the samples of persons and households in the region's Public Use Microdata Areas (PUMAs). The synthetic persons and households are balanced to match the PUMA controls at both the PUMA level (a collection of Census tracts within counties) and the county level. The activity patterns and trips in the ARC model were generated based on the statistical analyses with travel survey data from Columbus, Atlanta and the San Francisco Bay Area. The activity patterns and trip attributes are associated with the person types and household characteristics. Regarding the locations, the ARC model used small TAZs to represent the locations of activities (trip origins and destinations). Therefore, in the ARC model, the activities are embedded in zones, and are not assigned to specific locations. In 2015, Transportation Research Board released a report that synthesizes well-agreed concepts and practices on activity-based travel demand models (Castiglione et al., 2015). Generally, in existing practices, the method of preparing data for ABM may be regarded as the method of "start-from-scratch". This method is to prepare data from the raw data that are related to travel demand, including PUMA, LEHD (Longitudinal Employer-Household Dynamics), land-use data, travel surveys, etc. As a matter of fact, existing trip-based travel models are also built upon such data through a rigorous process of data processing. Many Metropolitan Planning Organizations (MPOs) or Transportation Planning Organizations (TPOs) have developed such trip-based models for their jurisdictions. Trip-based models also have information about population/households and travel trips (by purpose) aggregated at TAZ level. Compared with the raw data, the information in trip-based models is more structured. Further, the data (including both the current- and future-year data) in trip-based models must be approved by officials before transportation practitioners use them for travel demand forecasting. In sum, the existing trip-based travel models use the familiar data sources for model input data; the information in trip-based models is more structured and cleaned; and the information in trip-based models is accepted and approved by local officials who have a good sense of the local situations and future developments.

To this end, the objective of this study is to develop a methodology utilizing existing trip-based models to prepare the disaggregated travel demand data for ABM. The advantages of using existing trip-based models rather than “start-from-scratch” include: 1) the information in trip-based models is structured, 2) trip-based models often contain data for future years that are accepted and approved by officials. Since trip-based models use the same raw data for inputs as the existing ABM practices, either the method proposed in this study or the “start-from-scratch” would result in the similar outcomes, as long as the data contained in trip-based models are valid.

This study is particularly useful for transportation practitioners who develop and apply trip-based travel models in their jurisdiction since the input data used in this study are commonly available for them. The methodology offers insights in preparing the data for ABM that help simulate and understand the individuals’ travel patterns, and evaluate the transportation policies/strategies under the environment of shared economy and new travel modes, e.g., shared connected and autonomous vehicles. This study presents an example of using data that are easily accessible by the public. Other data sources, such as transportation’s Big Data platforms like Streetlights (www.streetlightdata.com) and AirSage (www.airsage.com), which (may be private but provide great travel data) can also be helpful in preparing activity-based model input data.

15.2 Methodological Framework

This chapter proposes a methodology of preparing the disaggregated input data for ABM. The input data may be summarized as “4Ws” for each traveler’s choices, as shown in Figure 15.1. The core of the framework consists of a series of algorithms that output “4Ws” by inputting the aggregated data at zone level. The framework starts with generating synthetic persons and households based on land use and socioeconomic data. The output at this step provides information of “Who,” defining travelers individually based on age, gender, job, car ownership, and household characteristics. The next step is locating of households and jobs, the information of “Where”, taking advantage of the Open Street Map (OSM) data that contains the layout of buildings in a region. These locations are designated areas for conducting activities. This study assumes that all activities are either household or employment-related. Home activities occur at household locations, while other activities are generally employment-related, though not all other activities are for work. For example, shopping activities are associated with the employment of salespersons, and school activities are linked with the work of teachers. The following two steps together output the information of “What,” a chain of daily activities that form a travel tour. Zone level travel demand is converted to person-level travel demand by chaining the trips between zones and assigning locations for trips’ origins and destinations (that are also the activity locations). The last step is to prepare the information of “When,” a tentative schedule for traveling or performing activities. This schedule is only a tentative timeline for an individual to travel and perform the planned activities. The travel plan may change during the activity-based modeling process in order to make the most optimized use of a person’s time (e.g., leaving the office early to avoid afternoon traffic congestions).

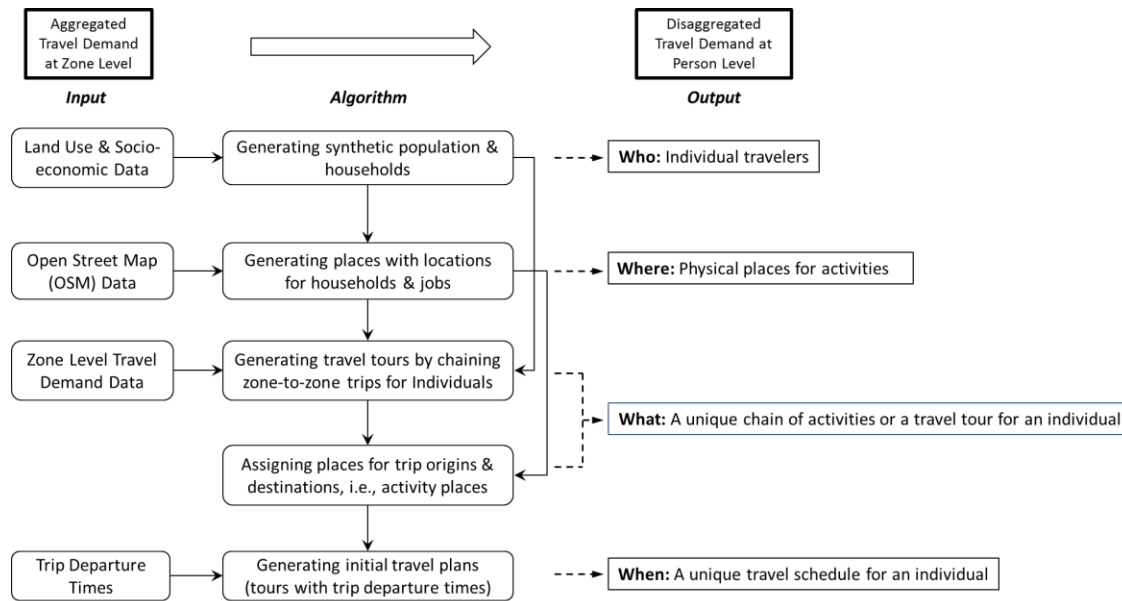


Figure 15.1 Methodological framework of outputting personal level travel demand from zone-level travel demand

15.3 Data Preparation

Three data types were suggested for synthesizing a region’s population and generating their travel tours or itineraries: 1) travel demand data from trip-based or four-step travel models, 2) model equations’ parameter values, and 3) open-source map data. Table 15.1 lists the specific data sets used here, for method illustration.

Travel Model Data

Travel model data are extracted from Austin’s (CAMPO’s) regional travel demand model. The region covers over 5,000 square miles, including Bastrop, Burnet, Caldwell, Hays, Travis, and Williamson Counties in Texas. CAMPO’s 2010 Planning Model is a largely traditional four-step macroscopic travel demand model (CAMPO, 2015). The model’s base year is 2010, and the model supports future-year forecasts from 2015 to 2040 with 5-year intervals. This study used data in the model’s 2020 scenario: including TAZ land use data and trip tables. The TAZ land use data is important for population synthetization. In synthetic population, every person has an individual profile with their socio-economic information including age, gender, job, car ownership, household members, household size and household income. The synthetic population is the basis for generating tour data for individuals. Census data also provide land-use or socio-economic data, as an alternative source. This study used CAMPO model’s estimates for the year of 2020. The trip table is also called origin-destination matrix (OD matrix), offering a big picture of possible trips between/within TAZs (trips are not specified to a specific person in four-step models). Six types of trip purposes (implying a destination’s activity type) were considered in the tour generation process: Home-based work (HBW), Home-based school (HBSc), Home-based retail (HBR), Home-based other (HBO), Non-home-based work (NHBW), and Non-home-based other (NHBO) trips. There are five associated activities including home, work, school, shopping and other activities. Time skims from CAMPO model represent the average travel time between TAZs. The data is critical for generating initial travel plans which include the duration a traveler may spend in a trip.

Table 15.1 Data Sources for Preparing ABM Inputs

Source	Data	Key information	Data source
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Travel model data	TAZ land use data and its shape file	<ul style="list-style-type: none"> - Population - Household size <ul style="list-style-type: none"> - Worker - Car ownership - Income level 	Regional travel demand models: https://www.campotexas.org/ Alternative sources: Longitudinal Employer-Household Dynamics https://lehd.ces.census.gov/data/ Census Demographic and Economic Data https://www.census.gov/geo/maps-data/data/tiger-data.html
	Trip table (i.e., OD matrix)	<ul style="list-style-type: none"> - Trip purpose - Number of trips between TAZs 	Regional travel demand models: https://www.campotexas.org/
	Time skims	<ul style="list-style-type: none"> - Travel time between TAZs 	Regional travel demand models: https://www.campotexas.org/
Parameter data	Population age distribution	<ul style="list-style-type: none"> - Age - Percent 	Census: https://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml
	Trip departure time distribution	<ul style="list-style-type: none"> - Trip purpose - Time of day - Percent 	Regional travel demand models: https://www.campotexas.org/ Alternative source: NCHRP Report 716 http://www.trb.org/Publications/Blurbs/167055.aspx
	Trip patterns	<ul style="list-style-type: none"> - Number of trips in a daily tour - Percent 	NHTS datasets: http://nhts.orl.gov/download.shtml
Map data	OpenStreetMap data	<ul style="list-style-type: none"> - Road network - Building/housing footprint 	OpenStreetMap data: http://www.openstreetmap.org/

Parameter Data

Parameters are used to shape the attributes of generated data (e.g., synthetic population and tours). The age distribution parameter is used to control population age structure in a model region. A person's age is related to many travel characteristics, including the number of trips in a daily tour, trip purposes, travel mode (and car ownership), etc. Some assumptions in the tour generation process are related to the traveler's age. For example, a person younger than 5 years old or older than 85 years old is likely to make zero trips in a day; and a person whose age is between 5 and 24 is likely to have a trip to school on a weekday basis. Further, it may be impossible that all members in a household are minors (< 16 years old), and minors are rarely permitted to own a car or drive (alone). The trip pattern parameter informs that how many trips a person may make in one day. Such information is not available in the four-steps travel models. Therefore this study used the data of the 2009 National Household Travel Survey (NHTS). According to NHTS, the average number of daily trips for Texans is 3.76 trips (or 3.78 trips-per-day nationally). Figure 15.2 (a) presents the distribution of daily trips per person, with 15.7% of Texans making zero trips on any given day, and 22.6% making exactly two trips in one day.

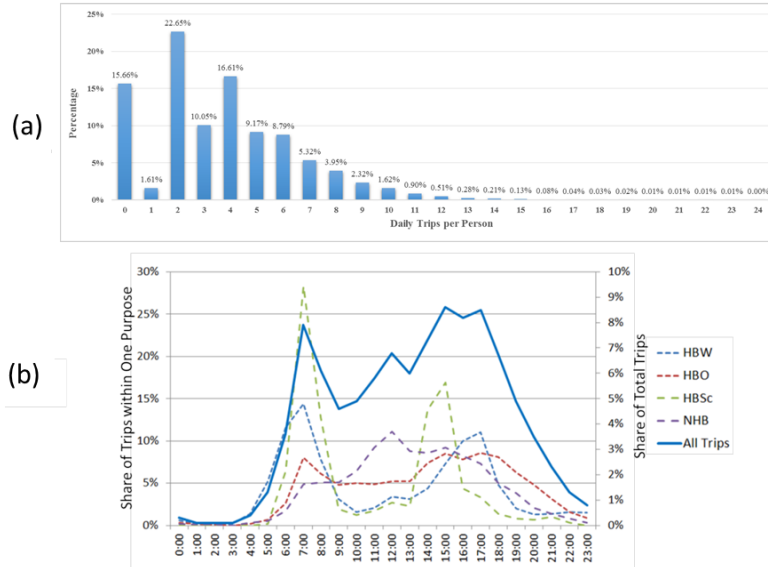


Figure 15.2 Parameter data: (a) trip count in daily travel tours and (b) time-of-day distributions

The trip departure time shows how many trips (in percent) may start at certain times. This parameter is important for observing the time-of-day (TOD) variation of travel demand. Four-step models often take into account four TOD periods including morning peak, afternoon peak, mid-day and night time. CAMPO model has the hourly TOD factors to simulate temporal variations of travel demand. Figure 15.2 (b) shows TOD factors for trip departure times used in CAMPO’s model. Four trip purposes are considered in this study: HBW, HBSc, HBO (including HBR), and non-home-based (NHB, including NHBW and NHBO). NCHRP Report 716 is an alternative source for this parameter data (NCHRP, 2012).

Map Data

In trip-based models, location-related information is aggregated at the TAZ centroids. For example, trip generators and attractors are at TAZ centroids, and a trip starts from or ends at a TAZ centroid. ABM requires the information for specific locations for activities, i.e., origins and destinations. This study used the Open Street Map (OSM) data from www.openstreetmap.org to generate specific locations for individuals and their activities. The data contain the road networks and the house/building footprints. The road networks are composed of nodes and links. The nodes are identified by their IDs, longitudes and latitudes. The link attributes are identified by link IDs, from and to node IDs. In addition, the links have attributes such as link length, link capacity, free flow speed, number of lanes, and travel mode. Link length can be calculated based on the geo-coordinates of two nodes. Link capacity and free flow speed are determined according to the roadway types indicated in OSM. The number of lanes is also available in the data. All public drivable roadways are included in the modeling network.

The house/building footprint data provide information about possible locations for performing activities and receiving or starting a trip. Note that, it is possible that the number of OSM houses/buildings in a TAZ is substantially smaller than the number of households and employers in the travel demand data. This is mainly due to two reasons: 1) the OSM data is not complete and missing some house/building footprints; and 2) OSM data show the current or recent geographies, and the travel demand is in future year. Therefore, more households or employments may be expected. In this study, if there are not enough OSM buildings to house the population or employments, additional building footprints are added into the OSM data.

15.4 Programming

This section presents key programming algorithms for preparing disaggregated travel data. The algorithm codes are available from authors, and will be released as open source.

Generating Synthetic Population

The ABM requires the input information from individual travelers. However, it is difficult to obtain such disaggregated information directly from open sources or through conducting a comprehensive survey which could be extremely pricey. In addition, the privacy concerns may discourage the acquisition of the information from all individuals in a region. The publicly available survey data (e.g., household travel surveys and Census data) offer insights in socio-economies or land uses at an aggregated level, for instance, blocks/tracts in census data. A four-step model often starts with the socio-economic data to estimate the trip generations and attractions for a TAZ. The socio-economic data in the model may be a synthesis from various data sources including household travel surveys and census data. For modeling of future years, the projected socio-economic data is also provided in travel models by coupling with experts' opinions, general population growth rates and regional land use plans. This study uses the CAMPO Model's 2020 socio-economic data to demonstrate how to generate the synthetic population, including individuals' personal information (age, gender, job, car ownership) and associated household's information (household size and income level). Car ownership is assigned to a specific household member according to the car availability in a household, a person's age and employment status. Figure 15.3 presents the algorithms to generate synthetic households using the socio-economic data in the regional travel models. Figure 15.4 shows the algorithms to generate synthetic persons based on synthetic households.

Allocating Locations for Households and Jobs

Activity locations are the trip origins and destinations. Daily activities include home, work, school, shopping and other activities. Home activities are performed at homes, and work-related activities are at job locations. School, shopping and other activities (e.g., eating, exercise, etc.) are also likely to occur at certain locations that are associated with jobs (e.g., teacher, salesman, chief or servant, or physical couch). Therefore, this study assumes that almost all daily activities are performed at either household- or job-associated locations.

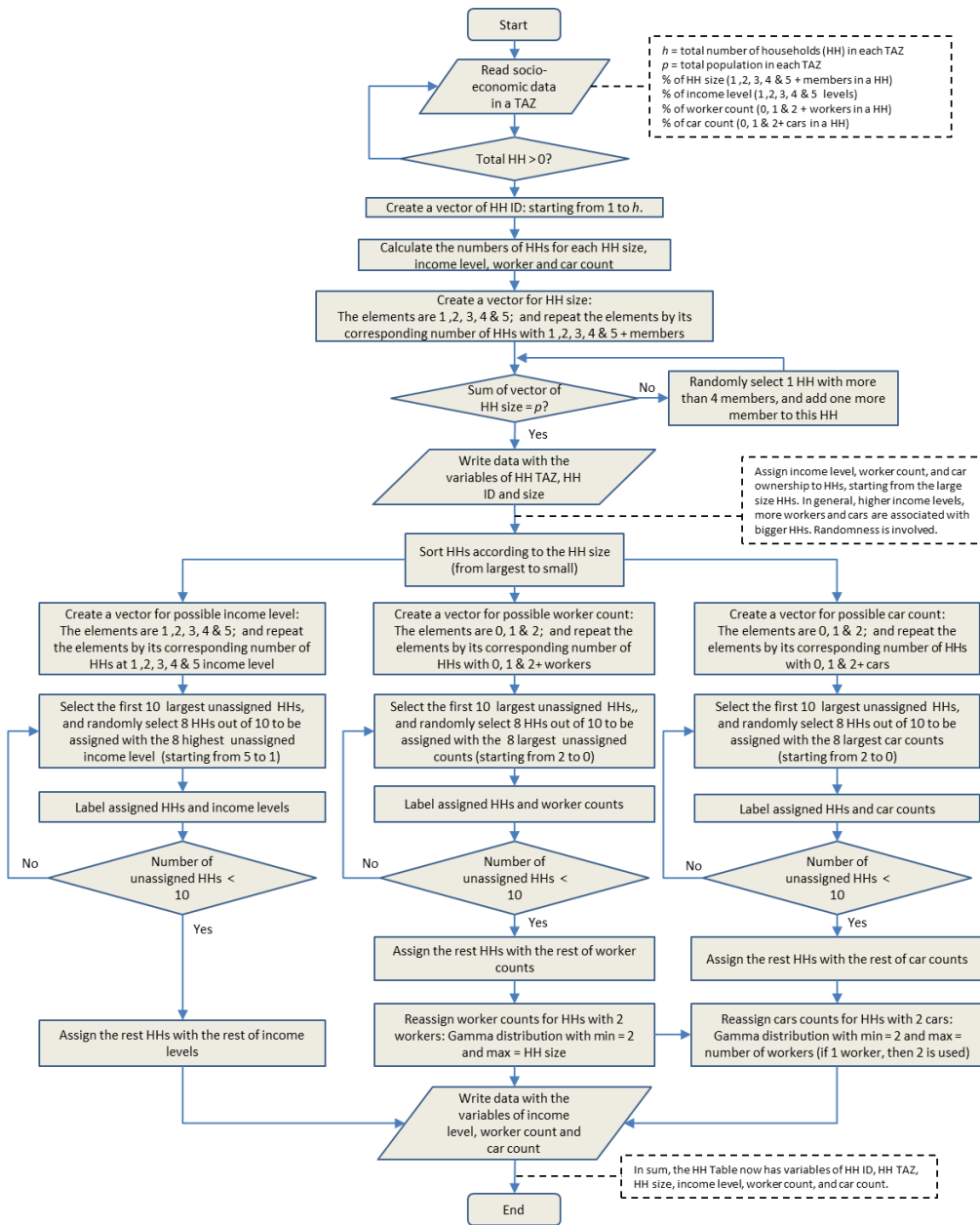


Figure 15.3 Algorithms for generating synthetic households using the socio-economic data in the regional travel models

The publicly available databases including PUMA (Public Use Microdata Areas), LEHD (Longitudinal Employer-Household Dynamics) and household travel surveys provide the either sampled or aggregated data that do not have information about individual locations in a region. This study is to generate information for individual locations where activities can actually perform (instead of imaginarily performing activities at the centroids of TAZs or Census Blocks). This study uses freely available OpenStreetMap (OSM) data to generate household and job locations for activities. This study extracted the polygon information from the OSM’s building layer and obtained the physical locations (longitude and latitude) and site areas of buildings in CAMPO region. The floor area may be more meaningful for multi-floor buildings. However, the data used in this study does not contain such information. If better data is available from other resources (e.g., land use planning organizations or fire department), it is recommended to use such data in the effort.

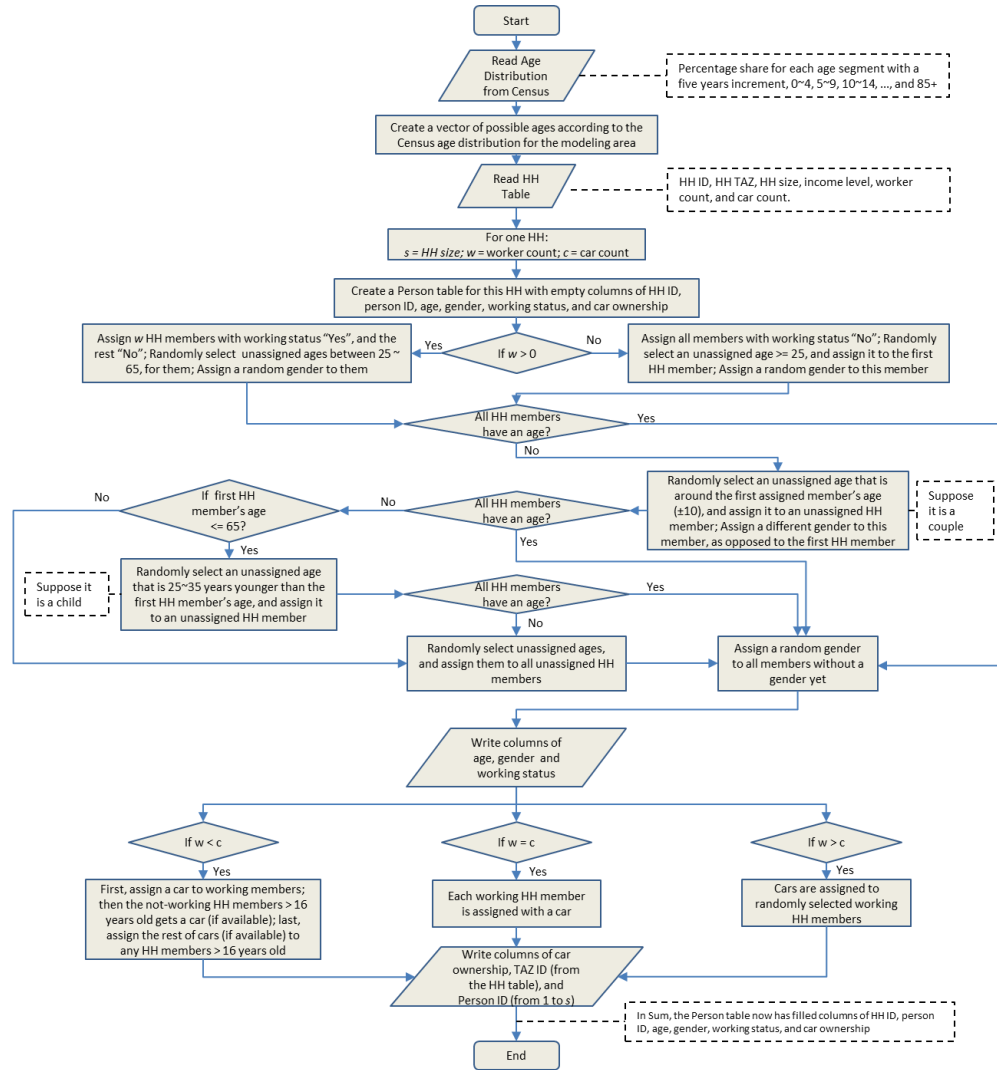


Figure 15.4 Algorithms for generating synthetic persons based on synthetic households

This study categorizes buildings according to the site area. The physical locations obtained from OSM data are grouped into: 1) small size, < 5000 sq ft, 2) medium size, 5000 to 10000 sq ft, and 3) large size, > 10000 sq ft. Small sized buildings are assumed to be single-family homes, medium sized ones are apartments, and large sized buildings are places for jobs. The household income is regarded as a key factor in the building/location allocation. Single-family homes are likely to be medium and high income households; and apartments are for lower to medium household incomes levels. All assumptions are not strict but just represent the most likely situations. Randomness is involved in algorithms.

Since this study uses the future year’s travel demand model data and the OSM data contains the information about current or recent houses and buildings, it is fairly reasonable to generate new job locations to handle additional jobs (from the future development) in a TAZ. The new locations for jobs are randomly generated around the roads where no existing structures are nearby.

As mentioned above, activities are in general associated with jobs. Activity types discussed in this study include basic work, shopping/retail, education and other. A location may be only for basic work, such as office buildings. A location can also have multiple functions, such as schools where faculty work and students attend for educational activities, or shopping malls where some people work as a seller and others visit for shopping or leisure as customers. Figure 15.5 outlines the algorithms of allocating locations for possible jobs.

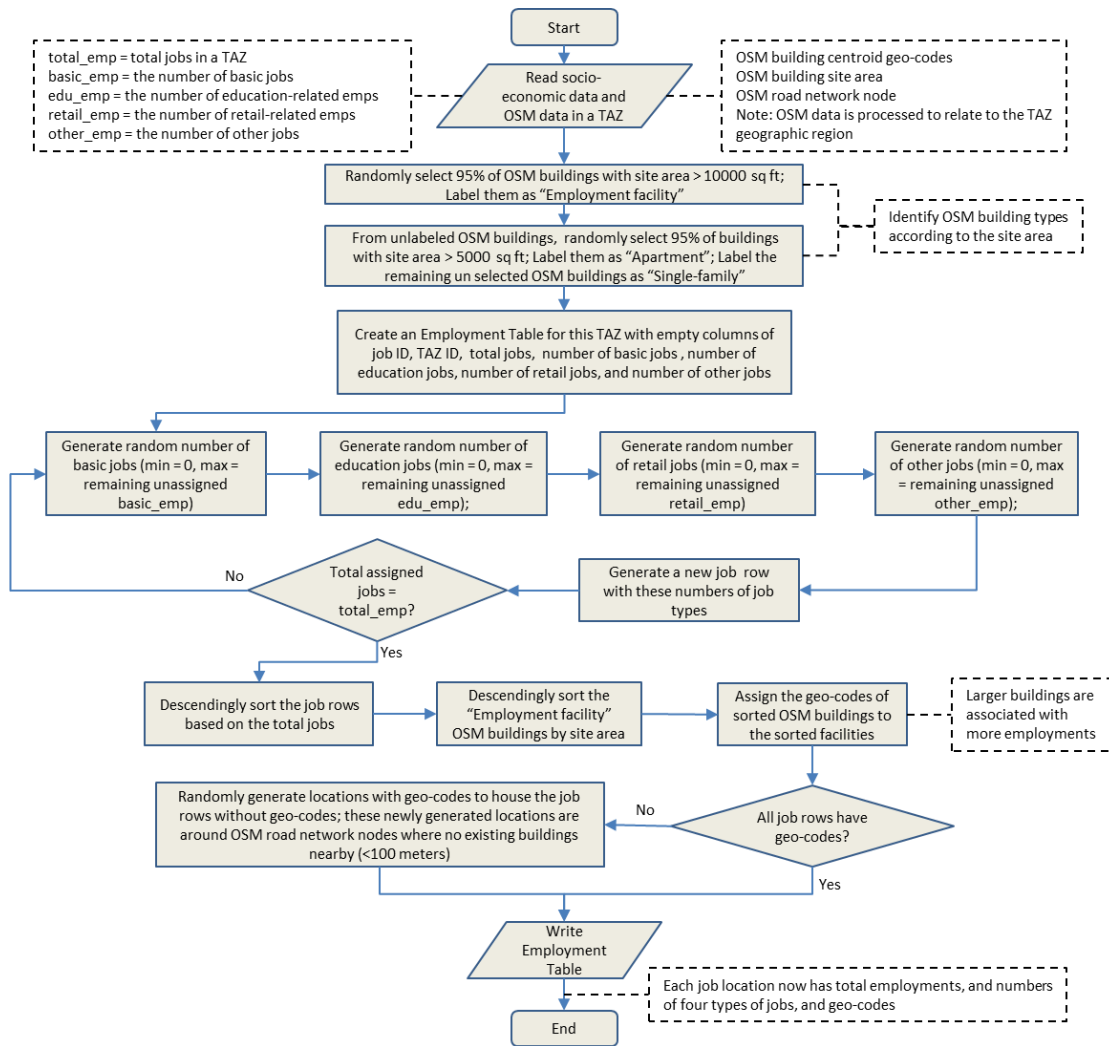


Figure 15.5 Algorithms of allocating locations for possible jobs

The location allocation for households starts from high-income households who are likely to live in larger properties. In general, a higher income level household is assumed to be associated with a larger single-family house. The households with lower level incomes are likely to be limited to apartment buildings. Unlike houses, the apartment buildings can house multiple households. Assuming most apartment buildings are 2 to 3 floors and each unit is about 1000 sq ft, the apartment buildings are split into multiple pieces by dividing the site area over 500; and these units from the same building share the identical location. Projected households are included in the future year’s demand model; therefore, additional houses may be generated in some TAZs. This method is also useful for some model regions (especially small MPOs) where the building information in OSM data is limited. Figure 15.6 shows the key procedures of allocating locations for households.

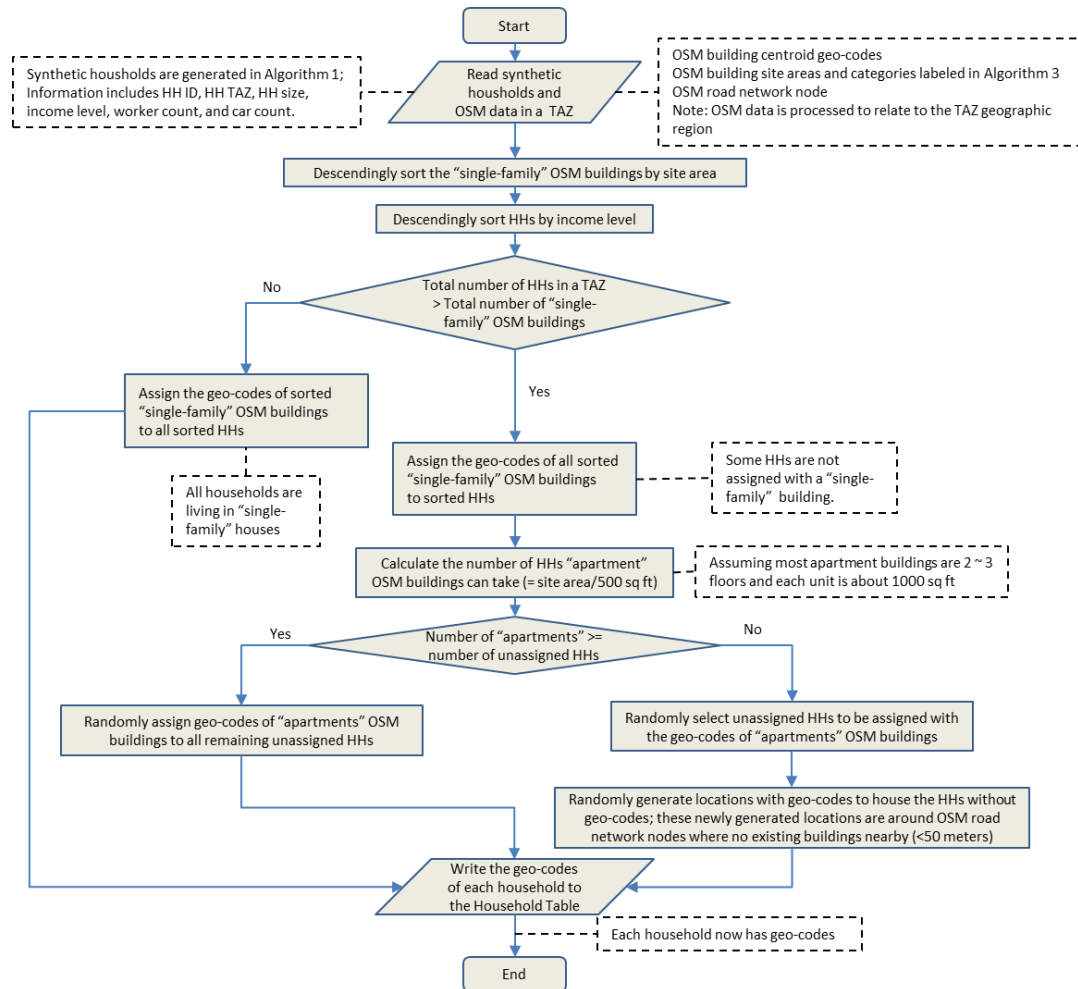


Figure 15.6 Algorithms of allocating locations for households

Chaining Trips between TAZs

Trips made by one traveler in one day form a trip chain, also called a tour if it starts and ends at the same location. Based on the OD matrices (i.e., trips between TAZs) from four-step travel models, this study develops algorithms to chain the TAZ trips to generate a tour for individual travelers. The tour pattern, i.e., number of trips in a tour, is defined according to 2009 National Household Travel Survey (NHTS), as shown in Figure 15.2. Zero-trip makers are likely to be either too young or too old to make a travel on a daily basis, i.e., younger than 5 years old or older than 85 years old. In addition, the individuals who do not have a car and are unemployed have a greater likelihood of making zero trips daily than those who have a car and a job. The number of trips for travelers who own a vehicle is generally more than that for those who do not have a vehicle.

The OD matrices specify trips by purposes, including home-based work (HBW), home-based school (HBSc), home-based retail (HBR), home-based other (HBO), non-home-based work (NHBW), and non-home-based other (NHBO). The trip purposes tell the origin and destination characteristics. For example, a HBW trip links a home and an job location; an HBSc trip connects a home and an educational facility; and a NHBW trip starts from non-home and non-work place to a work place. In general, a traveler is assumed to have one home, one place for work, one place for educational activities, and may have multiple places for other activities.

Almost all tours start and end at homes, except for one-trip makers (e.g., those who stay overnight at a workplace). If a traveler is between 5 and 24 years old, an educational activity is likely to be associated with him or her. If a person is employed, it is assumed that he or she has at least one work-related trip in his or her daily tour. At most, a traveler can have two trips for work or educational activities on a daily basis.

Figure 15.2 (a) shows that about 1.61% travelers make only one trip on a daily basis. For these travelers, the trips are assumed to be work-related (either coming back to home from work, or going to work from home), and these trips are in general long (assumed to be greater than 75 percentile of all possible trips in a model region). Figure 15.7 presents the algorithm of key procedures to chain trips between TAZs for individuals.

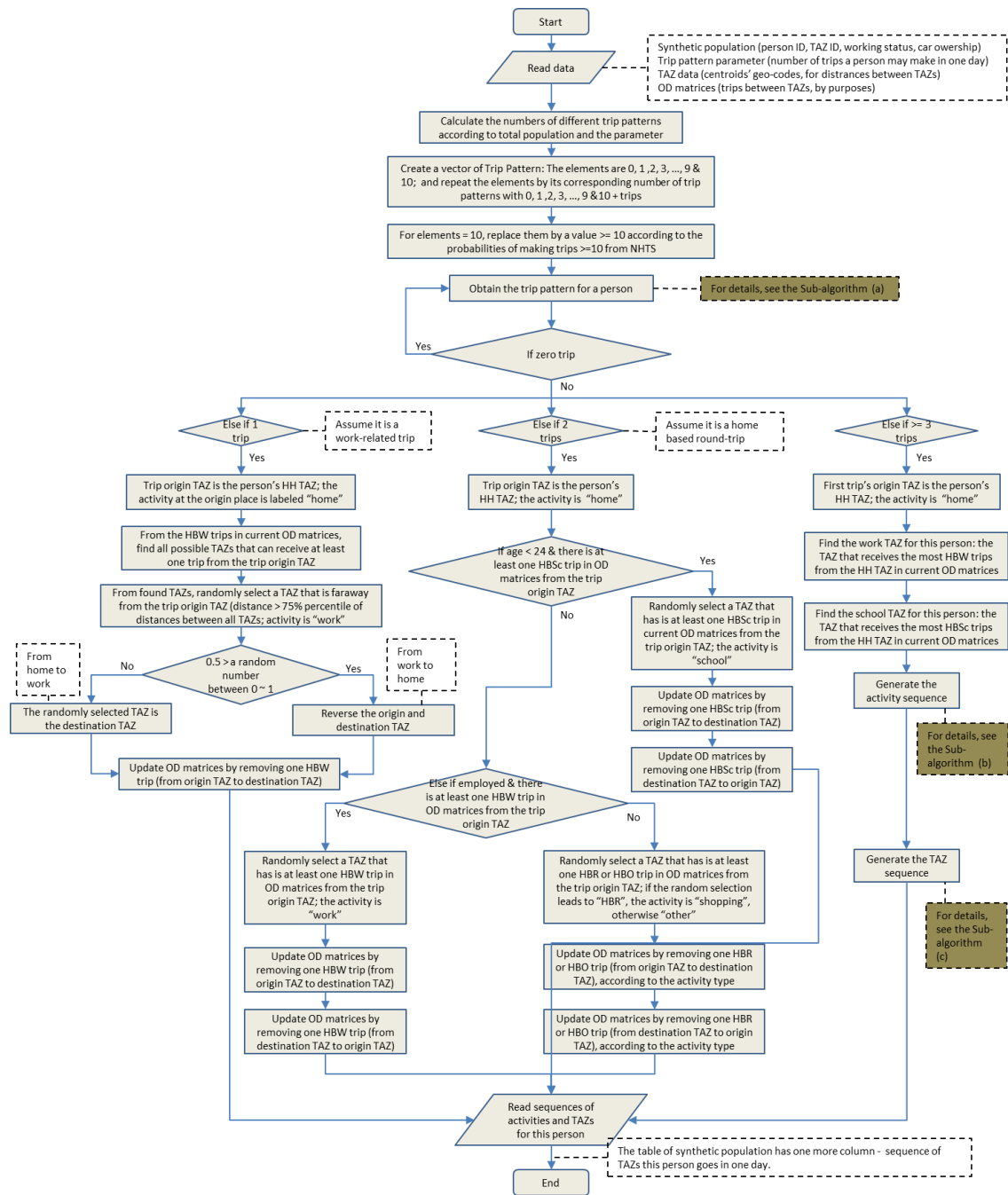
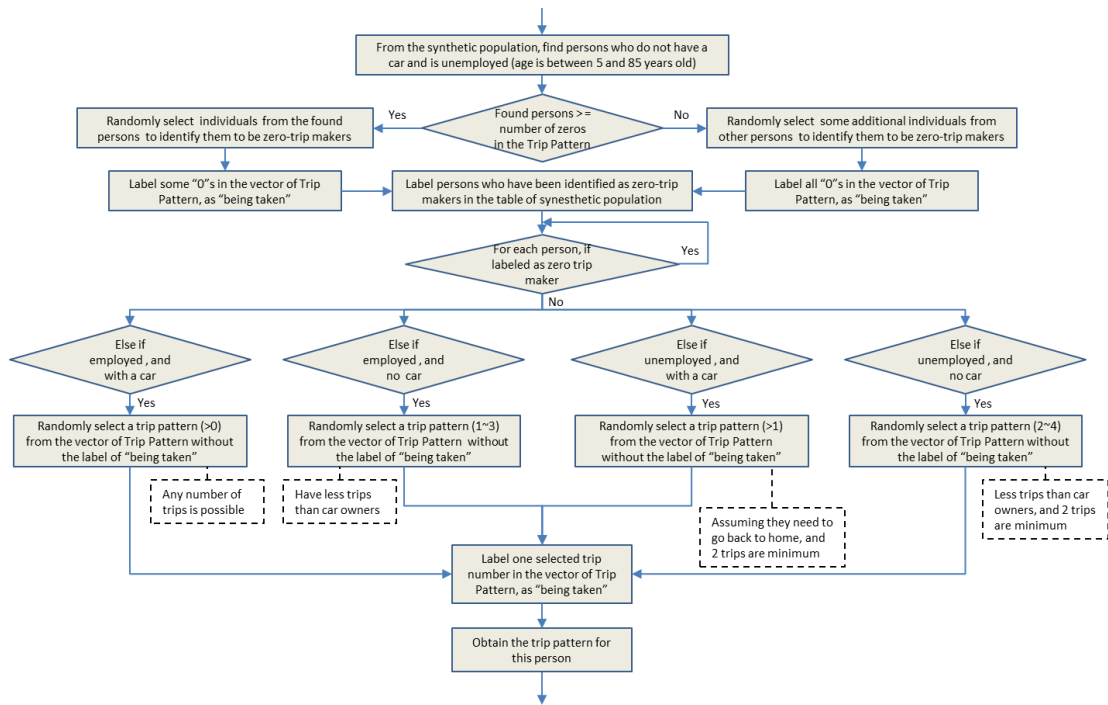
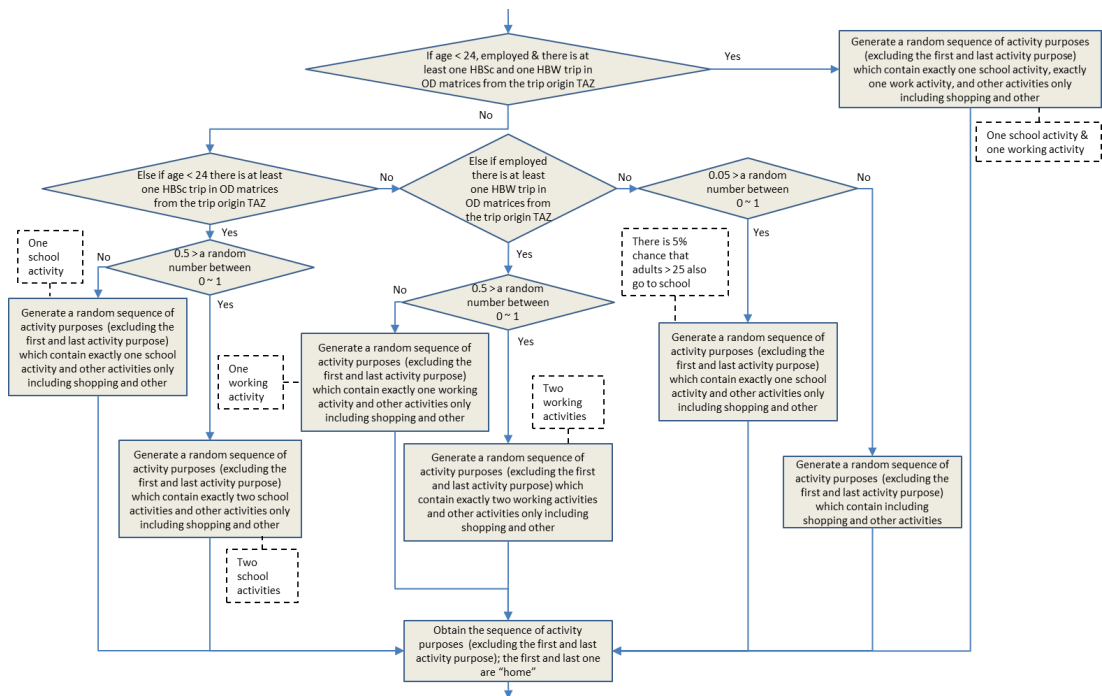


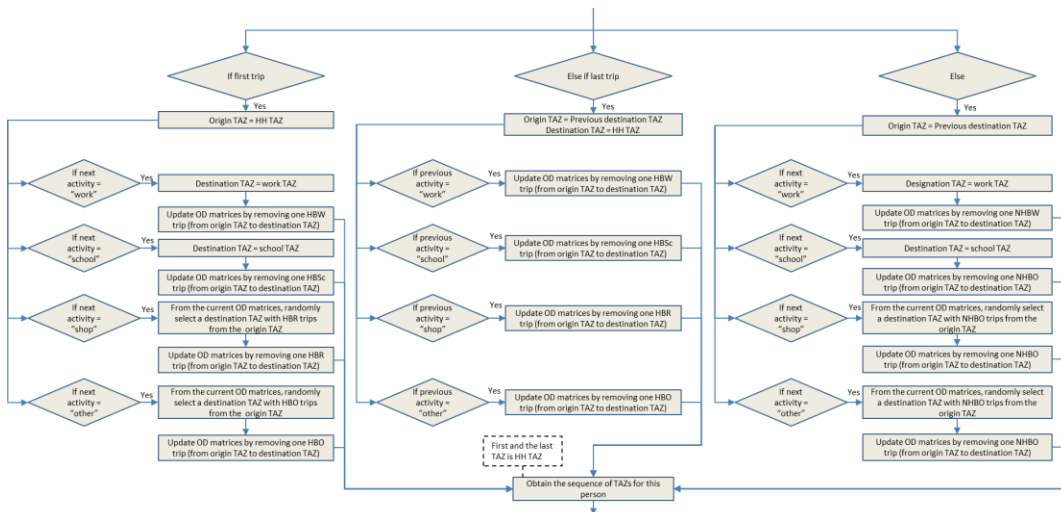
Figure 15.7 Algorithms of chaining trips between TAZs



(a) Sub-algorithms of obtaining the trip pattern for a person



(b) Sub-algorithms of generating activity sequence



(c) Sub-algorithms of generating TAZ sequence

Figure 15.8 Sub-algorithms of chaining trips between TAZs

Allocating Locations for Trip Origins and Destinations

The previous step chains trips between TAZs, while the locations of trips’ origin and destination are not specified yet. In traditional four-step travel models, trips are assumed to start and end at a TAZ centroid. The activity-based models require specific locations for trips’ origins and destinations. Based on the outputs from Algorithm 5, this step allocates locations for a trip’s origin and destination within a particular TAZ. The allocation process is according to the trip-associated activity type. For example, a HBW trip connects one home and one work location, requiring a search for the associated traveler’s home location (which is pre-specified in the synthetic households after home location assignment) and his or her work place from all possible job locations within a specific TAZ. All work-related trips for one person are linked with the same work place. For other types of trips including HBR or HBO, a location is needed for shopping or other activities within the target TAZ. Different trips for shopping or other activities may be connected with different places as long as the location’s type is correct and it is in the corresponding TAZ.

With the exception of home locations, the number of trips received by a facility or building is proportional to the number of employees generated in an early step (it can also be obtained from land use surveys if available). For example, a shopping facility has ten salesmen; therefore it may receive more (not exactly twice) trips than one facility which has five salespersons.

With the exception of home locations, the number of trips received by a facility or building is proportional to the number of employees generated in an early step (it can also be obtained from land use surveys if available). For example, a shopping facility has ten salesmen; therefore it may receive more (not exactly twice) trips than one facility which has five salespersons.

The travel mode is also determined in this process, according to the vehicle ownership. Assumptions include: if a person owns a vehicle, he or she drives; if a person does not own a vehicle but his or her family owns at least one, he or she may carpool; and if the entire household owns no vehicle, he or she has to choose other modes. Note, this is only the initial determination of travel mode, not the mode choice in travel demand modeling. Figure 15.9 shows the key procedures of allocating locations for trip origins and destinations.

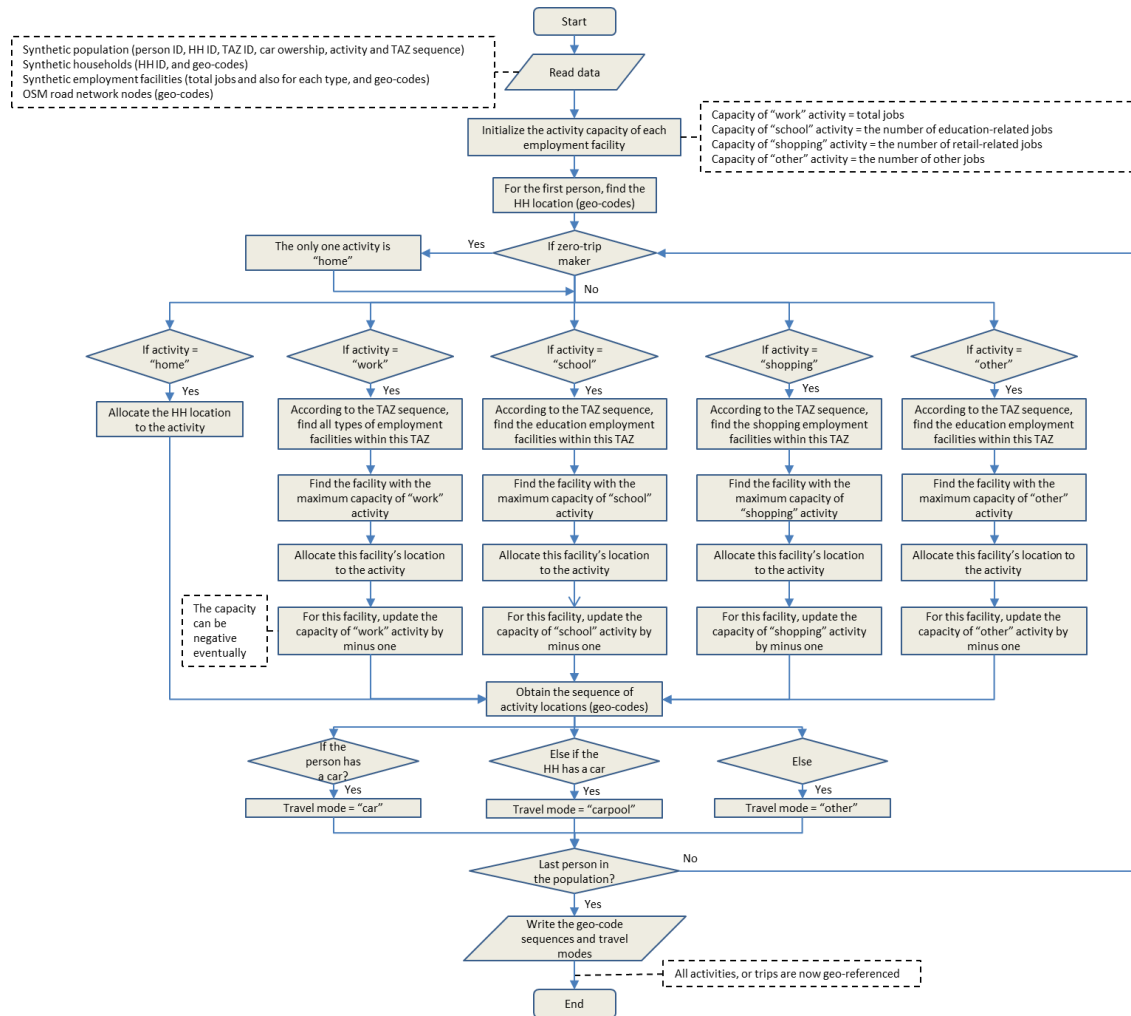


Figure 15.9 Algorithms of allocating locations for trip origins and destinations

Generating Initial Travel Plans

Previous steps generate information about where a traveler may tour in one day, and this step generates information about when a traveler may start a trip. CAMPO model provides the patterns of trip departure times, showing in general when a trip may begin in Austin Texas, as shown in Figure 15.2 (b). In tour-/activity-based models, in addition to the trip departure times, the activity durations and trip durations are also important, as they are major time consumers. Time may be regarded as the resource of making travel plans; and 24 hours is the total resource for an individual to make his or her travel plan in one day.

Typical activity durations and start times are assumed in this study. For example, most work activities may start around 8 AM in the morning and last about 8 hours; and if there is a lunch break (denoted as mainly other activities) two 4-hour work durations may be given. The activity durations are also dependent upon the number of activities planned. The more activities are planned, the shorter the average activity duration is.

The trip durations can be determined by the trip distance and average trip speed. The trip duration for a specific trip is unknown before the simulations reach the equilibrium. In this study, the time skims (between TAZs) from CAMPO model outputs are used to indicate most likely trip durations from a trip's origin and destination. The time skims from CAMPO model represent the average travel time from a TAZ centroid to another. The trips in this study connect two specific activity locations rather than TAZ centroids. Thus, the TAZ skims may be appropriate for the majority of travelers, and randomness is involved in the process of determining initial trip durations.

Initial travel plans only tell when a traveler is likely to make a trip for performing an activity. Travelers may modify their plans (such as changing trip departure times, or re-scheduling the activities) in order to avoid the excessive time spent on roads, reaching the user-equilibrium situation, which is discussed in the section of Case Study in this paper.

Figure 15.10 shows the algorithms to initialize the durations for trips and activities. Figure 15.11 presents the key procedures of initializing travel plans. The key task of the algorithms is to initialize start time of each trip in a tour.

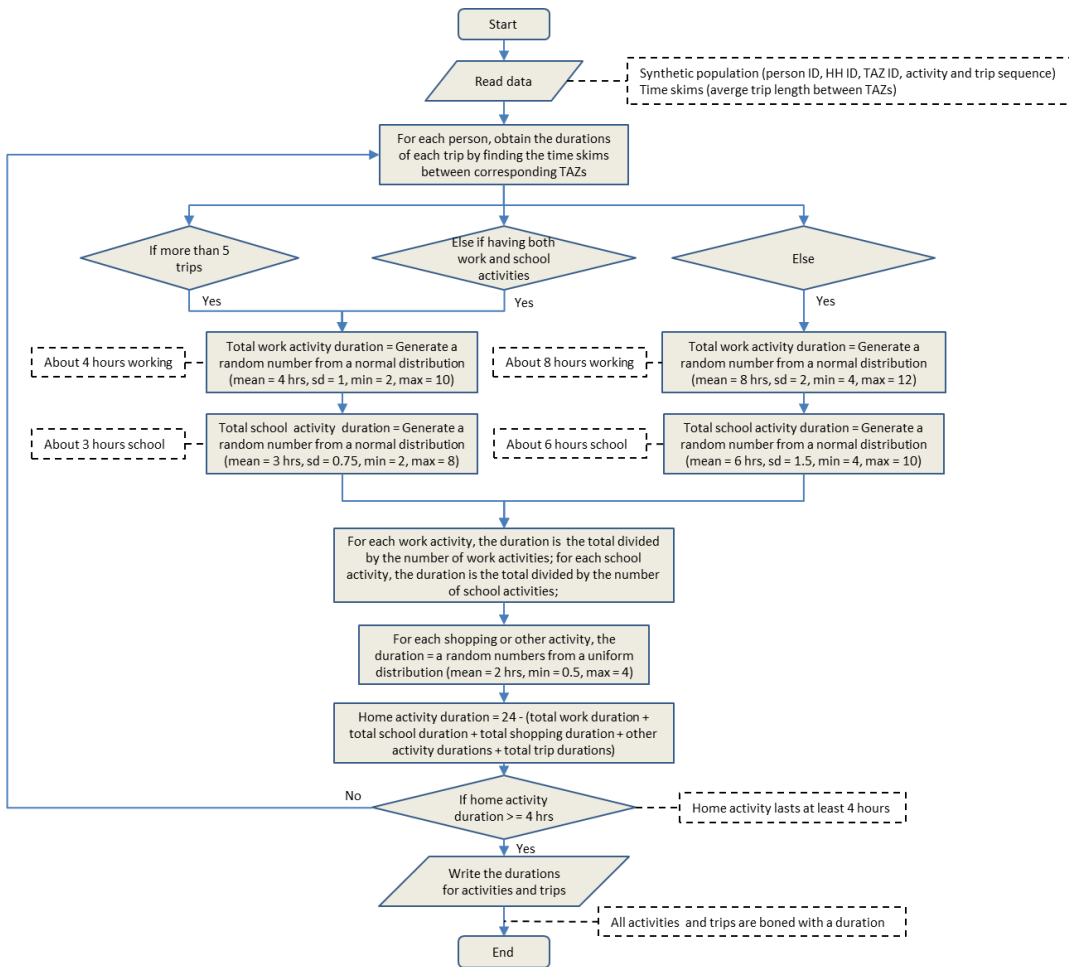


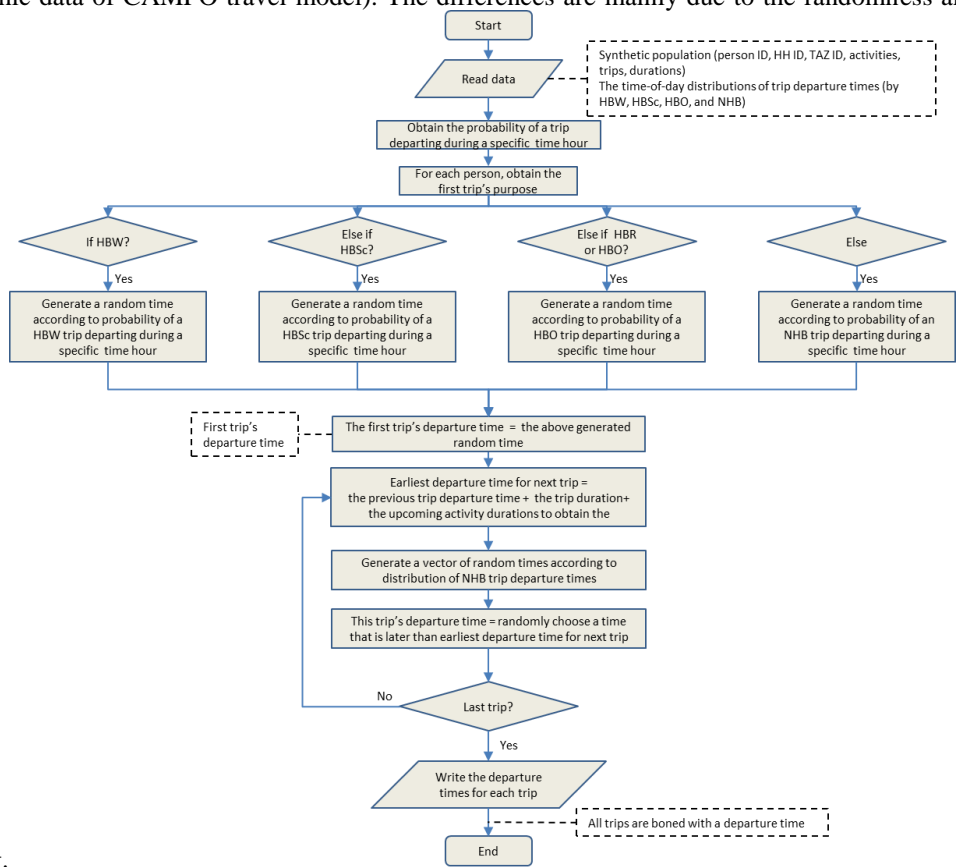
Figure 15.10 Algorithms of initializing the durations for trips and activities

15.5 Program Outputs

Synthetic Population

The program was designed to use the surveyed data and projected demographics used in travel models (summarized at TAZ level) to generate a synthetic population, though the randomness is included in the generation process. The data outputted from the program is supposed to match the statistics of input data at a large extent. Minor differences (<1%) are found between the outputted synthetic population and the inputs

(socio-demographic data of CAMPO travel model). The differences are mainly due to the randomness and



number rounding.

Figure 15.11 Algorithms of initializing travel plans

Using the CAMPO's 2020 model inputs, the program generated a synthetic population of 2,325,116 individuals of 895,082 households in the model region. Each individual is generated with age, gender, job and car ownership. In addition, individuals are also linked with their household characteristics including household size, household income level, number of employed members, number of vehicles and household locations (longitude and latitude). All these factors are important in activity-based travel modeling process. Figure 15.12 (a) and (b) presents the example data of synthetic population at the level of individual persons and households. From the spatial perspective, the synthetic population is also expected to mirror the aggregated input data. Figure 15.12 also presents (c) the input data of population and households aggregated

at TAZ level from the CAMPO's 2020 Travel Model, (d) the spatial

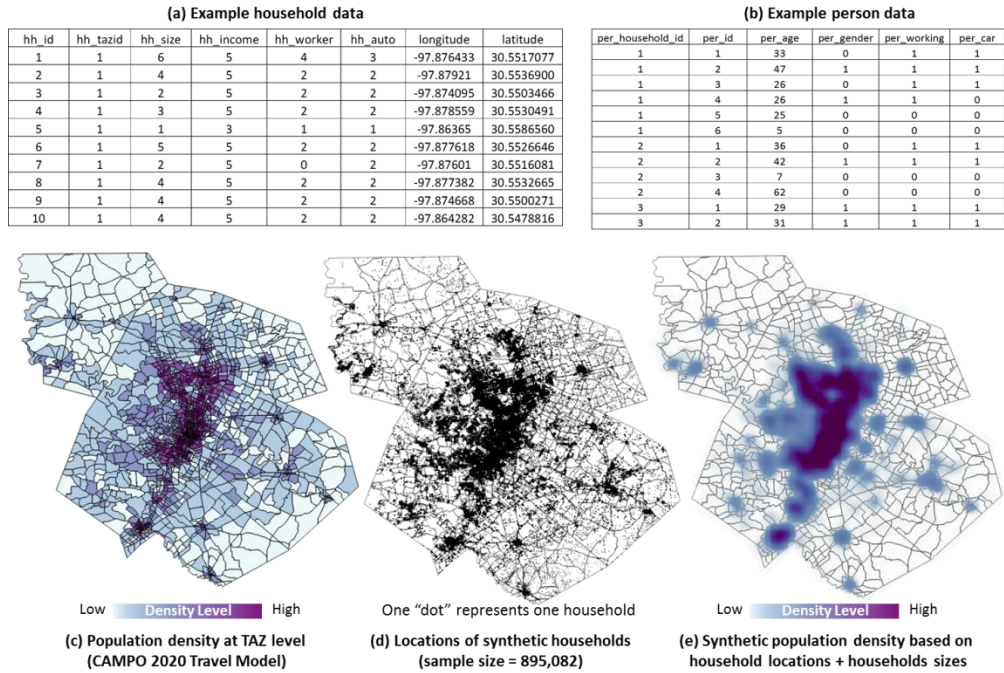


Figure 15.12 Synthetic population and households

Activities and Synthetic Locations

The trip-based travel models offer information about trip purposes which are associated with the activity types at the trip origins and destinations. Five major activity types were generated in the program proposed in this study, including home, work, school, shopping and other activities. Besides home activities, the program generated about 1.5M work activities, 0.46M school activities, 2.5M shopping activities, and 2.4M other activities. Synthetic locations are needed to house these activities in the model region. The household locations are for home activities. For the other types of activities, the program generated job-based locations to house them, though people may not go there for work but for other purposes such as shopping or taking classes. Figure 15.13 presents the example data of generated facilities for activities and the locations for four types of activities. Compared with the household locations (as shown in Figure 15.12), the school and shopping locations are more likely to concentrate to the urban centers; locations for other activities are close to how households are spatially distributed in space.

Example Data of Synthetic Facilities for Employments and Activities

facility_id	Total_employment	basic_work	shop	other	school	TAZ_id	longitude	latitude
1	94	0	18	6	70	1	-97.86418	30.55943
2	65	0	14	2	49	1	-97.865997	30.55937
3	34	0	26	0	8	1	-97.864968	30.56016
4	11	0	8	0	3	1	-97.86087	30.55812
5	14	0	11	0	3	1	-97.858756	30.54917
6	14	0	11	1	2	1	-97.863279	30.55795
7	20	0	20	0	0	1	-97.859803	30.55556
8	29	0	29	0	0	1	-97.863641	30.54751
9	19	0	19	0	0	1	-97.861061	30.55083

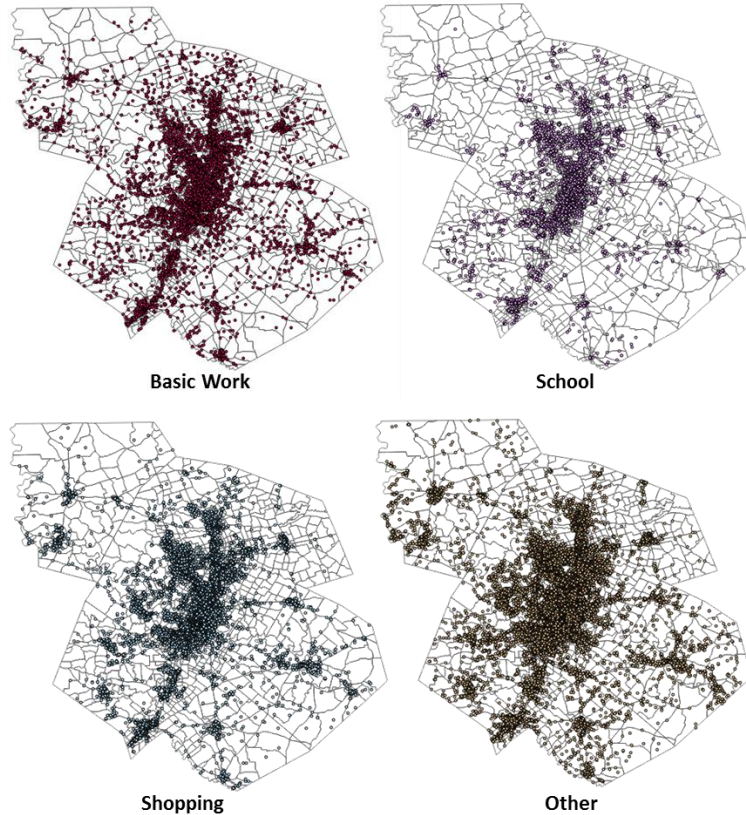


Figure 15.13 Example data of synthetic facilities and spatial distributions of facilities for different types of activities (except home activity)

Trip Chains

Travelers make trips to perform activities. An activity can be regarded as a chain or linkage between two sequential trips, and therefore travelers make a tour to perform a series of activities planned for the day. The program proposed in this study took advantage of the existing CAMPO’s travel model (which is trip-based) to generate the daily travel tours for each individual in the model region. The core procedures of tour generation involved chaining the trips between TAZs (estimated in CAMPO’s model) to form a tour for an individual, according to this traveler’s demographics and NHTS’s survey about the daily tour-making patterns (i.e., the number of trips made by a person, as shown in Figure 15.2). The program generated in total 1.96M tours that chain 8.7M trips for 1.96M individuals who actually travel on a daily basis (which leaves 0.36M persons who do not travel during 24 hours and are assumed staying at home for the whole day). The output resulted in about 3.9 trips per traveler in model region. Figure 15.14 presents the example data of synthetic trip chains, and two example tours in space: a four-trip tour with HBO ⇒ NHBO ⇒ NHBO ⇒ HBO trips, and a five-trip tour with HBW ⇒ NHBO ⇒ NHBW ⇒ NHBO ⇒ HBR trips.

Example Data of Synthetic Tours or Trip Chains

PerId	TripId	activityType	OriginFacilityTAZ	DestinFacilityTAZ	OriginFacilityID	DestinFacilityID
1	0	other	1	1866	1000001	56690
1	1	school	1866	1057	56690	35852
1	2	shop	1057	1595	35852	47825
1	3	home	1595	1	47825	1000001
2	0	work	1	162	1000002	6880
2	1	other	162	929	6880	34081
2	2	work	929	162	34081	6880
2	3	shop	162	118	6880	3937
2	4	home	118	1	3937	1000002

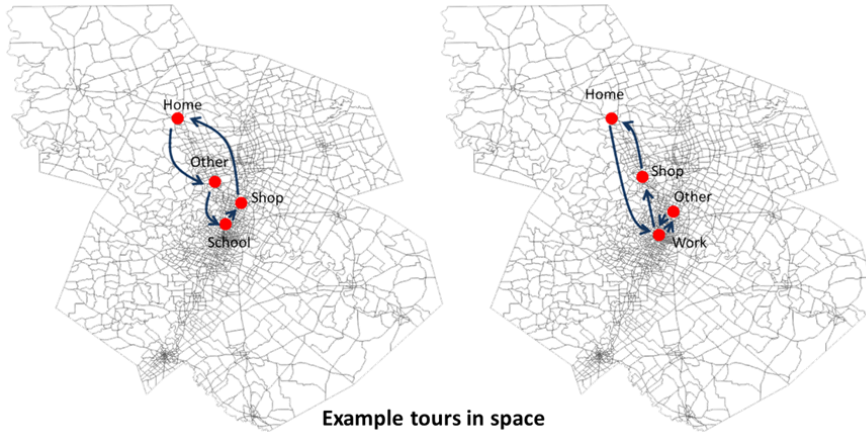


Figure 15.14 Example of Synthetic Tours or Trip Chains

Travel Plans

The travel plans provide critical information about when a trip may depart from its origination. The outputted travel plan contains information about the person’s age, employment status, and a chain of activities with a tentative schedule. Figure 15.15 shows two example travel plans. The scheduled times were determined by considering the three pieces of time information: 1) activity durations, 2) trip duration, and 3) distributions of trip departure times. The travel plan is the core input of ABM. The travel plan reveals a typical schedule for travel and activities. During the modeling process, the travel plan may be modified given constraints of one-day time and space in roadway network. Late arrival, early departure, or cancelling an activity will cause loss of utility, while being stuck in traffic will also negate the production of values. Therefore, travelers will tend to stick with the schedule but may also adjust the schedule to avoid excessive waste of time on road owing to the traffic congestions. More details are presented in the case study in this paper.


```

<person id="1" age="33" employed="yes">
  <plan selected="yes">
    <act type="home" facility="1000001" x="-97.87921008" y="30.55369003" end_time="08:56:59"/>
    <leg mode="car" dep_time="08:56:59"/>
    <act type="other" facility="56690" x="-97.86081666" y="30.53089811" end_time="09:33:00"/>
    <leg mode="car" dep_time="09:33:00"/>
    <act type="school" facility="35852" x="-97.77755189" y="30.43983589" end_time="15:12:00"/>
    <leg mode="car" dep_time="15:12:00"/>
    <act type="shop" facility="47825" x="-97.79296572" y="30.5232782" end_time="17:53:59"/>
    <leg mode="car" dep_time="17:53:59"/>
    <act type="home" facility="1000001" x="-97.87921008" y="30.55369003"/>
  </plan>
</person>
<!------->
<person id="2" age="47" employed="yes">
  <plan selected="yes">
    <act type="home" facility="1000002" x="-97.87409538" y="30.55034662" end_time="08:11:59"/>
    <leg mode="car" dep_time="08:11:59"/>
    <act type="work" facility="6880" x="-97.7487424" y="30.34361178" end_time="12:05:00"/>
    <leg mode="car" dep_time="12:05:00"/>
    <act type="other" facility="34081" x="-97.80691386" y="30.47037602" end_time="12:45:02"/>
    <leg mode="car" dep_time="12:45:02"/>
    <act type="work" facility="6880" x="-97.7487424" y="30.34361178" end_time="16:32:00"/>
    <leg mode="car" dep_time="16:32:00"/>
    <act type="shop" facility="3937" x="-97.69170071" y="30.45757895" end_time="19:07:24"/>
    <leg mode="car" dep_time="19:07:24"/>
    <act type="home" facility="1000002" x="-97.87409538" y="30.55034662"/>
  </plan>
</person>

```

Figure 15.15 Example travel plans

Spatial Details

The program proposed in this study generates specific physical locations for individuals to perform activities and these locations are the origins and destinations of trips (rather than TAZ centroids in 4-step travel models). These locations are scattered in TAZs, as shown in Figure 15.16 (a). There are two types of scatter patterns. One type has quite clear patterns, shown in Figure 15.16 (b), along the road links, as these locations are known places for households and jobs according to the open-source data. The other type seems to be irregular patterns, shown in Figure 15.16 (c). These locations were generated according to the road link/node locations and the number of households and jobs in a TAZ. The irregularity is due to the limitations in open source data (e.g., incomplete records) and the need for understanding future travel modes.

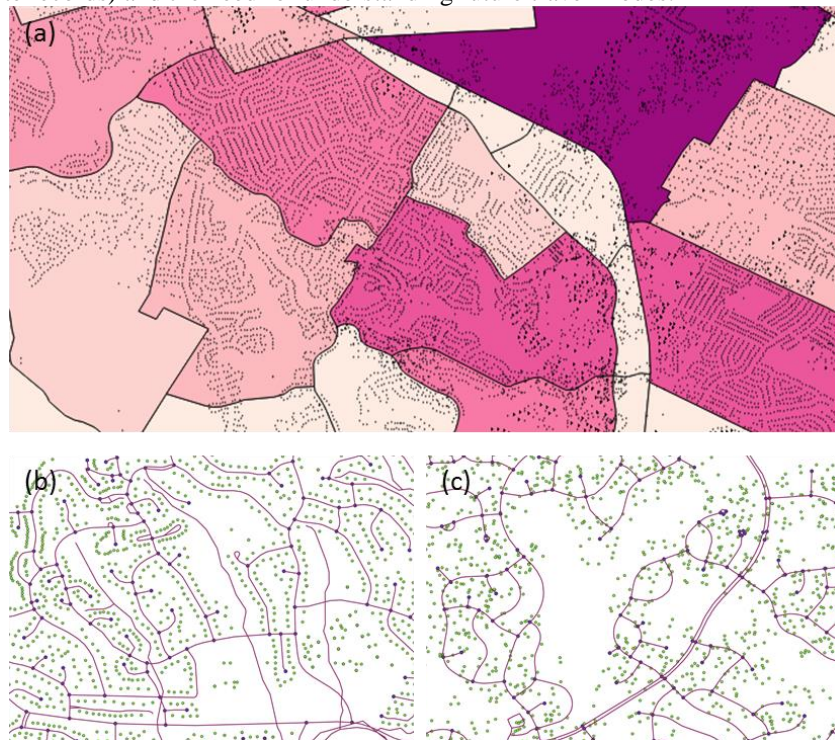


Figure 15.16 Spatial Details for Activity Locations

15.6 Case Study

This section briefly presents a case study, to construct an activity-based model using the synthetic activity data generated by the program in this study. The model was built on the platform MATSim, an open-source agent-based simulation tool for large-scale activity-based microsimulations. MATSim is based on the co-evolutionary principle. Every agent (i.e., traveler) repeatedly optimizes his or her travel solutions based on their initial travel plans while competing for limited space-time slots with all other agents in the transportation network (citation, MATSim book). A MATSim run starts with initial travel plans, i.e., the chains of trips or activities a person plan to make on a daily basis. During iterations, the initial travel plans are then optimized individually. Every agent possesses a memory containing a number of day travel solutions, where each solution is composed of a daily trip chain and an associated score. The MATSim scoring function is based on the econometric utility of time. Unlike studies or programs where the utility is calculated for travel only (the mode or route choice), the utility function in MATSim accounts for both the travel and the activities an agent performs one a daily basis:

$$U = \sum_{i=1}^q U_{travel,i} t_{travel,i} + \sum_{j=1}^{q+1} U_{activity,j} t_{activity,j} \quad (15-1)$$

where U = Total utility of a travel solution composed of a daily trip chain; $U_{travel,i}$ = Utility of travel for i^{th} trip in a day; $i = 1, 2, 3, \dots, q$ trips; $t_{travel,i}$ = Travel time for i^{th} trip; $U_{activity,j}$ = Utility of performing the j^{th} activity in a day; $j = 1, 2, 3, \dots, q+1$ activities; and $t_{travel,i}$ = Duration of j^{th} activity. Moreover, $\sum_{i=1}^q t_{travel,i} + \sum_{j=1}^{q+1} t_{activity,j} = 24$ hours.

Monetary payments (e.g., tolls and fares) and the value of travel time (VOTT) are included in the $U_{travel,i}$. The utility of performing an activity, $U_{activity,j}$ is related to value of activity time (e.g., hourly wage). The travel utility is generally negative while the activity utility is positive. The travel solution optimization is to maximize the total utility of a chain of trips an agent may take to perform his or her planned activities. More details about the MATSim scoring function are available in the MATSim Book. The MATSim's iterative process is to improve the utility by re-planning the travel trips i.e., modifying time choice, mode choice, or destination choice, and finally to reach dynamic user equilibrium (DUE). After reaching DUE, the MATSim outputs a most executable travel solution for each agent. As MATSim simulations are to mimic the process of travelers looking for the best travel solutions for their daily activities in real-world, the MATSim simulation results have been revealed to match the real-world travel modes very well (Bösch et al., 2016; Ciari et al., 2016).

The outputs of MATSim simulations include an optimal travel plan for each agent. Through a closer look at the plan, researchers or modelers can track each agent in the network. In other words, at any time of a day, where an agent is and what this agent is doing can be presented. The animation of simulated activities and travel trips is available at <https://www.youtube.com/watch?v=kqHI3xc3nC0>.

15.7 Limitations

The accuracy of synthetic data generated in this study is heavily dependent upon the accuracy of inputs including the travel demand data, parameter data and map data. The travel demand model data in future years may contain inaccurate predictions about regional population growth and economic development. The parameter data include the age distributions, tour patterns, and trip departure times. The age distribution parameter may cause inaccuracy in the vehicle ownership assignment and trip making characteristics (as the kids cannot own a vehicle, and seniors are expected to make fewer trips than young people do). The tour pattern parameter affects the number of trips in a daily travel tour. The inaccurate time parameter in the trip-departure model may not reflect Austinites' actual schedules. In addition, the program presented in this study generates synthetic activity and travel data according to limited data sources with a number of assumptions. The validity of these assumptions remains unknown, and surveys are needed to validate these assumptions in the future. If using a desktop level computer or laptop, the generation of synthetic data using the current program may be a computational burden for large-scale travel model regions (population > 1 M), due to the

massive searching cases (e.g., assigning a location for an activity), and matching requirements (the disaggregated synthetic data are required to match the aggregated data at TAZ level from various prospects, e.g., the total population, household, vehicle ownership, and jobs). The use of workstation level computers may facilitate the run of the program.

15.8 Conclusions

New travel modes, like car-sharing and ride-sharing, present an opportunity and a challenge for transportation planners and researchers to explore travel choices at the level of individual travelers, over the course of a continuous day, in addition to simple one-way trip counts, aggregated by zone or neighborhood for broad times of day. New opportunities require transport experts to confront new questions emerging and future modes (like shared autonomous vehicle fleets, and demand-responsive transit systems), but the difficulty of obtaining disaggregated input data for advanced travel demand modeling practice can hold planners and researchers back. To support more realistic travel demand modeling practice, this study delivers a framework for detailed input-data preparation, to support ABM applications. A series of algorithms exploit and extend common and publicly available data sources (like household travel surveys and Open Street Maps) to provide highly disaggregated travel data.

ABM data can be described as “4Ws” for each person’s daily travel: **who** this person is, **where** he/she live and work, **what** his/her daily activities entail, and **when** does he/she perform those activities. The program first generates a synthetic population for the desired region or community based on zone-level land use and demographic data. Every individual in the modeling region is included in synthetic population; generated attributes include age, gender, job, car ownership, and household characteristics. Second, places for households and jobs were generated to answer where a person lives and works. Open Street Map (OSM) data provide the information about possible locations/places for households and jobs. Then the program converted the zone-level travel demand (i.e., trips between zones) to person-level demand (i.e., a unique chain of activities, forming a travel tour which connects specific physical locations instead of zone centroids in trip-based models). The program gave answers to what activities a person does. Last but not least, a schedule for traveling or performing activities was generated by the program to tentatively answer when a person plans to perform activities. Example outputs are showed in this paper. The outputs show great temporal and spatial details about individuals’ travel modes.

This work was designed to support the use of ABM modeling platforms, like POLARIS (Auld et al., 2016) and MATSim (Horni et al., 2016). This paper offers insights into the “4Ws”, as inputs to activity-based travel models, and explains what public data sources are useful in preparing such information. The resulting tool (a computer-based program coded in R) is designed to help transportation planners and researchers prepare “4W” information for ABM applications. The program’s algorithms exploit publicly available data sets and produce person-level information for ABM applications. Such tools are particularly useful for transportation planners who already have developed trip-based regional travel models that contain most of the program’s key inputs. Additional efforts will be helpful for integrating other data sources, such as those now being sold by Streetlight, INRIX and AirSage.

CHAPTER 16 EMERGING TRANSPORTATION APPLICATIONS

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16.1 Introduction

Connected and automated vehicles (CAVs) have the potential to significantly change surface transportation systems. CAVs will likely influence and hopefully diminish externalities associated with driving, such as crashes, congestion and emissions, with further impacts on connecting communities, land use patterns, and the economy. However, CAVs' ultimate impacts remain quite uncertain, and much depends on how they are adopted, deployed and used.

This chapter evaluates the potential costs and benefits of using smart transport or CAV technologies in contexts where the Department of Transportation (DOT) or other public transportation agencies are likely to have a role in deployment. This is accomplished here using a benefit-cost analysis for a variety of strategies.

In Section 16.2, agency objectives and measure of performance are defined. Strategies to be evaluated are outlined in Section 16.3, along with anticipated impacts to overall transport system. Each strategy entails extra costs for vehicle users (not considered here, since they will be carried by individuals, rather than public agencies) and in infrastructure provision or system operations and maintenance. All benefits and costs, from the perspective of transportation or roadway management agencies, are considered, delivering a suite of benefit-cost ratios, with summary Conclusions delivered in Section 16.4.

16.2 Transportation Objectives and Performance Measures

Thoughtful management of transportation systems typically requires the understanding and use of key performance measures. These are defined to reflect a variety of different system or agency objectives and may be applied across different types of transportation system users, modes, problems and solutions (Litman 2011). Here, mobility, safety, sustainability, connectivity, economic impacts, and land use are assumed to be the key objectives.

Safety

Understanding, tracking, and improving transportation safety will generally require analysis of past crashes, as well as forecasting methods for anticipating future crashes by motorists, cyclists, and pedestrians. Safety performance measures regularly include the number, rate and/or severity of crashes and incidents, but may also include factors like emergency response times and public perceptions of safety (Hedlund 2008). For example, TxDOT utilizes a 5-year moving average for assessing the statewide fatality rate per 100 million VMT, the number of fatalities, the statewide serious injury rate per 100 million VMT, and the number of serious injuries (TxDOT 2015b). Other state DOTs use similar metrics, along with other, relatively indirect safety-influencing measures. For example, Connecticut measures seat belt use (CTDOT 2015), Oregon considers rail crossing incidents and public satisfaction with transportation safety (ODOT 2015), and

Pennsylvania reports the number of DUI drivers, aggressive driving incidents, distracted driving incidents, pedestrian fatalities, and work zone crashes (PennDOT 2015).

The best way to assess traffic safety is by directly measuring safety outcome data itself that is crashes and crash severities. For estimating unit crash costs, Blincoc et al.'s (2015) unit estimates are applied here, using Texas' past crash severity distributions as a case study (TxDOT 2013). By applying this methodology, an average comprehensive cost per crash can be obtained, as follows:

$$C = \sum_i \frac{N_i \times CC_i}{N_i}$$

where i = crash severity (K, A, B, C, and O categories), N_i = Number of crashes of severity i , and CC_i = Crash cost (comprehensive or economic) by severity i .

This method delivers an average comprehensive cost¹¹⁹ per crash of \$202,880, or \$46,580 in purely economic crash costs¹²⁰. A similar method, as shown in Table 16.1, delivers average comprehensive crash costs per VMT of \$0.37 (or \$0.085 per VMT when considering only economic costs). In this chapter, direct crash cost savings are considered when a strategy should reduce a given number of crashes by a certain percentage (e.g., total crashes fall 20% at an intersection from a base of 20 crashes), while per-VMT crash exposure costs are considered when the strategy may alter the amount of travel. Moreover, in this chapter a comprehensive cost assessment was used rather than economic cost, because comprehensive cost includes measures such as the statistical value of life and willingness to pay figures to avoid crashes and injuries.

Table 16.1 Texas Crash Costs, by Type (in 2015 dollars)

Average cost per crash		Average crash costs per VMT	
Economic Cost	Comprehensive Cost	Economic Cost	Comprehensive Cost
\$46,580	\$202,880	\$0.085	\$0.37

Mobility

The movement of people and goods is key to the economic and social vitality of cities and states. A number performance measures have been used to measure mobility, including travel time index¹²¹ and speed and traffic volumes, which are used by the Texas Transportation Institute (Sen et al. 2011) and the Chicago Metropolitan Agency for Planning (CMAP 2015).

Conklin et al. (2013) have categorized mobility measures in three groups namely, basic measures, derived measures and advanced measures. Basic measures include traffic speed, traffic volume and lane occupancy. While these are valuable metrics by themselves, additional measures can be derived from them with no additional data requirements, such as travel times between key locations. Advanced performance measures commonly are normalized performance metrics (e.g., travel time index), usage and performance metrics (e.g., vehicle-miles traveled (VMT)), and person throughput metrics (e.g., person volume, or person miles traveled).

TTI has also suggested three measures for mobility (Urban Mobility Report 2014):

- **Travel delay:** the amount of additional time spent in travel, relative to free-flow conditions, and composed of recurring delays due to congestion, and non-recurring delays due to traffic incidents, bad weather or special events.

¹¹⁹ Comprehensive crash cost includes economic crash cost and external measures such as quality-adjusted life years and willingness-to-pay measures for avoiding crashes

¹²⁰ Economic crash cost includes property damage, delay, medical costs, lost productivity, and other factors.

¹²¹ Ratio of peak-period travel time to free-flow travel time

- **Buffer (reliability) index:** a measure of network reliability estimating the additional time that a traveler needs to budget during peak-period travel, such that he or she will arrive on time with a 95% confidence level.
- **Annual congestion costs:** passenger vehicle delay costs, freight vehicle delay costs, and the cost of additional fuel consumed due to slower and uneven travel speeds.

For this chapter, travel delay is considered the critical mobility performance measure due to the simplicity of its nature in estimating costs or benefits for individual strategies and applications. Here, travel time is valued at \$17.67 per person hour, consistent with methodology as used in the Urban Mobility Report (2014).

Connectivity

Connectivity (or accessibility) refers to the ability to reach desired goods, services, activities and destinations (collectively called opportunities). It reflects both mobility and land use patterns (the location of activities). This perspective gives greater consideration to non-motorized modes and accessible land use patterns. Connectivity is evaluated based on the time, money, discomfort and risk (i.e., generalized cost) required to reach opportunities. Connectivity can be difficult to measure because it can be affected by so many factors. Activity-based-models utilizing utility-based traveler benefit valuations and integrated transportation/land use models are most suitable for quantifying these types of metrics (Litman 2011).

Since the utilization of such models is not within the scope of this project, qualitative judgments are used here to estimate impacts on connectivity. Travel cost, and travel risk are already incorporated in mobility and safety measures, respectively, so the quality of travel is the only qualitative measure to be selected for connectivity perspective. Three levels of impact are adopted for it: negative, no impact and positive.

Sustainability

Sustainability, as referred to in transportation, can encompass holistic considerations of economic, social, and environmental progress—usually referred to as sustainability dimensions—with a long-term perspective (Zietsman et al. 2011). However, this concept is quite comprehensive, some of the metrics are overlapped with other performance measures examined in this document, such as mobility and connectivity. Therefore, sustainability as discussed in this chapter focuses only on environmental components.

Within the surface transportation sector, air pollutant emissions are typically considered the most critical environmental sustainability component. Pollutant emissions can be either local or global in scope. Local air pollution impacts air quality and human health in the areas surrounding the emissions source, while global air pollution affects atmospheric greenhouse gas concentrations on a worldwide scale. Climate change impacts are experienced globally. Federal regulations limit local air pollutant emissions stemming from motor vehicles, with new cars required to meet EPA emissions standards (and older cars too, by agencies such as TxDOT, Washington State Department of Ecology, and Cook County Department of Environmental Control, Illinois) in locations where air quality conformity is an issue (Zietsman et al. 2011). In planning stages, estimated impacts by direct traffic related indicators (e.g., VMT or travel time) is likely more suitable than indirect measurements and is therefore used here.

Land Use

Transportation planning decisions influence land use patterns directly, by affecting the amount of land used for transport facilities, and indirectly, by affecting the location and design of development. For example, extending urban highways increases pavement area, and encourages more dispersed, automobile-oriented development (sprawl), while walking, cycling and public transit improvements encourage compact, infill development (smart growth) (Litman 2016).

The relationship between transportation and land use is complex and it is difficult to directly measure transportation's impact on land use patterns. However, land use patterns can be evaluated based on certain attributes (Litman 2016), such as:

- Density (number of people or jobs per unit of land area)
- Land use mix (locating different types of activities close together)
- Non-motorized conditions (quality of walking and cycling facilities)
- Network connectivity (number of connections within the street and path systems)
- Accessibility (ability to reach desired activities and destinations)
- Greenspace (portion of land used for green space)
- Impervious surface (land covered by buildings and pavement, also called the footprint)

Within the context of this project and evaluation feasibility, some attributes (namely non-motorized condition, network connectivity and impervious surface) are not considered as viable performance measures because non-motorized transportation modes and network design does not fall within the scope of CAV-related strategies. Moreover, earlier connectivity objectives already account for accessibility measures. Therefore, this chapter considers potential impacts on density, land use mix and greenspace as land use performance measures relevant to this investigation. Additionally, sprawl is also considered here since it imposes added external economic, social and environmental costs. Similar to connectivity measures, a qualitative evaluating is adopted here which includes three levels of impact: negative, no impact and positive.

Economic Impacts

Economic impacts stemming from the transportation system can be divided by two categories: internalities and externalities. Transport system internalities directly address specific benefits or costs realized from a given project, such as changes in crash costs, fuel consumption or travel delays. While these are accounted for through other performance measures in this chapter, economic externalities focus on economic activities that result in indirect benefits or costs. These types of impacts may include positive impacts such as new jobs created, new supply chains, and changing land values, as well as potential negative impacts like job losses and air pollutant emissions. Since pollutant emissions were covered earlier, this economic externality is not considered here.

The FHWA recommends using several external economic impacts when evaluating transportation impacts on local economies (Sharkey and Fricker 2009). Here, we consider two metrics to anticipate economic impacts: changes in job counts (changes in the number of full-time equivalent jobs in a city or region), and average income. Each factor is measured using three levels of impact: negative, no impact, or positive, representing anticipated changes to area-wide employment, incomes, and impacts to local business, as shown in Table 16.2.

Table 16.2 Economic Impact Measures

Measurement	Effect
Number of jobs	Negative / No impact / Positive
Average income	

Objective	Metrics	Qualitative & Quantitative Measures
Safety	Number of crashes by fatality	\$/Crash, \$/VMT
	Number of crashes by VMT	
Mobility	Delay	Value of Travel Time (\$17.67 per person hour)
Connectivity (Accessibility)	Quality of travel	Negative / No impact / Positive
Sustainability	Ozone (O3), Particulate Matter (PM10), Carbon monoxide (CO), Nitrogen Oxides (NOx), and Sulfur Dioxide (SO2)	\$/Tons, \$/VMT
Land Use	Sprawl, density, land use mix, greenspace	Negative / No impact / Positive
Economic Impact	Number of jobs, average income, number of activities	Negative / No impact / Positive

Figure 16.1 Summary of Transportation Objective Performance Measures

Benefit-Cost Analysis Implementation

With the emergence of CAVs, state DOTs and other transportation agencies will have the ability to deploy infrastructure to harness their capabilities. In order to properly evaluate the potential effectiveness of these strategies, it is crucial to conduct benefit-cost analyses. This work is conducted in this section by considering related published research for each strategy, with potential benefits estimated quantitatively or qualitatively, depending on the performance measure type and available existing research. Here, installation and maintenance costs are also estimated (when figures are available) that would be the responsibility of TxDOT, or other transport agencies. Finally, a tentative B/C ratio is estimated for each strategy using available benefit and cost information. The strategies that are evaluated here include:

- Dynamic route guidance systems
- Incident warning systems
- Congestion pricing
- Intelligent signal systems
- Cooperative intersection collision avoidance systems
- Cooperative ramp metering
- Smart-priced parking
- Shared autonomous vehicle transit
- Transit with blind spot detection and automated emergency braking
- Automated construction vehicles

16.3 Benefit-Cost Analysis Implementation

Dynamic Route Guidance Systems

A dynamic route guidance system (DRGS) is an Advanced Traveler Information System service that provides shortest path information to travelers or vehicles in real time. This system communicates with fixed or dynamic infrastructure systems to send and receive the latest traffic data. Recent years have seen a growing interest in the study of route-guidance system in intelligent transportation systems, due to DRGS advantages in reducing traffic congestion and pollutant emissions, minimizing travel time, and conserving energy. In recent years, vehicle manufacturers have increasingly embedded route-guidance system into their products to assist drivers.

Benefits

When considering the practicality of DRGS, mobility, safety, connectivity, emissions, land use, economic impacts, and cost were examined.

Mobility

To calculate the potential delay reduction benefits using DRGS, Levinson’s (2003) estimates are used, with delay reductions for congestion experienced on freeways and surface streets corresponding to various levels of CV (or otherwise informed driver) market penetration, as shown in Table 16.3.

Table 16.3 Potential Delay Reduction Benefits from DRGS

Strategy	Area Type	Facility Type	Benefit Type	Impact by CV (informed) Market Penetration			
				0%	10%	50%	90%
DRGS	Urban	Freeway	Delay reduction for informed users	0%	6%	11%	10%
		Surface streets		0%	10%	19%	17%

To assess the potential mobility benefits of a DRGS, Austin was used as a test case. According to the Urban Mobility Scorecard (Schrank et al. 2015), congestion on freeways constitutes around 39% of total delays and 61% on surface streets for urban areas with over 1 million residents. Since Austin currently experiences around 51.1 million person hours of delay per year (assumedly split similarly to national profiles), a DRGS interacting with CVs may be able to realize the mobility benefits shown in Table 16.4.

Table 16.4 Potential Annual Delay Reduction Benefits from DRGS, as Applied in Austin

Benefits	Study Area	Impact by CV (informed) Market Penetration		
		10%	50%	90%
Delay Reduction (M hours)	Austin	0.43	4.06	6.56
Travel Time Savings (\$M)		\$7.66	\$72.08	\$116.59

Of course, these estimates come with several important caveats, potentially biasing the results in both positive and negative ways. On the over-inflation side of the ledger, these figures assume that every informed driver will choose the optimal route, while in reality individual users may prioritize factors other than travel time. Second, Levinson’s (2003) study assumed that a reasonable alternative path exists, which may not be the case for many drivers, and these figures assume that the system will be deployed across the entire metro region. Third, while a DRGS may be implemented using CVs and infrastructure, much of this similar information already exists for many drivers, enabled through in-vehicle navigation systems, mobile devices, variable message signs, and even highway advisory radio.

Yet there are also other factors that could influence DRSG implications for the good. The benefits estimated in Table 16.5 account for benefits to informed drivers, but it also may be possible to improve conditions for uninformed drivers, as congestion is somewhat relieved when other vehicles are diverted from the congested

roads. Additionally, it is possible that the benefits of DRGS may be most pronounced when an unexpected event occurs, meaning that benefits from more optimal routing may be even greater than what is projected here. However, while these caveats are important to acknowledge, their impacts are not accounted for in this chapter.

Safety

It is extremely difficult to estimate crash impacts associated with DRGS (NHTSA 1995). Studies show that there are no adverse or significant impacts on safety using this technology. When a network-wide evaluation (equipped and unequipped vehicles) was performed in a study by Imam (1996), an overall reduction of crash risk of up to 4% was predicted for motorists using the system. Elvik et al. (1997) conducted two studies regarding DRGS. One study found that DRGS would not affect the total number of crashes, but that crash costs would fall by 1.5% at 100% market penetration (due to lower severity crashes being substituted for higher severity ones), with lesser benefits at lower levels of market penetration. Elvik et al.'s other study showed that the system which provided the shortest travel time often resulted in a higher number of crashes because traffic is spread evenly throughout the network, including at higher conflict areas such as intersections. McKeever (1998) found an overall 1% reduction in fatal and injury crashes for people using navigation devices. The USDOT (2001) reported that simulation modeling predicted that access to pre-trip traveler information systems could reduce user crash risk by as much as 8.5% in the event of a major freeway incident, and by 11% when information was available en-route. A survey conducted by the Tokyo branch of the Japanese Automobile Foundation in October 2001 showed that car navigation systems enhance perceived safety and confidence by providing better information.

While the above studies note potential positive impacts of DRGS on safety, CVs providing en-route information to drivers may have negative safety impacts due to increased opportunities for distraction. The European Commission (2000) reported that in the CLEOPATRA project in Turin, Italy, 20% of the test drivers expressed concern over being distracted from the driving task. Moreover, DRGS may encourage drivers to take more trips in unfamiliar areas and divert them to routes with different inherent relative risks (Elvik and Vaa 1997). Abdulhai and Look (2003) projected an increasing pattern of collisions as the percentage of DRGS-equipped vehicles rises across a hypothetical network (Figure 16.2).

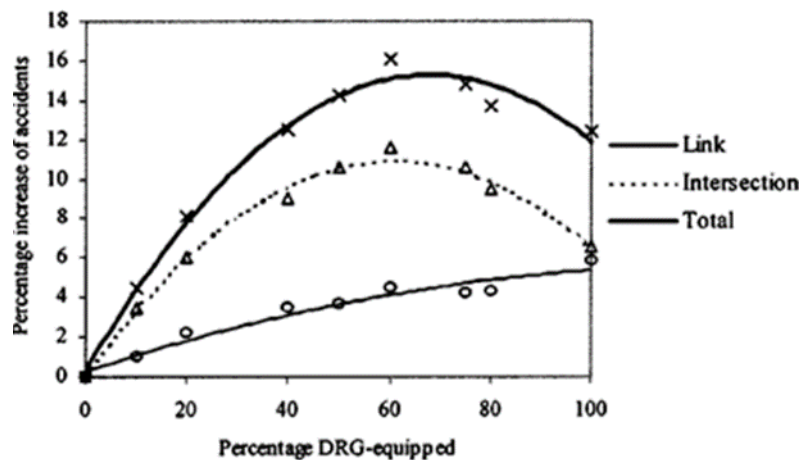


Figure 16.2 Collision Risk Increase for DRGS Cars (Abdulhai and Look, 2003)

In summary, some studies have shown small crash reductions associated with dynamic route guidance systems, while others show the potential for increased crash risk due to distraction and increased exposure on potentially unfamiliar while re-routing (Elvik and Vaa 1997). However, more related, detailed data collection and research are needed since this technology is becoming more prevalent in vehicles, and most research to date on these systems has focused on mobility impacts, rather than safety. Therefore, due to the uncertain nature as to whether DRGS will ultimately lead to more or fewer crashes, no impact is assumed here.

Connectivity

Stress reduction is said to be one of the benefits of traveler information, and giving travelers increased certainty about delay durations (irrespective of the potential for shorter travel times due to alternative routing) can be helpful. Additionally, DRGS may be used to assist persons traveling in unfamiliar areas, thus partially alleviating the stress of such travel. These factors should both contribute to a positive impact on the quality of travel.

Emissions

DRGS influence fuel consumption and emissions since it changes the traffic flow pattern by increasing travelers' knowledge of transportation options. If conditions are particularly congested in certain corridors, travelers may avoid those areas altogether, thus avoiding further congestion contributions to the congested roads. These factors can lead to a decrease in emissions by reducing travel time, the number of stops and fuel consumption.

An experiment conducted in a 30 square-kilometer area in southwest Tokyo reported that guidance systems reduced CO, HC, and NO_x emissions by 6.5%, 6.2%, and 0.4%, respectively. The study authors also estimated 3 to 7% improvements in fuel economy. To arrive at the authors' conclusions, emissions estimates were calculated using simulation models, while fuel savings were determined using the relationship between gasoline consumption and vehicle speed (Little and Wooster 1994).

Land use

As noted previously, the key purpose of DRGS is to improve traveler mobility through more optimal routing, thus reducing travel times. Location theory holds that as transportation costs and the time to travel decline, households and businesses tend to move further away from city centers to areas where the cost of land is cheaper. Since travel-time savings is the chief benefit of DRGS, widespread implementation may lead to patterns of decentralized land use. Reduced travel times and greater access provide more incentive to develop activities in suburban and rural areas, where land prices are lower, thus, leading to a loss of green space in these areas (provided that there are alternative routes to take advantage of DRGS capabilities). These effects typically occur both at the origin and destination of trips, and as origins and destinations will become more dispersed, the connecting roads might become more congested. In turn, congestion levels could lead to even wider dispersion as businesses and employment centers relocate to avoid the congestion (Grovdahl and Hill 2000).

Thus, DRGS could indirectly lead to increasing sprawl, and negative impacts on urban density, though likely have no apparent impacts on land use mix.

Economic impacts

Considering the impacts DRGS could have on land use, it can be concluded that this system allows the dispersion of employment. Besides, over the long term, such systems may reduce the need to construct additional highway infrastructure by distributing traffic to different parts of transportation network (Levinson et al. 1999).

According to the sources mentioned above, DRGS have positive impacts on business expansion and negative impacts on number of jobs and activities. It does not seem if it has any impacts on income level while it can have positive impacts on individuals' net income by reducing the transportation costs.

Cost

The project team was unable to determine the cost of deploying a regional DRGS based on existing literature, and the ultimate costs would inevitably depend on the extent of the system and nature of coverage. For example, the addition of a few cameras linked to an existing regional traffic operation center would be relatively inexpensive; conversely, deploying video, inductive loops, radar or other sensors to provide coverage across the entire transport network could be quite costly. At the same time, private firms are using

onboard vehicle data to estimate traffic speeds and congestion levels (and feeding results to in-vehicle DRGS devices), in addition to using data obtained from public agencies. As such, if a local transportation agency wishes to deploy a DRGS, it should consider such external data sources when scoping deployment objectives and breadth.

Benefit-Cost Analysis

In a city such as Austin, total annual monetary benefits of a DRGS may be around \$7.66 million in travel time savings at the 10% market penetration level, and could continue to rise with increasing levels of market penetration. However, since the costs of such a system would be unknown, a computation of a benefit-cost ratio is not feasible at this time.

Incident Warning Systems

Incident warning systems make use of a variety of ITS technologies to successfully detect, manage, and clear traffic incidents. The outcomes are mainly improving safety for travelers by reducing the risk of secondary crashes and reducing time lost and fuel wasted in traffic backups (USDOT 2009).

Benefits

When considering the practicality of implementing Incident Warning Systems, mobility, sustainability, and costs were examined.

Mobility

Incident warning system can have significant positive impacts in mobility. Integrating traveler information with incident management systems can increase peak period freeway speeds by 8–13%, improve travel time, and according to simulation studies, reduce crash rates and improve trip time reliability with delay reductions ranging from 1 to 22% (USDOT 2009).

Safety: The most significant finding is likely the ability of the programs to dramatically reduce the duration of traffic incidents, from 15 to 65%, with the bulk of studies finding savings of 30 to 40%. These reductions in incident duration impact the safety of travelers through reduced likelihood of secondary incidents. A deployment in San Antonio, Texas as part of a case study of dynamic message signage, combined with an incident management program, resulted in a 2.8% decrease in crashes. The Coordinated Highway Action Response Team in Maryland reduced incident duration and related secondary incidents by 29% in 2002, eliminating 377 crashes within its coverage area (USDOT 2009).

Sustainability

Incident warning systems impact the environment through reduced fuel consumption by idling vehicles. A simulation study indicated that integrating traveler information with traffic and incident management systems in Seattle, Washington could reduce emissions by 1 to 3%, lower fuel consumption by 0.8%, and improve fuel economy by 1.3%. In Georgia, the NaviGator incident management program reduced annual fuel consumption by 6.83 million gallons and contributed to decreased emissions: 2,457 fewer tons of carbon monoxide, 186 fewer tons of hydrocarbons, and 262 fewer tons of nitrous oxides (USDOT 2009).

Costs

The project team was unable to determine the cost of deploying a regional incident warning system based on existing literature; the ultimate costs would inevitably depend on the extent of the system and nature of coverage.

Benefit-Cost Analysis

Not reported in the literature.

Congestion Pricing

Congestion pricing refers to the application of variable fees or tolls on roadways to manage available capacity, potentially cutting travel demand and resulting VMT, while maintaining free-flowing traffic. This can address traffic congestion while also generating new revenue to fund transportation improvements.

Since existing research has shown that CAVs have the potential to increase total vehicle miles traveled, congestion pricing strategies can improve the level of service and motivate the purchase of CAVs.

Benefits

When considering the implementation of congestion pricing, mobility, sustainability, land use, and economic impacts were examined.

Mobility

There are several case studies evaluating the mobility impacts of congestion pricing implementation. In the City of Singapore, the number of vehicles entering the charging zone dropped by 24% and average vehicle speeds increased by approximately 28% after area-wide electronic pricing was introduced in 1998. In London, implementation and expansion of cordon pricing in 2007 reduced the number of vehicles entering the charging zone by 14%, reduced journey times by 14%, and increased average travel speeds by approximately 30%. With implementation beginning in 2000, travel time savings of up to 20 minutes were observed on the New Jersey Turnpike and on interstate bridges and tunnels of the Port Authority of New York and New Jersey (PANYNJ) (Mahendra et al. 2011).

Danna et al. (2012) evaluated the associated costs and benefits associated with a potential congestion pricing strategy in downtown Seattle. They used available data from London, Stockholm, and Milan to estimate potential demand elasticity, with results showing a potential reduction in average travel time of 3.5%. Sharon et al. (2016) developed traffic models that showed that employing a type of tolling could reduce average travel times by up to 35% when compared to a system without tolling. Additionally, a synthesis report by USDOT in 2014 estimated that congestion pricing, when used, could achieve benefits ranging from 4% -30% increases in travel speed, 15%-20% traffic volume reductions and 8%-14% travel time reductions. Additionally, according to this chapter, the addition of Open Road Tolling (ORT) to an existing Electronic Toll Collection (ETC) mainline toll plaza in Florida decreased delay by 50-55% for customers, and increased speed by 57% in the express lanes.

Safety

In addition to mobility benefits, congestion pricing can also reduce collisions due to reduced traffic volumes. However, the net safety effect of congestion pricing can be mixed because while crashes are more common under congested conditions, crashes that occur on less congested roads are more severe due to higher speeds. The 2014 USDOT report estimates that congestion pricing can reduce collisions by approximately 4 to 5.2%, and Danna et al. (2012) similarly predict a 3.6% reduction in accidents in affected areas.

Sustainability

Reduced congestion, trip making, and VMT should result in corresponding reductions across all types of pollutant emissions and fuel consumption. The ITS Knowledge Resource Database (USDOT 2014) estimates a 3 to 16% reduction in CO₂ due to congestion pricing strategies, and emissions reductions for other pollutant species may be similarly estimated. Burris and Sullivan (2006) applied a benefit-cost methodology on QuickRide (QR) high occupancy toll (HOT) lanes in Houston, Texas, with emissions savings shown in Table 16.5, for volatile organic compounds (VOC), carbon monoxide (CO) and nitrous oxides (NO_x). Since this is one of the longest running variable pricing projects in the United States, it provides useful historical data and trends upon which to estimate future benefits and costs.

Table 16.5 Emission Savings Estimates for QuickRide in Texas (Burris et al. 2006)

Year	QR (days)	Total Emission Savings			
		VOC (\$)	CO (\$)	NO _x (\$)	Total (\$)
1998	238	164	2	-316	-150
1999	253	192	0	-416	-224
2000	254	181	0	-387	-205
2001	252	224	5	-405	-175
2002	253	264	15	-321	-42
2003	254	411	26	-367	70
2004*	253	389	24	-353	60
2005*	253	395	25	-358	61
2006*	253	400	25	-363	62

Table 16.6 summarizes the current emissions levels of these pollutants, percentage changes induced by road pricing (which are estimated from the elasticities of the emission level of air pollutants to the changes in vehicle volume), and values for monetization (Muller and Mendelsohn 2007; Muller et al. 2009; McCubbin and Delucchi 1999).

Table 16.6 Summary of Current Emission Levels, Estimated Changes, and Monetization Values

Types of Emissions	Current Emissions Estimate (ton/year)	Estimated Change	Value (per ton)
GHG Emissions	2,682,600	-8.5%	\$45
CO Emissions	93,790	-9.8%	\$81
NO Emissions	11,580	-6.0%	\$838
VOC Emissions	7,590	-8.6%	\$7,408
PM Emissions	206	-9.8%	\$45

Land Use

The ultimate impacts of congestion pricing strategies on land use remain unclear. This strategy does not seem to have any impacts on land use in short term. In the long run some researchers have argued that it would discourage sprawl, while others believe it would increase decentralization (Benko and Smith 2008).

Economic impacts:

Congestion pricing is not anticipated to have a significant overall impact to jobs, incomes, or businesses, beyond the aforementioned economic impacts stemming from reduced fuel consumption, travel time savings, and reduced crash rates. Benko and Smith (2008) also note that congestion pricing may alleviate some need for new construction to manage peak period demand, while also reducing parking demand.

Cost

Typically, the highest costs for congestion pricing stem from converting existing toll lanes to HOT lanes or building new ones. Operations and Maintenance, including enforcement, and maintaining toll readers, dynamic message signs and surveillance equipment is also a significant expense. In many cases these costs are borne or shared by a private entity that builds and manages the HOT lanes in exchange for some or all of the revenue generated by them. The USDOT (2014)'s ITS Knowledge Resource Database estimates the capital costs across a number of proposed and active projects. Capital costs from \$1.85 million to convert an HOV lane to an HOT lane on an 8-mile section of I-15 in San Diego to a theoretical \$749 million capital cost effort to implement network-wide variable tolling in Seattle. Meanwhile, annual operating costs range from \$35 million for the Stockholm and \$161 for the London cordon charges, while the cost of a comprehensive VMT-based charging system across the entire country of the Netherlands is estimated at \$667.6 million.

Benefit-Cost Analysis

A benefit-cost analysis of the central London congestion charging strategy suggests that the identified benefits exceeded the costs of operations by a ratio of around 1.5:1 with an £5 charge, and by a ratio of 1.7:1 with an £8 charge (USDOT 2014). The ITS Knowledge Resource Database also summarized benefit-cost ratios of congestion pricing resulting from different projects, with 1:1 to 8.2 ratios estimated for dynamic pricing on freeway shoulder lanes; 7:1 to 25:1 ratios for integrated corridor management strategies; and a 6:1 estimated ratio based on the network-wide variable tolling system in Seattle.

Intelligent Signals

CV technologies are facilitating research in new advanced signal systems such as Multi-Modal Intelligent Traffic Signal System (MMITSS) and the GlidePath eco-driving application. For MMITSS, the Intelligent Traffic Signal System (ISIG) application uses high-fidelity data collected from vehicles through vehicle-to-infrastructure (V2I) wireless communications, as well as from pedestrian and non-motorized travelers. This ISIG application seeks to control signals and maximize flows in real time, with priority focus possible across different user types. As such, this ISIG application can accommodate transit or freight signal priority, emergency vehicle preemption, and pedestrian movements to maximize overall network performance (USDOT 2014).

Eco-driving is simply changing driver patterns and styles to reduce fuel consumption and emissions. When used in combination with in-vehicle communications, customized real-time driving advice can be given to drivers so that they can adjust their driving behavior to save fuel and reduce emissions. This advice includes recommended driving speeds, optimal acceleration, and optimal deceleration profiles based on prevailing traffic conditions and interactions with nearby vehicles. Feedback may be provided to drivers on their driving behavior to encourage driving in a more environmentally efficient manner (USDOT 2014). GlidePath is a strategy to make eco-driving easier for drivers at intersections.

This section discusses further details about the performance and potential benefits and costs related to the MMITSS and GlidePath.

Multi-Modal Intelligent Traffic Signal System (MMITSS)

MMITSS is a next-generation traffic signal system that seeks to improve mobility through signalized corridors using advanced communications and data to facilitate the efficient travel of passenger vehicles, pedestrians, transit, freight, and emergency vehicles through the system. An impacts assessment (IA) plan for MMITSS was prepared in a report by FHWA considering travel time and delay time as measures of effectiveness. Ahn et al. (2015) identified major findings from the work. These include a field study estimate that the intelligent signal (I-SIG) operation could reduce average delay by up to 13.6% for both equipped and non-equipped vehicles, with up to 35.5% delay reduction possible estimated in simulation. Simulation results indicate that transit signal priority (TSP) could reduce signal delay by transit vehicles up to 51.4% and freight signal priority (FSP) could reduce trucking delays by up to 53%.

GlidePath

GlidePath is a connected automated eco-driving system using wireless V2I communications at signalized intersections. It supports a more sustainable relationship between surface transportation and the environment through fuel-use reductions and more efficient use of transportation services.

Through this system, signal phase and timing (SPaT) and Geographic Information Description (GID) messages are passed to vehicles from the signal using V2I communication. Approaching vehicles then application performs calculations to determine the vehicle's optimal speed to pass the next traffic signal on a green light or to decelerate to a stop in the most ecofriendly manner. Then, it provides speed recommendations to the driver using a human machine interface or sent directly to the vehicle's longitudinal control system to support partial automation (Pincus, 2015). For GlidePath applications, up to 10-40% delay reductions could be realized, with 5-20% fuel savings (Boriboonsomsin, 2016).

Cooperative Intersection Collision Avoidance (CICAS)

The goal of Cooperative Intersection Collision Avoidance (CICAS) is to prevent intersection crashes by using vehicle-based and infrastructure-based ITS technologies. According to the USDOT, CICAS consists of three key components (USDOT 2015) (Table 16.7):

- Vehicle-based technologies and systems-sensors, processors, and driver interfaces within each vehicle;
- Infrastructure-based technologies and systems-roadside sensors and processors to detect vehicles and identify hazards and signal systems, messaging signs, and/or other interfaces to communicate various warnings to drivers; and
- Dedicated short-range communications (DSRC) systems that communicate warnings and transmit data between the infrastructure and equipped vehicles.

This program was launched in 2013 and has been divided into three functional segments based on crash type (Misener 2010). CICAS-V (Violation) is the largest programmatic segment and it works by sending alerts to motorists seeking to help prevent stop sign or traffic signal violations at intersections. CICAS-SSA (Stop Sign Assist) operates by sending warning messages to drivers that another vehicle is approaching on the minor road. CICAS-SSA can also be implemented to send drivers messages that they are about to cross high-speed rural road at an unsignalized intersection. Lastly, CICAS-SLTA (Signalized Left Turn Assist) provides information to help motorists identify gaps, in support of making permissive left turns at signalized intersections.

Table 16.7 CICAS Programs

Name	Target Crash Type	Research Institutes
CICAS-V (Violation)	Straight crossing path collisions, which tend to be the result of stop sign or signal violators	CAMPO, Virginia Tech
CICAS-SSA (Stop Sign Assist)	High-speed, rural road collisions, at stop controlled intersections from the minor road approach	MnDOT, U. of Minnesota
CICAS-SLTA (Signalized Left Turn Assist)	Crashes caused by vehicles making permissive left turns at signalized intersections	Caltrans, U.C. Berkeley

These systems are anticipated to impact intersection traffic safety. However, the impacts to the other criteria metrics conducted in this investigation remain unclear. For instance, CICAS-SLTA use may result in more cautious left-turning behavior, resulting in decreased effective intersection capacity and increased delays. Alternatively, assuming that CICAS-SLTA helps avert crashes, collision-related non-recurring congestion should also fall. Therefore, given the minor or uncertain impacts to mobility, connectivity, economic development or other criteria metrics, only safety benefits are evaluated here for CICAS applications.

Benefits

Li and Kockelman evaluated three CICAS applications and associated CV technologies. They utilized 2013 nationwide GES data, Najm's (2007) precrash scenario topology, and Blincoe et al.'s (2014) crash costs. The result represents that the number of precrash related to CICAS¹²² is 1.08 million and they could potentially save \$25 billion annually with 90% of CAV market penetration (Li and Kockelman 2015). Additionally, they suggested safety performance function of CICAS by severity and assumed that CICAS could reduce fatalities,

¹²² Running Red Light, Running Stop Sign, Left Turn Across Path of Opposite Direction (LTAP/OD) at Signalized Junctions, Vehicle Turning Right at Signalized Junctions, LTAP/OD at Non-Signalized Junctions, Straight Crossing Paths at Non-Signalized Junctions, and Vehicle(s) Turning at Non-Signalized Junctions

A, B, C, O, and unknown injuries at 60%, 70%, 80%, 90%, 100%, and 40% respectively; a similar assumption was used here.

Costs

Implementing CICAS at an intersection is relatively simple. The system needs roadside unit (RSU) and a processor to help determine when to send vehicles warning messages. Of course, to be effective it must be able to communicate with CVs equipped with DSRC capabilities and a Driver-Vehicle Interface (DVI) to present timely and essential warnings (Maile and Delgrossi 2009). According to the Michigan DOT, the cost of embedded onboard equipment (OBE) for CVs is \$350 per vehicle in 2017 (Michigan DOT and Center for Automotive Research 2012). Their research targeted to DSRC-capable OBEs, surveying a diverse set of vehicle and communication equipment manufacturers. Additionally, RSU for DSRC communication costs \$51,600 per one site and operations and maintenance cost is approximately \$2,500 per year in 2013. Finally, average lifespan of roadside DSRC equipment is seven to eight years (Wright et al. 2014).

Benefit-Cost Analysis

For initial deployment, CICAS applications would likely focus on intersections where collision rates and severities are highest. To get a picture of what this might look like, crash rates across the top 25 intersections in Austin were considered (Table 16.8), averaging 22.1 collisions annually, per intersection (Austin Transportation Dept et al. 2013). The MAIS scale was then used to estimate monetary benefits of crash savings. As a result, CICAS could save 100 crashes in 25 intersections and save \$7 million of comprehensive costs. If a CICAS application were installed at one of these intersections in 2015, annualized installation, maintenance, and operations cost would be approximately \$333,000 per year for seven years of analysis. A 10% discount rate is also assumed, which is higher than the 7% rate required for federal TIGER grant applications, to account for the greater uncertainty surrounding CAVs. These cost and discount rate values are consistent with those used in prior research conducted by Fagnant and Kockelman (2015b).

Table 16.8 Benefit-Cost Analysis of CICAS, as Applied to One of Austin's Top 25 Highest Crash Intersections

		CV Market Penetration		
		10%	50%	90%
Benefits	Crash savings (\$/Year)	\$858,000	\$4,288,000	\$7,718,000
Costs	Installation costs (\$/Year)	\$270,000		
	Maintenance & Operation (\$/Year)	\$64,000		
	Sum of costs (\$/Year)	\$333,000		
Net Present Values (\$)		\$3,074,000	\$24,152,000	\$45,230,000
Benefit-Cost Ratio		2.4	12.0	21.6

Cooperative Ramp Metering (CRM)

Ramp metering (RM) is often regarded a good way to facilitate high throughput on limited access facilities by managing the number of vehicles entering on highway ramps. Yet this method only focuses on the vehicle stream merging onto the main lanes. With ramp metering, the on-ramp throughput rate is managed via a signal indication located on the ramp, and depends on the main lane occupancy and operating speeds. Unfortunately, vehicles merging from the on-ramp onto the main lanes may still generate congestion shockwaves that propagate up the traffic stream when they are forced to merge into tight gaps within the existing traffic stream. Cooperative ramp metering (CRM) improves upon traditional RM by helping to more seamlessly facilitate this merging action through the control of vehicles on both the main lanes and on the on-ramp. This new system seeks to rearrange gaps on the main lanes by requesting cooperation from participating vehicles in order to ease the merging of on-ramp vehicles released by signals already present on-ramps equipped with traditional RM (Scarinci et al. 2013).

Benefits

According to the FHWA, mobility, safety, and sustainability are all considered benefits of conventional RM (FHWA 2014), and it is assumed here that CRM would provide the same types of benefits, only to a greater degree. First, conventional RM can reduce main lane congestion and overall delay, while increasing traffic throughput. Ramp queue wait time can also decrease when RM is implemented. Conventional ramp meters can break up platoons of vehicles that are entering the freeway and competing for the same limited gaps in traffic. CRM can add to these RM features by seeking to adjust gaps between vehicles on main approach so traffic flow will be much smoother than conventional RM. The net effect of these factors should smooth traffic flow, thus enabling more stable mainline traffic flow, greater throughput, higher average speeds, less emissions and fuel consumption.

Scarinci et al. (2013) evaluated one CRM application through simulation, which targeted an 8.25km 1-lane highway with 250m of auxiliary lane, seeking to address issues related to late-merging vehicles. Their findings showed that congestion and delay could be reduced, as long as on-ramp flow remained under 800 vehicles per hour (Scarinci et al. 2013). Another study by Greguric et al. (2014) simulated CRM through the use of variable speed limits combined with traditional RM. Their findings showed that travel times along a 3-mile 2 lane freeway facility, which located in Zagreb bypass, with traffic volumes averaging 52,801 of average annual daily traffic (AADT) would see up to a 53% decrease in travel time, from a base level of 7 minutes.

Lu et al. (2010)'s evaluation showed similar results, which also evaluated the potential impacts of CRM, simulated through the use of variable speed limit in cooperation with RM. They conducted their study on a 2.77-mile segment of I-580 located in Berkeley, CA, with nine on-ramps, eight off-ramps, and five lanes in each direction, over a 10-hour simulation period (2:00 p.m. to 12:00 a.m.). Lu et al. found potential travel time improvements of 31.8%, and increased traffic flows of 12.9% when CRM was in use. Moreover, average speeds over the course of the simulation improved from 30.6 mph to 50.6 mph with the application of CRM.

Lee et al. (2006) conducted a microsimulation experiment to estimate the safety effects of traditional RM in I-880 in Hayward, California. They estimated crash potential by using three variables: speed coefficient of variation, average speed difference, and average covariance of volume difference, between upstream and downstream traffic flows. Lee et al.'s findings estimated that RM could reduce 5% crash potential from base condition (i.e., 2.2 miles, 5 lanes without ramp meters).

Li et al. (2014) estimated that CRM as modeled via variable speed limits in conjunction with RM could reduce total travel time, stop time, number of stops, and emissions based on simulation which targeted critical bottleneck section (five on-ramps and four off-ramps) on State Highway 1 in Auckland, New Zealand. According to their simulations, total travel time, Carbon dioxide, Carbon monoxide, and Nitrogen oxides were reduced as 22.6%, 7.1%, 7.4%, and 2.3% respectively.

Costs

RM is varied because base condition of deployment area is different. In this research, the cost of RM was assumed to consist of basic infrastructure cost and incremental deployment cost. The combined cost of traditional RM and CV cost (DSRC transmitter) were both assumed to be necessary components of the CRM costs. Table 16.9 illustrates the costs of CRM and support facility based on previous research (Cambridge Systematics 2008, Wright et al. 2014). All costs have been adjusted to 2015 dollars.

Table 16.9 Estimated Costs of CRM

Type	Installation Cost (\$/year)	O&M Cost (\$/year)
Infrastructure	\$51,000	\$288,000
Ramp meters (one ramp)	\$18,000	\$18,000

Benefit-Cost Analysis:

To estimate the potential implications of applying CRM, conditions similar to those applied in Lu et al.'s (2010) investigation were assumed (5 lanes in each direction, averaging 1,259 vph per lane, tight on-ramp spacing around every 0.3 miles, and average space mean speed of around 30 mph over the course of a 10-hour evaluation period). This would likely be somewhat similar to some of the more congested facilities in Texas' major cities, though perhaps with larger spacing between ramps. Travel time reduction on a 2.77 mi freeway stretch was 1,640 veh-hr over the course of 10 hours including the PM peak. Travel time reduction of 410 veh-hr/hr were achieved using CRM during peak hour (3 to 7 p.m.). In this project, travel time reduction was assumed to only affect 8 hours of the day (4 hours for a.m. peak and 4 hours for p.m. peak based on the average speed graph in Lu et al.), and only during weekday operation. This would therefore result in travel time reduction within this segment equal to 3,280 person hours per day and 855,000 person hours per year. With a \$17.67 VOTT applied to these travel time savings, mobility benefits could reach \$15 million per year.

From a safety perspective, a RM crash modification factor of 0.95 was assumed based on Lee et al.'s (2006) previous study. Here, estimated expected crash frequency was then estimated based on AADT, segment length, and safety performance function as follows (AASHTO 2010).

$$N_{spfrd} = e^{(a+b \times \ln(AADT) + \ln(L))}$$

where:

$$a = -9.025 \text{ for 4 lane divided roadway}$$

$$b = 1.049 \text{ for 4 lane divided roadway}$$

AADT was assumed to be 284,200 vpd¹²³, with 10 lanes total for both direction. Thus, the expected crash frequency in this segment should be around 175 crashes per year, and RM could therefore potentially reduce by 8.8 crashes per year. In this case, RM could save \$ 1.8 million per year in this segment.

From a sustainability perspective, Li et al.'s (2014) results cannot be readily adapted, as they are not directly translatable to those estimated in Lu et al.'s (2010) investigation (as is considered in this benefit-cost analysis), due to significantly different base conditions. Li et al.'s results indicate that CRM should be able to reduce emissions to some degree, by reducing stopping time and idling, though the exact quantity of potential emissions reductions remains unknown. Thus, it can be assumed that CRM should have positive impacts on sustainability, but the exact degree for a project like this remains uncertain.

When considering potential congestion and safety savings against installation, maintenance and operations costs, significant benefits may be achievable. Using a 10-year analysis period and a 10% discount rate (Fagnant and Kockelman 2015b), this research indicates that CRM as applied in similar conditions to those discussed here could result in a very favorable benefit cost ratio of 23.0. This indicates that CRM may be an attractive strategy to use, even in conditions with lower traffic volumes.

Table 16.10 Benefit-Cost Analysis of CRM

Savings/Costs		Values (\$/Year)
Benefits	Travel time savings	\$15,110,000
	Comprehensive safety savings	\$1,778,000
	Sum of benefits	\$16,889,000
Costs	Annualized installation costs	\$293,000

¹²³ Average flow rate during 10 hours (1,421 vphpl) × number of lanes (10 lanes for both direction) × hour of day (10 hours for PM and 10 hours for AM)

	Maintenance & Operation	\$446,000
	Sum of costs	\$739,000
Net Present Values (\$)		\$99,271,000
Benefit-Cost Ratios		23.0

Smart-priced Parking (SPP)

Smart-priced parking (SPP) is a strategy that seeks to dynamically adjust parking prices in order to achieve a target occupancy rate. SFpark at San Francisco is one of the better-known examples of SPP. SFpark adopted demand-responsive pricing since August 2011 to make it easier to find parking, reduce street congestion, improve roadway's as well as municipal's speed and reliability, and increase public safety and economic vitality (SFMTA 2014a). To do that, San Francisco Municipal Transportation Agency (SFMTA) has adopted several different strategies according to parking zone, land use, and typical peak parking occupancy rates (see Table 16.11).

Table 16.11 Strategies of SFMTA

Parking Zone	Peak Occupancy		
	>80%	60%-80%	<60%
Residential-Low Density	Residential parking permit only	Unregulated	Unregulated
Residential-Medium Density	Further analysis	Further analysis	Unregulated
Residential-High Density	Meter	Further analysis	Unregulated
Mixed Use	Meter	Further analysis	Unregulated or time limit
Industrial/PDR	Meter	Further analysis	Unregulated or time limit
Neighborhood Commercial	Meter	Meter or time limit	Unregulated or time limit
Public	Meter	Meter or time limit	Unregulated or time limit

To detect parking spot occupancy, SFMTA installed 8,200 wireless sensors at on-street parking spaces. Parking rates fluctuated from \$0.50 to \$7 per hour, depending on real-time parking demand.

Benefits

Transportation risk is directly linked to exposure, which can be quantified through the amount of VMT within a given system. SPP systems are designed to reduce extra time spent searching for parking, thus reducing unnecessary VMT, and by extension improving safety. That is, within the central business district (CBD) or other area with limited cheap or free on-street parking where SPP may be implemented, many drivers spend time searching for rare but valuable parking spaces. However, SPP virtually guarantees the availability of parking spaces (though potentially at higher prices), thus reducing unnecessary travel. According to SFMTA (2014c), during the weekday, SPP reduces 30% of VMT (3.7 miles to 2.6 miles) while the control area, where no changes were made to parking management or technology, saw 6% reduction in VMT. It is reasonable that VMT of the control area also decreased because one of the control areas is located next to the pilot area (see Figure 16.3). The parking meters in the control and pilot areas are also the same so drivers may have thought that the control area had adopted running dynamic pricing as well.

Houston collected \$7.4 million in parking revenue from meters in 2015, spread across 2.6 million transactions (Parking Management Division 2016). Parking conditions in Houston are much less tightly constrained than

those seen in San Francisco, so while a 1.1-mile reduction per trip might not be realistic, a 0.5-mile per trip reduction in downtown Houston may be a reasonable estimate. Therefore, it is assumed that if SPP was implemented in Houston, in the areas with the highest demand that could capture around a quarter of total parking transactions (650,000 trips per year), with reduced VMT at 0.5 miles per trip, total annual VMT reduction would be around 959,000 VMT, saving approximately \$354,000 in safety costs.

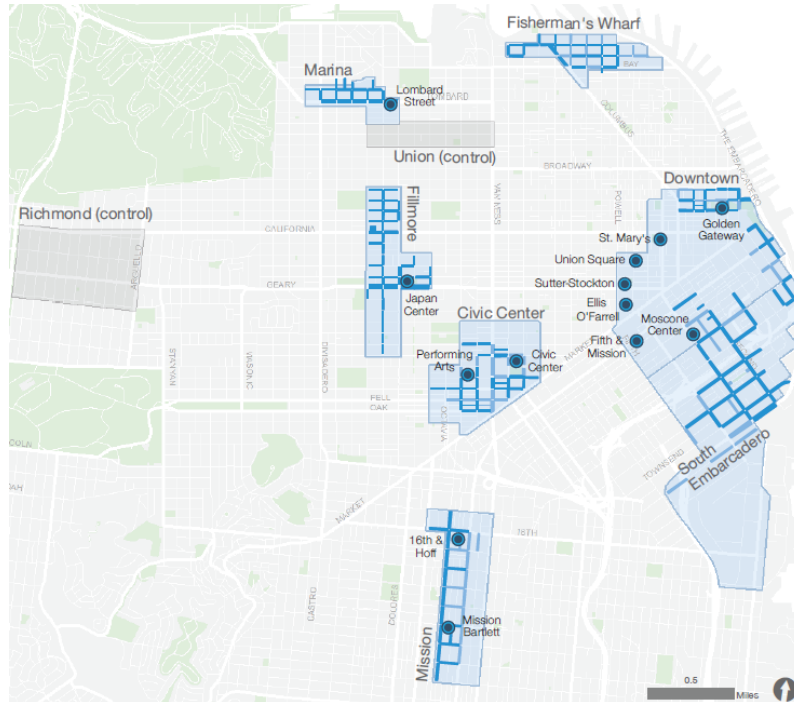


Figure 16.3 SFpark Pilot and Control Area

SPP also reduces parking searching time. According to the SFMPA, pilot area's parking search time decreased by 43% (14.6 minutes to 6.6 minutes) while the control area's parking search time decreased by 13% (6.4 minutes to 5.6 minutes). As with VMT reduction, it was assumed that time saved previously spent searching for parking in Houston would be around half of that as in San Francisco, or around 2.5 minutes of time saved per trip, rather than 5 minutes per trip. When applying a \$17.67 per hour value of travel time across the 650,000 trips, total valued travel time savings should amount to \$480,000.

Additionally, this system could increase transit speed. In the case of two sites, 21-Hayes and 30-Stockton, transit speeds increased by 3.9% and 4.6% respectively due to reduced congestion and double parking.

Environmental effects are also likely to be positive. Without demand responsive pricing, 85 tons of greenhouse gases were produced per day. However, in pilot areas, CO₂ generated by travelers searching for parking were found to have fallen around 30% (7.0 to 4.9 metric tons), though emissions in the control areas fell by 6% (2.7 to 2.5 metric tons), indicating a 24% differential. Based on vehicle's body type composition (Santos et al. 2011), unit cost of emissions per VMT averages around \$0.99, meaning around \$323,000 per year could be saved in emissions reductions.

Moreover, SPP may influence land use in the target areas in which it is applied. Based on a survey in San Francisco after implementing SPP, drivers visiting the area for shopping, dining, and entertainment increased by 30% in pilot area, while these same factors increased by 9% in the control area over the same period. This indicates that SPP may serve to increase land uses that cater toward high-value short-term commercial activities, and away from land uses geared toward activities that require longer-term parking.

Relatedly, SPP systems may also help to stimulate local economic vitality. Between August 2011, when the SFpark pilot project began, to 2013, when the target area's sales tax revenue rose by 22%, compared to a 15%

increase in all other areas. This reflects a somewhat greater inflow of visitors into the area and increase in commercial spending, compared to the rest of the city. The pilot areas were implemented in a historically commercialized area, so a direct apples-to-apples comparison with the rest of the city is not possible. This noted, the previous two years' tax revenue growth rate averaged 15%, indicating a potentially positive effect on economic growth (in the pilot area). In the SFMTA report, there is no direct information related to changes in employment or average incomes due to the program, though these indirect metrics suggest a positive impact.

Another important consideration here is the potential for increased meter revenue. During pilot survey, average revenue per meter rose 24% within the pilot areas, compared to a 4% decrease in control areas. From a benefit cost analysis perspective, this is considered a transfer payment, with funds shifted from private individuals to a public agency. As such, this transfer payment is counted as neither a benefit nor a cost in itself, though it is of obvious importance when considering the tradeoffs and feasibility of implementing such a system.

Costs

In case of SFpark, SFMPA only paid for added sensors installation costs, with a monthly leased cost for operating software to the firm StreetSmart (now renamed Fybr). Installation costs were \$330 per space, with an added monthly operating fee of \$10 per space (SFMTA 2014b). Houston has 9,200 public parking spaces. Earlier it was assumed that SPP would be applied in the areas with the highest average occupancies, covering a quarter of all parking transactions. Therefore, though parking transaction distributions parking data was not available, it can be conservatively estimated that 20% of parking meters covering the highest use areas in Houston would at least cover this many transactions. Under these assumptions, total installation costs for sensors should be around \$759,000, with annual operating costs of around \$233,000.

Benefit-Cost Analysis:

According to the SFMPA, the sensor batteries are designed for up to five years of use, though the agency opts for replacement every three years to avoid battery failures. As such, this analysis assumes recurring installation costs every three years. Additionally, a five-year analysis period and a 10% discount rate is assumed here (Fagnant and Kockelman 2015b).

The results indicate that the benefit of time savings comprises around 41% of total benefits, with crash savings and emissions savings accounting around equal shares of the remainder. Total estimated annual benefits are roughly equal to \$1.16 million. The sum of expected annualized costs is \$538,000 in the light of installation, operation, and maintenance, and the benefit-cost ratio for SPP is estimated at 2.2 over a three-year period. See Table 16.12.

Table 16.12 Benefit-Cost Analysis of SPP in Houston

Savings/Costs		Values (\$/Year)
Benefits	Comprehensive crash savings	\$354,000
	Time savings	\$479,000
	Emissions	\$323,000
	Sum of benefits	\$1,157,000
Costs	Annualized Installation costs	\$305,000
	Maintenance & Operation	\$233,000
	Sum of costs	\$538,000
Net Present Value (\$)		\$1,539,000
Benefit-Cost Ratio		2.2

Shared Autonomous Vehicle Transit

Once vehicles gain the ability to become completely driverless, a new transportation mode will emerge: the shared autonomous vehicle (SAV). SAVs may act as an on-demand service, taking passengers from origin to destination, and may be implemented as either a private (e.g., Google or Maven) or public transit (e.g.,

CityMobil2) service. SAVs could have the potential to overcome some key barriers, especially the limited accessibility and reliability of today’s car-sharing (e.g., Zipcar or Car2Go) and ride-hailing (e.g., Uber or Lyft) programs (Fagnant and Kockelman 2015a). SAVs combine features of short-term on-demand rentals with self-driving capabilities: in essence, a driverless taxi or shuttle (Fagnant et al. 2015b). Studies indicate that SAVs have the potential to reduce overall vehicle ownership and possibly VMT, if rides are shared, in addition to vehicles. For example, Zhang et al.’s (2015a) simulations show that SAVs could enable unrelated passengers to share the same ride with minimal increases in travel time, or costs (though actual passenger costs would likely be lower, since they would be split between two or more parties). If such a system was implemented as a public transit service, much of the focus would likely be centered around facilitating ridesharing, serving paratransit trips for disabled persons (though whether an accompanying attendant would be required would depend on the individual being served), and potential first-mile linkages with mass transit systems.

Mobility

Mobility represents one of the most promising features for SAVs, though quantifying and monetizing the estimated benefits remain quite unknown based on a review of existing literature. Here, the primary benefit of SAV use will likely depend on the user and the nature of his or her shift away from other transport modes. For example, a former bus transit user shifting to SAV may realize travel time savings but increased costs, while a person previously traveling by personal car may realize reduced direct costs. In order to quantify these potential impacts, a mode choice model with accompanying log sum valuations is likely needed (e.g., Ma et al. 2015), which to date has not yet been conducted to the research team’s knowledge.

Connectivity

Many people prefer to own personal vehicles for identity (to display their style and success) and convenience (because they need specialized vehicles, leave equipment in vehicles or carry dirty loads). SAVs reduce the service since they are driverless, while Drivers often help passengers (particularly those with disabilities) in and out of taxis, carry luggage, ensure passengers safely reach destinations, and offer guidance to visitors. Furthermore, depending on implementation design, SAVs could result in reduced comfort and privacy. Vehicles designed to minimize cleaning and vandalism risks will probably have less comfort (no leather upholstery or carpeted floors), and fewer accessories (limited sound systems). Reliability may also be an issue for fleet managers, since vehicles will frequently need cleaning and routine maintenance. End users of SAVs will not be responsible for routine maintenance or costly repairs, so reduced reliability may not be an issue to the user, but it is an important concern for fleet managers. Passengers will also need to accept that their activities will be recorded. All these mentioned points cause a reduction in quality of life and eventually, in connectivity (Litman 2015).

Sustainability

Fagnant and Kockelman (2015a) conducted an agent-based modeling simulation to evaluate potential behavioral shifts and environmental impacts of SAVs (with no ridesharing), as implemented across Austin’s transport network. Despite estimated increases in overall VMT from relocating empty SAVs, these results indicate that total emissions could fall, due to fleet substitution (passenger cars being used as SAVs, rather than passenger cars, SUVs, and pickup trucks used across the entire U.S. vehicle fleet), reduced parking needs and reduced cold-starting emissions. Table 16.13 shows anticipated emissions outcomes, as well as estimates generated by the authors in a prior study using a grid-based SAV model for an idealized representation of Austin. Moreover, this work indicates that emissions could be further reduced beyond those shown here if ridesharing were implemented, as would almost assuredly be done if an SAV fleet were managed and operated by a transit agency.

Table 16.13 Anticipated SAV Life-Cycle Emissions Outcomes Using the Austin Network-Based Scenario (Per SAV Introduced) (Fagnant and Kockelman, 2015b)

Objective	Metrics	Qualitative & Quantitative Measures
-----------	---------	-------------------------------------

Safety	Fatal crash count	\$ / Crash, \$ / VMT
	Crashes per VMT	
Mobility	Delay	Value of Travel Time (\$17.67 per person hour)
Connectivity (Accessibility)	Quality of travel	Negative / No impact / Positive
Sustainability	Ozone (O ₃), Particulate Matter (PM10), Carbon Monoxide(CO), Nitrogen Oxides(NOx), and Sulfur Dioxide(SO ₂)	\$/Tons, \$/VMT
Land Use	Sprawl, density, land use mix, greenspace	Negative / No impact / Positive
Economic Impact	Number of jobs, average income, number of activities	Negative / No impact / Positive

Land Use

SAV fleets could help limit the extent of urban sprawl, particularly when compared with personally owned AVs. This is largely because the SAV fleet works more effectively for smaller service areas (or areas with higher trip intensity) by reducing the number of empty miles and enabling a more efficient usage of the fleet. In contrast, personally owned AVs may lead to higher rates of unoccupied travel, increasing sprawl, and added VMT stemming from that development pattern. While the net combined effect of SAVs and personally owned AVs on land use remains quite uncertain, SAVs remain a valuable tool if density is to be encouraged (Pinjari et al. 2013).

Zhang et al. (2015) evaluated the potential impact of SAVs on urban parking demand. The authors concluded that SAVs can significantly reduce the demand for parking. Once those urban parking spaces are no longer in need, more sustainable designs, such as more open, green, and human-oriented space could be introduced, or alternatively such facilities could be repurposed for higher-order commercial uses (e.g., converting a parking garage into an office building).

Economic Impacts

From an economic perspective, car-sharing may also be more favorable than major road construction. Fellows and Pitfield (2000) related the net present value of the car-sharing model with that of major road strategies. The study found that even with relatively low car-sharing usage, the net present value of a car-share model compared favorably with two major road strategies prior to the subtraction of costs of construction, land take, disruption etc. for the road strategies.

Cost

Burns et al. (2013) estimated a set of base cost assumptions for driverless shared fleet vehicles. These include \$25,000 for the vehicle base price plus \$2,500 to add driverless technology. Depreciation, gas, maintenance and repair were estimated at \$0.31 per mile, with insurance, registration, taxes and overhead costs, and financing interest costs estimated at \$5,975 per year.

Ownership costs are made up of depreciation, financing, insurance, and registration and taxes. Depreciation costs include the cost of the vehicle and the components enabling driverless control. These costs are depreciated on a per mile basis due to the very high mileage that fleet vehicles accumulate, which means that their life in years is much less than that experienced by personally owned vehicles. The depreciation calculation makes the very conservative assumption that the vehicle has no value at the end of its life. Finance costs are estimated as the opportunity cost for using the money spent on vehicles; i.e., what could be earned by investing this money in alternative ways.

Benefit-Cost Analysis

No reported B/C ratio was found.

Transit with Blind Spot Detect (BSD) and Automatic Emergency Braking (AEB)

Some CAV applications could assist drivers in operating buses through technological enhancement and collision prevention. Blind spot detection (BSD) and automatic emergency braking (AEB) are two of the more promising systems. BSD can detect other vehicles, pedestrians, or any obstacles that cannot be detected by a driver. Additionally, AEB can be automatically applied to avoid a collision or at least to alleviate the effects on a situation in which a collision involving the host and target vehicles is imminent (Li and Kockelman 2015). These two systems could prevent bus crashes resulting from driver's sight obstacles. According to the Federal Transit Administration, while the overall trend of transit injuries per million passenger miles has fallen since 2003, the total number of injuries, the total number of casualties and the total liability expenses stemming from those incidents has risen (Lutin et al. 2016). In 2011, nationwide bus casualty and liability expenses amounted to \$483 million, or \$8,069 per bus annually. Many of these costs may be averted through the use of connected and/or automated vehicle technology. For instance, based on the Transit Risk Pool analysis in Washington state, forward collision avoidance systems with automated emergency braking could prevent 61% of claims greater than \$100,000 (Spears 2015). Additionally, the National Transportation Safety Board (2015) estimated that collision avoidance systems (CAS) including AEB and electronic stability control (ESC) could reduce rear-end collisions by 71%. Based on previous studies, BSD and AEB both have the potential to reduce rear-end crash and pedestrian-transit crashes, which were the crash reduction focuses for this study.

Benefits

In 2012, bus rear-ending collisions per 100,000 miles for region 6 (including Arkansas, Louisiana, New Mexico, Oklahoma, and Texas) averaged 0.010 (Morris and DeAnnuntis 2014). Since Houston buses average around 60 million miles¹²⁴ per year (TxDOT 2015a) the number of rear-ending transit crashes in Houston should be approximately 6 per year. Additionally, NTSB (2015) estimates indicate that AEB could reduce 71% of rear-end collisions for trucks, and it is assumed here that similar results should apply to transit vehicles. Therefore, around 4.3 rear-ending crashes per year could be averted on Houston transit vehicles by installing AEB systems. By monetizing these collisions, around \$863,000 in comprehensive costs per year could be avoided. This noted, these figures may underestimate true costs since a collision involving a transit vehicle may be costlier than one simply involving passenger cars only. On the other hand, crash cost valuations used here are also derived from across all crash types, and rear-end crashes tend to be less severe than other collision types, leading to potential crash cost valuation over-estimates. Therefore, with these caveats noted, the \$863,000 annual crash savings is assumed here.

Mobility may also be influenced by fewer bus-related incidents, though these effects are anticipated to be smaller than direct liability savings. Blincoe et al. (2015) estimate that 12% of economic crash costs are related to congestion, so it is reasonable to assume that costs beyond direct liability costs would be incurred whenever a bus incident occurred. Indeed, it is possible that these costs could be even higher, due to all of the bus passengers who may be delayed as a result of the incident, beyond other traffic disruptions.

As for the other factors, it is unlikely that BSD and AEB would have significant impacts. Sustainability would not notably affect BSD and AEB, though a small amount of emissions reductions may be possible, as a result of fewer incidents. Connectivity in the form of enhanced travel comfort and economic impacts in the form of employment or average income changes would not see substantial alterations, beyond the safety and mobility factors already accounted for. Likewise, land use would not be affected to any notable degree.

Costs

Anderson et al. (2014) estimated that camera, radar, and image processing technology for detectors and an automatic braking system costs around \$4,750. While these costs have likely fallen since then (the technology is rapidly evolving so costs are likely to fall accordingly), it is also likely that installation on a bus may be more expensive than a car or pickup truck. Houston has 1,545 buses (TxDOT 2015a) and the average age of

¹²⁴ Vehicle revenue miles of MTA and urbanized area (all active service miles except for deadhead travel from the bus yard to the beginning of the route)

a full size transit bus in 2012 was 8 years (USDOT 2015 #241). Therefore, the annualized cost of installing a BSD and AEB system across Houston's entire bus fleet is estimated here to be around \$917,000.

Benefit-Cost Analysis

Here an 8-year analysis period and a 10% discount rate is assumed for applying BSD and AEB on a transit vehicle. Based on benefit and cost of BSD and AEB, a B/C ratio of 0.94 is estimated. However, in this study, transit-passenger collisions were not accounted for since meaningful data was not available to estimate the rate of transit-pedestrian collisions, so the true B/C ratios for installing BSD and AEB on transit vehicles is likely greater than 1.0. Nevertheless, benefit and cost of BSD and AEB have limitations that cost of BSD and AEB is high because the number of buses is quite considerable relative to the number of crashes. See Table 16.14.

Table 16.14 Benefit-Cost Analysis of BSD and AEB

Costs/Savings		(\$/Year)
Benefits	Comprehensive crash savings	\$863,000
Costs	Annualized installation costs	\$917,000
	-\$288,000	
	0.94	

Automated Truck-Mounted Attenuator (ATMA)

As limited self-driving abilities become possible, one application within the transportation construction sector is the automated truck-mounted attenuator (ATMA). These vehicles are low speed, fully self-driving trucks equipped with truck-mounted attenuators (TMA). The purpose of an ATMA is to follow a mobile or short-term construction or maintenance crew, where positive protection is needed, but given the work zone nature and duration, installing a temporary barrier does not make sense. Relevant activities include striping, placement of cones and barrels during work zone setup, re-lamping luminaires, patching cracks and potholes, and similar activities. Unlike a human-driven truck with a TMA, an ATMA does not need a driver constantly in the vehicle (meaning potential for reduced labor costs), and if hit, a driver will not be exposed to the concussive nature of the collision.

For their ATMAs, Southwest Research Institute (SwRI) has developed gesture recognition system to help assist with vehicle control, or alternatively ATMA can follow another worker-driven vehicle at a pre-specified distance. ATMAs have been commercialized and were first deployed in 2015 (Rubinkam 2015).

Benefits

This technology would be predicted to increase work-zone safety as well as efficiency, though likely would have no impacts on mobility, connectivity, sustainability, land use, or economic development. According to Ullman and Iragavarapu (2014), TMAs can be assumed to relieve the severity of rear-end crashes in work zones, but not the frequency of these occurrences.

Primary benefits stemming from ATMA use would be in the form of helping reduce the severity of rear-end crashes within work zones. In 2014 19,435 work zone-related crashes occurred in Texas (TxDOT 2014b). Yet according to TxDOT's *Manual on Uniform Traffic Control Devices* (MUTCD), a shadow vehicle (truck equipped with an attenuator) is not mandatory for every work zone (TxDOT 2014a). Even if ATMAs fall in price (compared to a human-driven impact attenuator vehicle), they would not make sense in certain conditions (e.g., roads with low speeds and low volumes).

According to TxDOT (2016), there are more than 2,500 active work zones on the state roads at any given time. Thus, each active work zone in Texas averages a crash rate of around eight collisions per year, though factors such as traffic volumes, work zone length, and roadway geometric conditions invariably contribute to per-year crash rates on an individualized work zone basis. Since ATMAs would not likely be deployed across every work zone, here 10 crashes per work-zone-year were assumed to represent application on higher-risk work zones. Around half of work zone crashes were assumed to be rear-end collisions (subject to severity reduction by ATMAs). Severity distributions were estimated based on historical work zone crash data (TxDOT 2014b) and Blincoe et al.'s (2015) findings were used to estimate unit cost of crashes. Under these assumptions, the total rear-end crash costs that could potentially be averted in a given high-risk work zone over the course of a year could equal around \$998,000, as shown in Table 16.15.

Table 16.15 Rear-End Crash Cost in the Highest Risk Work Zones

Severity	K	A	B	C	O
Ratio of severity in	0.7%	2.8%	11.0%	18.5%	67.0%

work zone crashes (TxDOT 2014b)					
Number of rear-end crashes	0.04	0.14	0.55	0.93	3.35
Comprehensive cost of crashes by severity (Blincoe et al. 2015)	\$9,941,000	\$1,088,000	\$300,000	\$139,000	\$46,000
Total cost	\$351,000	\$150,000	\$165,000	\$129,000	\$154,000

However, since ATMAs cannot be present at every single location throughout the work zone, half of this valuation is used for a total annual benefit of \$499,000, since ATMAs could be used at locations and in situations where crash risk is highest, but they would still represent a set of single-point crash reduction sources.

Costs

The price of a conventional TMA and truck to mount it to averages around \$75,000— \$60,000 for vehicle and \$15,000 for TMA (Royal Truck & Equipment Inc. 2016). Here the cost of automation was assumed to be around \$25,000, though costs will likely be much higher for the first ATMA availability, but they could fall below that figure (Fagnant and Kockelman 2015b). Also, for every collision that would occur, the replacement costs of the TMA are considered for safety concerns. Additionally, operation and maintenance costs (including gas, tires, general maintenance, and insurance) were assumed to be double that of passenger cars and trucks used by most American households (American Automobile Association 2015). Thus, the yearly operation and maintenance cost is \$20,000 per vehicle. Additionally, four ATMAs were assumed to be used per work zone (two in each direction) in order to achieve the anticipated crash benefits.

Benefit-Cost Analysis

Benefit can be calculated based on the proportion of severity and unit cost of crash severity. Cost also be calculated by the previous study. Ten years of analysis years (ten years of ATMA life) and a 10% discount rate were used in this analysis. The result shows that B/C ratio is 2.5, as shown in Table 16.16, while the ATMA would successfully prevent rear end crashes successfully in the highest risk work zone.

Table 16.16 ATMA Benefit-Cost Analysis

Savings/Costs		Values (\$/Year)
Benefit	Comprehensive crash savings	\$499,000
Cost	Annualized initial costs (Vehicle costs)	\$65,000
	Maintenance & Operation	\$118,000
	Sum of costs	\$183,000
Net Present Values (\$)		\$1,634,000
Benefit-Cost Ratio (\$)		2.5

16.4 Conclusion

This work provides a preliminary high-level analysis regarding some of the potential benefits and costs for a suite of 10 intelligent vehicle and infrastructure technologies that TxDOT and other transportation agencies may wish to consider in the near future. Each strategy examines the public agency role regarding how key aspects of connected and automated vehicle technologies may be integrated into a state's transport system. This research considered how each of the strategies would potentially influence transportation safety, mobility, connectivity, sustainability, land use, and economic development. The examined strategies are quite novel, and in most cases either have not been deployed, have only been deployed in limited situations, or have been deployed in situations that only somewhat reflect conditions within the state. As such, there remains a measure of uncertainty regarding the high-level estimates contained in this chapter. This noted, these results are still useful as rough estimates for considering the broader implications of how these intelligent transportation strategies may be rolled out, seeking to harness new developments in connected and automated vehicle technologies.

The biggest benefit-cost ratio implementation in this study is CICAS. Because TxDOT does not need to support individual vehicle's onboard units (OBUs), one of the core components of CICAS, as well as CICAS could install only selected areas that show high crash risk. CRM also shows considerable benefits because regional transportation agencies like TxDOT could target highly congested ramps that would deliver the greatest benefits, rather than a broader-based but more costly approach. The similarity among these strategies is that they show high efficiency though low market penetration. In case of CRM, if the leading vehicle in a platoon is a connected or automated vehicle, every vehicle in the platoon has similar benefits. However, the benefit of these strategies only occurs locally, so it may be unequitable. On the other hand, some strategies such as SPP, BSD and AEB require installing facilities within the whole area. In this case, the beneficiary of these strategies is whole area, however, due to the high cost of installation and the low benefit, the efficiency of these strategies is relatively low.

Thus, investment prioritization for these and other intelligent transport strategy applications should take a balanced perspective, and a mix of applications may ultimately yield the best and most equitably distributed safety, mobility and other socially beneficial outcomes. Local needs and anticipated potential for improvement should drive the project application selection process, while also considering funding availability. Finally, pilot roll-outs for these applications may be used to better understand the actual benefits that may be realized before more broad-based applications are implemented, while also helping local transportation agencies to understand the pitfalls and keys to future deployment success.

CHAPTER 17 BENEFIT-COST ANALYSIS

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17.1 Introduction

In order to assess potential benefits to the transportation system and its users stemming from CAVs, it is first critical to assess the existing scope of problems faced by the traveling public. To these ends, this chapter attempts to quantify these problems across two major domains: congestion and crashes. During the course of the project, the team developed initial estimates, which were then refined using the results of the other analyses performed. Section 15.1 describes the preliminary estimates generated towards the start of the project, and Section 15.2 the updated estimates generated near the end.

17.2 Preliminary Estimates

Congestion

Congestion exists as a consistent economic drain on the state. The state of Texas, used as a case study in this work, is in an enviable position compared to many other parts of the nation. Given its growing economy and relatively plentiful jobs, it remains important to protect the state's advantage as a lower-cost, business-friendly location by avoiding scenarios where increasing congestion imposes costs harmful to the state's economy. Based on the 2015 Urban Mobility Report (Schrank et al. 2015), urban areas of all sizes are experiencing the challenges related to increasing levels of congestion. Data from 1982 to 2014 show how congestion has expanded over time on a national level and may continue to increase (absent systemic changes), as shown in Table 17.1.

Table 17.1 Major Findings of the 2015 Urban Mobility Scorecard (471 U.S. Urban Areas)

U.S. Congestion Costs	1982	2000	2010	2013	2014
Travel delay (billion hours)	1.8	5.2	6.4	6.8	6.9
Wasted fuel (billion gallons)	0.5	2.1	2.5	3.1	3.1
Congestion cost (billions of 2014 dollars)	\$42	\$114	\$149	\$156	\$160

While these dramatic changes are occurring nationwide, Texas' population growth continues to outpace the rest of the country, and thus the state is experiencing significant congestion strains. Table 17.2 summarizes the extent of Texas' road congestion problems, as measured across multiple performance measures for the state's major urban areas¹²⁵ in 2014.

¹²⁵ Defined as the developed area (population density more than 1,000 persons per square mile) within a metropolitan region.

Table 17.2 Congestion Data for Texas Urban Areas (TTI 2014 & Schrank et al., 2015)

	Austin	Dallas-Fort Worth	Houston	San Antonio	Others ¹²⁶	National level
Population (1000 s)	1,500	5485	5000	1935	2600	--
Daily Vehicle-Miles of Travel (1000s)						
Freeway	13,273	64,411	51,673	21,270	15,755	--
Arterial streets	11,237	41,713	39,211	12,956	20,746	--
Annual Excess Fuel Consumed						
Total Fuel (1000 gallons)	21,654	79,392	94,300	28,809	28,431	--
Fuel per Peak Auto Commuter (gallons)	22	22	29	20	14	19
Annual Delay						
Total Delay (1000s of person-hours)	51,116	186,535	203,173	64,328	58,823	--
Total Delay (Freeway) ¹²⁷	19,936	72,748	79,237	25,088	9,411	--
Total Delay (Arterials)	31,180	113,786	123,935	39,240	49,411	--
Delay per Peak Auto Commuter (person-hrs)	52	53	61	44	29	42
Travel Time Index	1.33	1.27	1.33	1.25	1.15	1.22
Freeway Planning Time Index (95th Percentile)	2.58	2.65	3.13	2.12	1.6	2.41
Congestion Cost (constant 2014 \$)						
Total Cost (\$ millions)	\$1,140	\$4,202	\$4,924	\$1,462	\$1,351	--
Cost per Peak Auto Commuter (\$)	\$1,159	\$1,185	\$1,490	\$1,002	\$676	\$960

When taken collectively, these measures show that Texans annually experience over 560 million hours of delay, going relatively slowly or sitting in traffic, with an economic cost of over \$13 billion. As should be expected, higher levels of VMT, total fuel consumption, delays, and congestion costs are seen in Texas' larger cities. On a per-commuter basis, Houston travelers experience the greatest congestion costs, followed by those from Dallas-Fort Worth and Austin. While not quantified in terms of direct economic costs, the travel time variability measures (which are the travel time index and freeway planning time index) represent real costs to travelers as well, since travelers must either leave increasingly early or risk being late. In sum, this data clearly illustrates the scope of congestion impacts to Texas in terms of wasted time and lost economic efficiency.

Furthermore, historical data shown in Figure 17.1 illustrates growing population trends along with several congestion performance measures in recent years from 2010 to 2014 (TTI 2014). These charts show how congestion continues to worsen across the state with continued population growth and economic activity.

¹²⁶ These include El Paso, Laredo, McAllen, Brownsville, Corpus Christi, and Beaumont, Texas. Values per peak-period automobile traveler were calculated using a weighted average by population as weights.

¹²⁷ These values were calculated using the base share of delay on freeways vs. arterials at the national level provided by (Schrank et al., 2015), and adjusted based on freeway vs. arterial VMT differences when comparing Texas to U.S. averages.

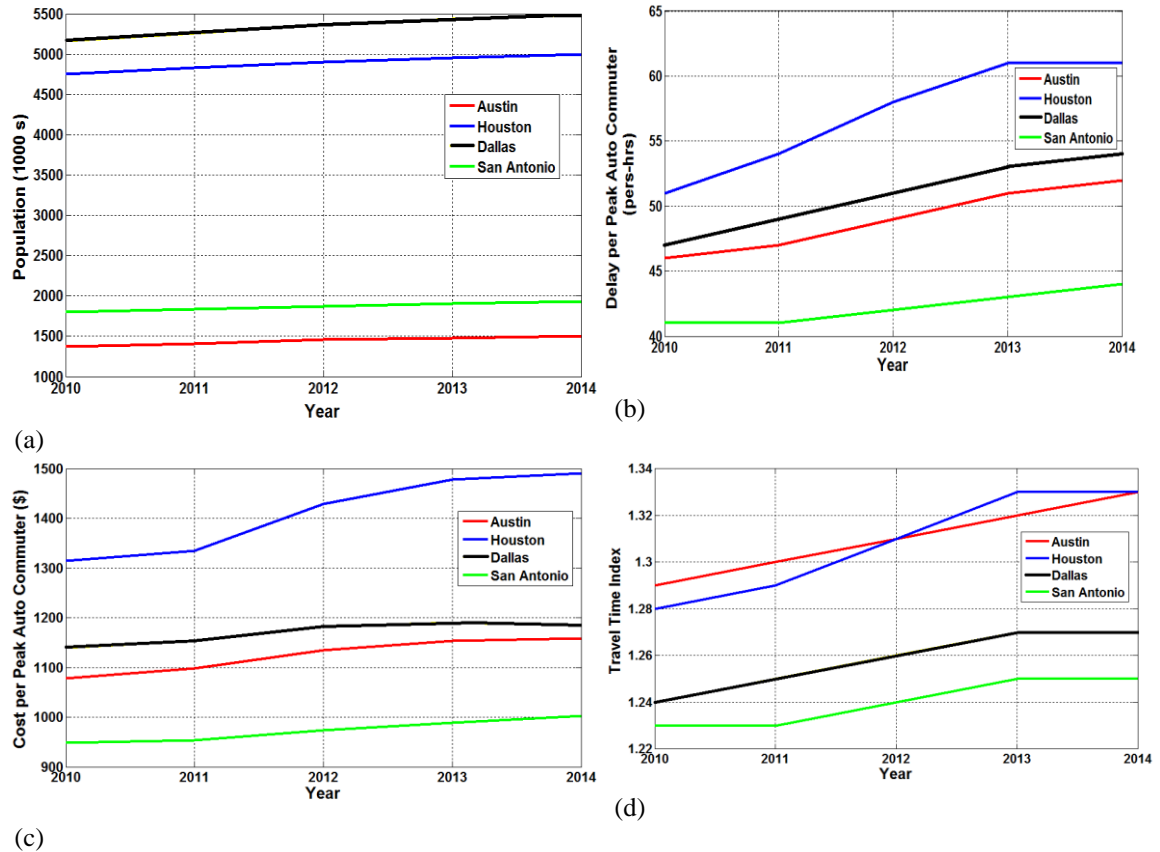


Figure 17.1 Trends of (a) Population, (b) Delay, (c) Cost and (d) Travel Time Index per Peak Auto Commuter from 2010 to 2014.

The congestion problem can be further broken down into its component parts based on roadway type. Nationally, more delay is experienced on surface streets than freeways, and larger urban areas experience higher shares of their delay on freeways than in smaller cities. Additionally, approximately 40% of delay occurs in off-peak hours, as shown in Figure 17.2, indicating a persistent problem that could be potentially ameliorated with carefully considered CAV strategies.

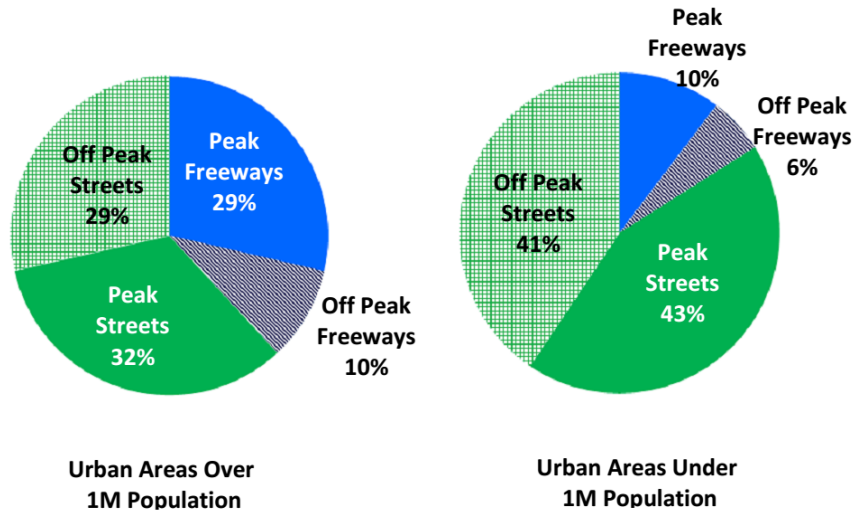


Figure 17.2 Percent of Delay, By Road Type and Time of Day

While the Urban Mobility Report outlines the total impacts of congestion costs in urban areas, there may be opportunities for some mobility enhancements in rural areas and small towns, too. For example, a small town may have 20 traffic signals, each with 2,500 entering vehicles during the highest traffic hour. If 10 seconds of delay could be shaved off each signal through cooperation with CAVs, over one half million hours of delay could be saved per year. Though this figure pales in comparison to the delay experienced in Texas’ major cities, the cumulative impacts across Texas’ numerous small towns could become sizable. Since the scope of delay and potential for improvement in small towns has not been quantified in the literature, this chapter cannot adequately quantify these potential impacts with any accuracy. Therefore, readers should note that the true potential for delay reductions could be greater than estimated in this chapter, due to the omission of potential improvements in small towns outside of large urban metro areas.

Crashes

In 2013, Texas experienced more than 446,000 crashes, resulting in 3,065 fatalities and over 296,000 injuries (TxDOT 2014). With nearly 250 billion VMT per year, this translates to one crash for every 532,000 VMT and one fatality for every 78 million VMT. This comes at a total comprehensive economic cost of \$83 billion (or \$3,000 per Texan per year), a tremendous social burden. While most collisions occurred in urban areas (75.2% of all crashes), fatalities in rural areas were typically more severe, accounting for 55.4% of all fatalities. Table 17.3 outlines crash count distributions, by severity and setting, across the state.

Table 17.3 Number of Crashes in Texas, 2013

Crashes	# Crashes			# Injuries		
	Rural	Urban	Statewide	Rural	Urban	Statewide
# of Fatal Crashes or Fatalities	1,648	1,417	3,065	1,887	1,521	3,408
# Incapacitating Crashes or Injuries	5,184	8,254	13,438	6,847	9,960	16,807
# Non-Incapacitating Crashes or Injuries	13,778	38,433	52,211	20,205	52,430	72,635
# Possible Injury Crashes or Injuries	16,218	72,591	88,809	26,236	116,921	143,157
# Non-Injury Crashes or Non-Injuries	70,655	201,946	272,601	203,259	694,664	897,923
# Unknown Severity Crashes or Injuries	2,950	12,755	15,705	8,539	51,766	60,305
<i>Total Number of Crashes or Injuries</i>	<i>110,433</i>	<i>335,396</i>	<i>445,829</i>	<i>63,714</i>	<i>232,598</i>	<i>296,312</i>

Rural and urban settings have their own unique characteristics in terms of traffic flow, roadway facility types, traffic control, operating speeds, and other factors. These characteristics also lead to differences in incidence rates. For example, NHTSA (2015) estimates a fatality rate per 100 million VMT in rural areas at 1.88 compared to just 0.73 for urban areas.

In addition, motorcycle crashes are of particular concern to CAVs. Collisions that a CAV can avoid in these instances are inherently limited, since a CAV can only prevent its own mistakes, and not those of a motorcyclist. While a motorcycle can be automated (see e.g., Brassfield 2014), the appeal of a self-operating motorcycle seems quite limited. With approximately half of all motorcycle fatalities being single-vehicle collisions (Fagnant and Kockelman 2015c), this share of crashes is assumed to remain unchanged.

Moreover, motorcycle crashes are often quite severe. While motorcycle-involved crashes represented just 0.8% of all collisions in Texas, they accounted for over 15% of statewide fatalities. This means motorcyclists are more vulnerable in the event of a crash, with associated higher likelihood of a fatality resulting, and along with higher expected crash cost per motorcycle. The number of motorcycle injuries is shown in Table 17.4.

Table 17.4 Motorcyclist Injuries in Texas, 2013

Types of Injuries	Motorcyclist Injuries	All Crash Injuries	Motorcyclists' Injury Share
Fatalities	503	3,408	14.8%
Incapacitating Injuries	1,969	16,807	11.7%
Non- Incapacitating Injuries	3,698	72,635	5.1%
Possible Injuries	2,002	143,157	1.4%
Non-Injuries	1,283	897,923	0.1%
Unknown Injuries	184	60,305	0.3%
<i>Total TX Motorcycling Injuries</i>	<i>8,356</i>	<i>29,312</i>	<i>0.8%</i>

Crash injury severities were then translated from the KABCO scale to the MAIS scale, using Blincoe et al.'s (2015) estimates, in order to calculate total economic and comprehensive crash costs. In addition to economic components such as property damage, delay, medical costs, lost productivity, and other factors, comprehensive crash costs also include external measures such as quality-adjusted life years and willingness-to-pay measures for avoiding crashes. Table 17.5 depicts the estimated number of injuries in Texas across the MAIS severity scale, along with per-crash economic and comprehensive valuations associated with each severity level.

Table 17.5 Number of Injured Persons in Crashes and Costs per Injured Person

Severity	# Injured Persons (all Injuries)	# Injured Motorcyclists	Economic Cost/Injury	Comprehensive Cost/Injury
Fatal	3,408	532	\$1,398,916	\$9,145,998
MAIS5	1,213	55	\$1,001,089	\$5,579,614
MAIS4	1,910	86	\$394,608	\$2,432,091
MAIS3	9,181	867	\$181,927	\$987,624
MAIS2	32,015	1,511	\$55,741	\$396,613
MAIS1	358,219	5,240	\$17,810	\$41,051
MAIS0	788,080	1,348	\$2,843	\$2,843

These valuations indicate that the total economic cost of the State of Texas' 446,000 crashes in 2013 exceeded \$19 billion, rising to \$83 billion once comprehensive costs are included.

It should be noted that this is markedly higher than TxDOT's 2013 crash cost estimate of \$27.8 billion, since TxDOT's figures rely on the National Safety Council's valuations (NSC 2012), which include economic components only, and are somewhat less current and rigorous than Blincoe et al.'s (2015) work.

Implications for Travel and Vehicle Ownership

As CAVs become more prevalent, they are bound to impact our interface with the transportation system. Texas may see an increase in VMT as park-period automobile users take their self-driving vehicles to work, then send them home to park for free or be used by other family members. Trip generation may rise as those previously unable to drive (e.g., children, the elderly, and disabled persons) achieve newfound independent mobility. Empty vehicles may drive themselves from one location to another, to park less expensively or serve the travel needs of another person. Airlines may see fewer passengers as more long-distance travelers take to the roadways (LaMondia et al. 2016). Ultimately, people may choose different destinations, home, work and school locations, as motorized travel becomes less onerous.

Household vehicle ownership patterns may also change. As fleets of shared on-demand driverless vehicles (SAVs) become available, households may choose to own fewer cars, relying on SAV services instead for some or even all of their travel needs. This section examines potential impacts across both VMT and vehicle

ownership dimensions, in order to predict potential changes that Texas may experience, and the resulting impacts on congestion and safety.

With the arrival of CAVs, it is quite likely that we will see a net increase in total VMT. Individual travelers will be able to read a book, use a laptop, relax, or perform other activities previously not possible to undertake while driving (at least safely). This should lead to an effective reduction in the perceived values of travel time (or alternatively, travel time burdens) for CAV users. Indeed, Gucwa (2014) estimated a potential 4–8% VMT increase due to lower perceived values of travel time and increased road capacity, due to CAV capabilities. Additionally, once fully automated vehicles arrive, CAVs may afford new mobility opportunities for those currently unable to drive. This development may also give rise to a new transport mode, the SAV. SAVs may act as on-demand driverless shuttles or taxis, transporting travelers from one location to the next throughout the day. It is highly probable that some of this travel will be unoccupied at times, thus introducing new VMT, though if enough ridesharing takes place, net reductions could possibly result. Fagnant and Kockelman (2015b) estimated that, when serving 1.3% of regional trips by SAV (with no ridesharing), total VMT rose by 8.7% on a per-trip basis. However, when ridesharing was incorporated into the model, just 4.5% VMT was added, and this figure could be pushed to below zero (i.e., VMT reductions) with greater SAV demand or looser ridesharing parameters. Moreover, (if not prohibited) it may also be possible for individual CAV owners to send their vehicles to cheaper parking locations, thus creating even more VMT.

When considering all of these factors together, several assumptions may be made in order to develop an order-of-magnitude estimate for the potential changes in VMT at various levels of market penetration. At the 10% market penetration level, a 20% VMT increase is assumed per CAV, to account for latent demand (i.e., those previously unable to drive) as well as falling values of travel time, and unoccupied CAV travel. Added VMT per CAV is assumed to fall to 15% at the 10% market penetration level (i.e., CAVs between the 10–50% range will see 15% per-CAV travel increases, on top of the 20% increases shown by the first 10% of CAV adopters), and just 10% at the 90% market penetration level. These falling values account for the increased potential for ridesharing via SAV (and less unoccupied relocation), as well as the fact that latent demand from those unable to drive would already have been served. Since there is likely greater utility for unoccupied travel in urban areas (e.g., due to avoiding pricy parking and unoccupied travel by SAVs), rural areas are assumed to experience half of the per-CAV travel as that seen in urban areas. These per-CAV increased travel values are consistent with prior estimates conducted by Fagnant and Kockelman (2015b).

This noted, additional VMT is estimated here, beyond estimates conducted in Fagnant and Kockelman's (2015b) work, for other travelers who are not CAV users. CAVs should improve operational efficiencies through freeway traffic flow harmonization and smoothing, platooning via cooperative adaptive cruise control (CACC), and an anticipated reduced collision rate. All of this should create an effective increase in capacity, leading to reduced travel times across all travelers. As capacity increases and traffic delays fall, as prior studies show, utilization increases on those same facilities. For example, Cervero's (2001) review of literature for cities in California and the U.S. across 30 years found that urban demand elasticity with respect to highway lane miles averaged 0.74. This implies that a 1% increase in a region's total lane miles should correspond to a 0.74% increase in VMT.

It is unlikely that the full magnitude of the 0.74 average elasticity found by Cervero will materialize due to effective capacity increases enabled via CAVs. In the past, roadway construction improvements were targeted to address specific needs, while CAV capabilities may have broad-based effects, regardless of whether any latent travel demand is present, or would otherwise materialize absent capacity increase. Therefore, a demand elasticity of non-CAVs with respect to capacity increase is assumed to be 0.40 at the 10% market penetration level. As with CAVs, the incremental impacts of added capacity is assumed to fall with greater market penetration (and thus greater effective capacity increases), and therefore elasticity values are assumed to fall to 0.20 and then just 0.10 at the 50% and 90% market penetration levels, respectively. Since congestion is a minimal factor if present at all in rural areas, no rural VMT increases due to latent demand factors are assumed in this analysis.

As CAVs enter the market, eventually the requirement for a driver to be present will fall, giving rise to SAVs. The value proposition inherent in SAVs is quite substantial—instead of owning your own vehicle, simply

summon an on-demand SAV via smartphone when you need one, and share a ride with someone else headed in the same direction if you wish to save some money. Indeed, in many ways this is a similar framework to what transportation network companies (TNCs) currently operate. Uber has publicly stated its intention of transitioning to SAVs as they become feasible (Harris 2015), and Google has similar plans with its recently introduced fleet of SAV prototypes. Yet SAVs have many advantages beyond current TNC models with human drivers. System-optimal vehicle fleet control will be possible (rather than relying on drivers to make decisions of when and where to operate that impact the entire fleet), SAVs do not need to take breaks and can work around the clock, and most importantly, cost savings may be dramatic. To this last point, Fagnant and Kockelman's (2015b) simulations estimated that a fleet of 2118 SAVs serving 1.3% of Austin regional trips could cut equivalent taxi fares from around \$3 per mile to just \$1 per mile, while still garnering an annual return on investment capital of nearly 20% per year. Moreover, this assumes a vehicle purchase price of \$70,000, and long-term market projections for the cost of added vehicle automation is anticipated to be around \$10,000 or less.

Consequently, it is highly likely that a significant share of households will come to rely on SAVs for their travel needs, and shed one or more personally owned vehicles. This will likely occur most frequently in more densely populated areas, since SAVs are most effective with increased trip intensity and high parking costs. The question then remains as to how large of a market share SAVs will comprise, as a proportion of all CAVs. It is possible that they will come to dominate the market (as projected by Zachariah et al. 2014), or alternatively comprise just a small part of the transportation ecosystem, perhaps just above current TNC and taxi shares. Both scenarios are certainly plausible, with economic efficiencies driving the first vision; and an implicit value of ownership, locked mobile storage, and vehicle availability certainty driving the second. Instead, here it is anticipated that SAVs will displace less-intensely used vehicles in urban areas, thus comprising a large but not overwhelming share of CAVs. Thus, this section projects roughly half of all CAV trips will be served by SAVs, consistent with Fagnant and Kockelman's (2015b) prior estimates.

Mobility

The potential benefits for enhanced mobility are also quite substantial. CAVs have the potential to increase effective road capacity and efficiency through reducing vehicle headways when platooning, operating more efficiently with traffic signals, utilizing intelligent merging with automated on-ramp metering, and harmonizing speeds to smooth traffic flow. On arterials and other surface streets, additional efficiencies may be gained through intelligent coordination with signals. Additionally, with fewer crashes anticipated due to safety improvements, non-recurring congestion stemming from crashes should fall. The FHWA (2005) estimates that around 25% of urban congestion is due to non-recurring events, around half of which is attributed to collisions.

CACC is one emerging technological application with the potential for significantly enhancing roadway efficiency. CACC aims to reduce gaps between communicating CAVs, facilitating the creation of tightly spaced vehicle platoons, with gaps between vehicles as low as just several meters. CACC utilizes V2V communication in combination with vehicle automation to form these platoons. V2V communication enables the precise transmission (10 times per second) of location, velocity, gap, and any acceleration or braking actions of other vehicles in the platoon, enabling safe and reliable platoon formation. Using these platooning strategies, CACC-capable vehicles can increase the effective freeway capacity (van Arem, van Driel et al. 2006).

Shladover et al. (2012) conducted series of microsimulation experiments (informed by field-testing of CACC-equipped vehicles) to estimate the impacts of platooning CACC vehicles on freeway traffic flow, at multiple levels of market penetration. This research found that the marginal increase in capacity enhancement increases at higher market penetration levels. When the entire traffic flow stream was equipped with CACC capabilities, lane capacity was estimated to increase to 3,970 vehicles per hour, or nearly double current freeway lane capacities. Moreover, two evaluation alternatives were tested based on the rest of the non-CACC vehicle fleet: as conventional unconnected vehicles, and as CVs that can transmit "Here I am" (HIA) messages via dedicated short-range communications-enabled (DSRC) V2V communication, to enable platoons to form behind them. Table summarizes the estimated potential impacts of CACC, across various market penetration levels.

Table 17.6 *Estimated Impacts of CACC on Freeway Capacity (veh/hr/ln)*

Method	Area Type	Facility Type	Benefit Type	Impact by market penetration					
				0%	20%	40%	60%	80%	100%
CACC	-	Freeway	Increase Capacity	2100	2200	2350	2500	2900	3970
CACC w/ HIA	-	Freeway	Increase Capacity	2200	2350	2500	2900	3300	3970

While in theory the CACC-with-HIA implementation should work, in practice there may be reluctance on the part of road users. That is, the driver in a vehicle that can transmit an HIA message but is not CACC capable might likely object to CACC-capable vehicles platooning behind it with very short gap spaces. Instead, it is envisioned here that platoons of vehicles would be more likely to be self-organizing across CACC-capable vehicles only, with each vehicle in the platoon (including the lead vehicle) operating in self-driving mode, thus reducing potential anxiety, nervousness, or other discomfort by potential non-CACC lead vehicles. Therefore, for the subsequent analysis conducted in this chapter, figures from the CACC-only analysis method are used.

Furthermore, similar information may be obtained from other downstream V2V-capable vehicles that are not in a platoon (or from roadside infrastructure relaying this information). Using this information, CAVs can identify such downstream traffic flow conditions, and adjust their speeds accordingly (e.g., letting off the accelerator prematurely when a downstream vehicle brakes, to avoid harder braking later). This phenomenon results in overall smoother traffic flow, lower fuel consumption, and reduced delays, additionally benefiting following vehicles (connected or not) even at lower levels of market penetration. Atiyeh (2012) estimates that on congested freeways, such traffic flow smoothing algorithms could achieve speed increases of 8 to 13%.

Similarly, Englund et al. (2014) evaluated the potential impacts of cooperative speed harmonization (CSH) on a highly congested freeway interchange, which acted by strategically adjusting CAV speeds to integrate merging traffic flow streams. They found that CSH should decrease CO₂ emissions by 11% and travel time by 16% and increase average speed up to 14%. Englund et al. (2014) conducted this research by simulating approaching vehicles that became grouped as they approached a convergence point at an on-ramp, thus resulting in fewer vehicles that would need to change lanes at the intersection. Milanés et al. (2011) conducted a similar evaluation using automated ramp metering and DSRC communication by enabling merging vehicles to fluidly enter major facilities, while avoiding congestion on the approach ramp. This was conducted in part by modifying the speed of the vehicles already on the main road, which in turn reduced the total effect of congestion on main facility. When using this strategy, total congestion delay experienced in the merge area was reduced between 7% and 16%.

At the surface street level, it should also be possible to achieve efficiency improvements, particularly at intersections. A CAV could communicate with a connected signal to improve operational efficiencies, enhancing existing signal detection system capabilities, and potentially accounting for modal consideration, as formulated in the Multi-Modal Intelligent Traffic Signal System algorithm (Head 2014). CAVs could coordinate acceleration and deceleration profiles in advance of a signal phase change, in order to minimize hard braking and acceleration. For example, strategically premature deceleration could allow a CAV to arrive just before the stop bar at the start of green, while rolling at 30 mph, thus effectively eliminating startup delay. Also, a small platoon of CAVs could simultaneously accelerate from stopped conditions, thereby removing startup time loss for every vehicle but the platoon leader.

Eventually, once all or almost all vehicles are equipped with CAV capabilities, tremendous intersection efficiencies may be possible, by facilitating alternative right-of-way assignment at signalized intersections (e.g., Autonomous Intersection Management, or AIM; Dresner and Stone 2008). The AIM protocol operates by assigning each vehicle approaching the intersection a dedicated time-space path, while ensuring that the path does not conflict with a previously assigned path of another vehicle. Yet in order to achieve such gains,

it is necessary that very high market penetration levels are present, likely in excess of 90%. Therefore, potential signalized intersection benefits due to fundamental operational paradigm shifts like those proposed in AIM are not assumed in the analysis conducted in this section.

In order to estimate the potential impacts of CAVs on congestion in Texas, the following assumptions and methodology were used. First, the relative levels of congestion were broken out between Austin, Dallas/Fort Worth, Houston, San Antonio, and other mid-sized Texas cities. Data from Schrank et al.'s (2015) Urban Mobility Report was then used to estimate base levels of congestion, segmented by peak vs. off-peak congestion, and freeway vs. surface street congestion, using prior values noted in Table 17.2 and Figure 17.3. Next, equivalent peak hour freeway congestion was estimated using each of these cities' travel time indices, which relates average peak hour travel times to travel times in free flow conditions. The Bureau of Public Roads link performance function (Eq. 14.1) was then used to estimate average effective regional freeway traffic volumes, assuming link capacity of 2100 vehicles per hour per lane.

$$T_c = T_f \left(1 + \alpha \left[\frac{v}{c} \right]^\beta \right) \quad (17-1)$$

In Equation (17-1), T_c represents congested link travel time, T_f the link free-flow travel time, v traffic volume, and c link capacity, while α and β are volume/delay coefficients with parameter values of 0.83 and 5.5, consistent with Martin and McGuckin's (1998) findings.

Once current assumed traffic volumes were obtained, effective link capacity was increased by 50, 325, and 1335 vehicles per hour per lane at the 10%, 50%, and 90% market penetration levels, consistent with Shladover et al.'s (2012) earlier findings. Next, increasing traffic volumes were incorporated, due both to greater travel per CAV, and due to increased travel by other road users as they see their travel times fall. This resulted in total average VMT increases of 3%, 12%, and 26%, respectively, at the 10%, 50%, and 90% market penetration levels. After this calculation, a flat 10% reduction in delay was assumed across all scenarios, to account for the combined congestion impacts of freeway traffic flow smoothing, CSH, intelligent ramp metering, and other CAV applications. Resulting delay values were compared against initial delay, in order to estimate the total percentage of delay reduction across each of the market penetration scenarios.

Since it is more difficult to readily compute off-peak delay on freeways than computed as peak hour delay without more granular details (e.g., traffic volume assumptions, incidents that may have caused the delays, etc.) the same share of delay reduction was assumed as was computed for peak hour delays. For surface street arterials and collectors, delay reductions of 5%, 10%, and 15% were assumed at the respective 10%, 50%, and 90% market penetration levels. These were used to account for greater signal and vehicle operational efficiencies, with values consistent with the estimates used by Fagnant and Kockelman (2015b). The resulting estimated potential congestion delay reductions across Texas may be seen in Table 17.7:

Table 17.7 Estimated Impacts of CAVs on Freeway Traffic Congestion in Texas

City	Impact	Market penetration			
		0%	10%	50%	90%
Austin	Annual Delay per Population (hr)	24.4	23.0	20.8	14.7
	Delay Reduction per Population (hr)	-	1.4	3.6	9.7
	Congestion Cost Savings per Population	-	\$25	\$64	\$172
	Regional Congestion Cost Savings (\$M)	-	\$31	\$79	\$213
Dallas/Fort Worth	Annual Delay per Population (hr)	24.9	23.4	21.2	15.0
	Delay Reduction per Population (hr)	-	1.5	3.7	9.9
	Congestion Cost Savings per Population	-	\$26	\$65	\$175
	Regional Congestion Cost Savings (\$M)	-	\$246	\$621	\$1,670
Houston	Annual Delay per Population (hr)	29.4	27.7	25.0	17.7
	Delay Reduction per Population (hr)	-	1.7	4.3	11.7
	Congestion Cost Savings per Population	-	\$30	\$77	\$206
	Regional Congestion Cost Savings (\$M)	-	\$288	\$727	\$1,957
San Antonio	Annual Delay per Population (hr)	22.5	21.2	19.2	13.6
	Delay Reduction per Population (hr)	-	1.3	3.3	8.9
	Congestion Cost Savings per Population	-	\$23	\$59	\$158
	Regional Congestion Cost Savings (\$M)	-	\$86	\$216	\$581
Others ¹²⁸	Annual Delay per Population (hr)	15.0	14.2	13.2	11.3
	Delay Reduction per Population (hr)	-	0.8	1.8	3.8
	Congestion Cost Savings per Population	-	\$14	\$32	\$67
	Regional Congestion Cost Savings (\$M)	-	\$73	\$162	\$340
Statewide	Congestion Costs (\$M)	\$13,079	\$12,319	\$11,185	\$8,078
	Congestion Cost Savings (\$M)	-	\$760	\$1,894	\$5,001
	System-wide Congestion Reduction (%)	-	5.8%	14.5%	38.2%

As Table 17.7 indicates, meaningful congestion reduction may be achieved even at the 10% market penetration level, with an estimated total system-wide delay reduction of nearly 6%, accounting for \$760 million in economic savings. By the 90% market penetration level, more than half of freeway congestion is assumed to be eliminated, with most of the remaining congestion due to collector and arterial surface street intersections. This results in a total system-wide delay reduction of more than 38%, for a cost savings exceeding \$5 billion. Of course, readers should keep in mind that these figures are meant to represent order-of-magnitude estimates of potential outcomes, and that there remains a great deal of uncertainty surrounding how these CAV systems will ultimately be implemented.

Safety

Motor vehicle collisions have existed since the world's first engines were installed in horseless carriages: the first recorded gasoline-powered auto crash occurred in 1891, involving a vehicle that lost control and crashed into a hitching post (Soniak 2012). From that time, auto manufacturers, civil engineers, planners, law enforcement, and others have sought to identify ways to reduce automotive crashes. In over 90% of incidents, the primary cause of the collision is human error, such as slow reaction time, poor sight, aggressive driving, drowsy driving, or other human factors (NHTSA 2008). While other environmental- and vehicle-related causes remain factors to be considered, this finding indicates a strong potential for reducing crash rates.

In this respect, Level 4 automation (explained in Chapter 2) may be the best option for reducing human errors. Here, the term *reducing* is used because human error will still exist, though it will be effectively transferred from the human driver to the human programmer coding the underlying logic and algorithms used to guide the vehicles' operations. This noted, the relative level of safety should improve as time and technology progress, since software and hardware developers can learn from and build upon past experiences. In contrast, each new 16-year-old driver must begin anew, so the difference in safe driving ability from one year's group

¹²⁸ El Paso, Laredo, McAllen, Brownsville, Corpus Christi, and Beaumont.

of 16-year-olds to the next is likely negligible (or perhaps worse in some ways, given increasing smart phone distractions). This noted, it may take 20 years or more before vehicle automation technology can safely and reliably handle the same variety of environmental and roadway locations, conditions, and speeds that human drivers regularly drive on today.

As previously noted, this chapter seeks to examine the potential benefits from Level 3 to Level 4 automation, assuming CV technology. With safe driving responsibilities transferred from the human driver to the vehicle, it is useful to broadly understand the types of human errors that were primarily responsible for collisions, and how similar failures may be handled differently for CAVs versus human drivers. One way to frame these differences is in terms of perception (P), interpretation (I), judgment (J), and reaction (R, which in this case also represents action), or PIJR, a key variable used when considering stopping sight distance reaction times. Today, PIJR times required for CAVs are much shorter than PIJR times for human drivers, and it is possible that these times could be further reduced with advances in processing power. Using that underlying framework, this analysis broadly groups human failings into the following categories: intoxication (drugs or alcohol involvement), aggressive driving (characterized by speeding, erratic operation, or other prohibited maneuvers), inattention and distraction, judgement failure (failures to keep in lane or yield), and performance errors, with corresponding PIJR elements as follows:

- Intoxication (PIJR),
- Aggressive driving (JR),
- Distraction or inattention (P),
- Judgment failure (IJR), and
- Performance (PJR)

While it is unknown how many of these collisions may be completely avoided, educated estimates may be used to assess potential order-of-magnitude scales for potential crash reductions. Therefore, the following crash reduction factor (CRF) estimates are provided at the 10% market penetration level, using the following justification:

- **Intoxication (99%):** A vehicle cannot consume alcohol or ingest drugs. The closest analogy would be a malicious cyber-attack against one or more CAV, which should almost assuredly occur at a dramatically lower frequency than current rates of drunk or drugged driving in Texas. Therefore, a 99% CRF is assumed for crashes where intoxication was involved.
- **Aggressive driving (90%):** CAVs will likely be programmed to prohibit aggressive driving. This noted, it is still possible that a CAV could misinterpret conditions, or behave erratically due to sensor, software, or actuator failures, and thus behave similarly as an aggressive driver would. It is highly unlikely that these failures should be common, so a 90% CRF is assumed.
- **Inattention and Distraction (75%):** While it should be impossible for a CAV to become inattentive or distracted, it may encounter other errors due to sensor limitations or interpretation failures regarding information received from the sensors. Therefore, a 75% CRF is assumed, to account for these new errors that may be introduced.
- **Judgment failure (75%):** CAVs should be better at staying in their lanes than human drivers, since occasional willingness to drive outside of lane lines on curves, and other human behaviors will not apply. Similarly, range finders, communication abilities on CAVs, and other sensors may be used to better assess when a turn is safe to make (particularly compared to human drivers), and establish right of way for turning operations. However, since a CAV should still be able to misinterpret lane lines, pavement edges, safe turning decisions, and other judgements, a 75% CRF is assumed.
- **Performance Error (67%):** IIHS (2015) notes that teenagers have crash rates at three times those of drivers over 20, while at a minimum, CAVs must be at least as safe as a good human driver. Therefore, a 67% CRF for causes due to inexperience is assumed to achieve this basic level of safety. Similar safety improvements are assumed for general performance-related crash causes, such as inadequate surveillance, overcompensation, panic/freezing, and poor directional control.

- **Other factors (50%):** Even after accounting for all aforementioned potential crash causes, it remains highly likely that CAVs will be required to be able to drive safer than a sober, attentive, experienced and relatively cautious human driver. Indeed, rider acceptance will likely demand this: a minor mistake resulting in a near-collision may be waived off with a human driver, though the same action would cause a dramatic loss of confidence in the self-driving capabilities of a CAV. In the event that a crash actually occurs, the loss of confidence may lead the owner to sell the vehicle outright. Therefore, a 50% CRF is assumed for all other crash types, at a range that is lower than other human failure CRFs, but still twice as safe as a human driver.

Additionally, it is assumed here that a crash where multiple of the above factors were involved that highest applicable CRF is applied. This may therefore underestimate the total possible crash reduction, since, for example, in a collision involving aggressive driving and distraction, both contributing factors would be addressed through CAV capabilities.

In subsequent years it is assumed that the level of safety will continue to improve for CAVs. Though it is impossible to truly appreciate how far they may drop, this chapter assumes that between the 10% and 50% market penetration level all collision rates are halved, and that collision rates are halved again between the 50% and 90% market penetration levels. Thus, for example, the 90% CRF for aggressive driving would become a 95% CRF at the 50% market penetration level and exhibit a 97.5% CRF at the 90% market penetration level. Therefore, total crash reduction potential is estimated for CAVs as shown in Table 17.8:

Table 17.8 Assumed Crash Reduction Factors for CAVs

Crash Factor	Types of Human Error	CAV Market penetration		
		10%	50%	90%
Intoxication	Alcohol, Drugs	99%	99.5%	99.75%
Aggressive Driving	Speeding, driving too fast for curve or conditions, erratic operation, illegal maneuver, other prohibited driver errors	90%	95%	97.5%
Distraction & Inattention	Internal and external distraction, inattention	75%	87.5%	93.75%
Judgment Failure	Failure to keep in lane, failure to yield, misjudgment of gap or other's speed, false assumption of other's action	75%	87.5%	93.75%
Performance	Inexperience / over-correction, inadequate surveillance, panic / freezing, sleep, heart attack	66.67%	83.34%	91.67%
Other Factors	All other crashes	50%	75%	87.5%

NHTSA's (2015) Fatal Analysis Reporting System (FARS) database was then used across the set of 2013 Texas roadway fatalities to estimate the share of fatal collisions that were attributable to each of these factors. As noted previously, where more than one of these factors was observed for a single crash, the crash factor associated with the higher CRF was assumed (e.g., if alcohol and aggressive driving were both noted in a crash, Table 17.8 attributes the crash to intoxication and not aggressive driving, in order that crash reductions are not double-counted).

Similarly, NHTSA's General Estimates System (GES) database contains some of this information, though the collision data contained therein is more sparsely populated, making it difficult to truly get a sense of how crashes were attributed to each of these crash factors. Therefore, the set of critical reasons for the critical pre-crash events from NHTSA's (2008) Motor Vehicle Crash Causation survey is used here for non-fatal crashes, to estimate what total proportion of collisions is attributable to each of the various crash causes. This data is further augmented by non-fatal alcohol and drug-related crash information from the GES database, since drugs and alcohol are not listed as a critical pre-crash event, with resulting shares across the various crash factors shown in Table 17.9.

Table 17.9 Shares of Fatal and Non-Fatal Crashes Attributable to Various Crash Factors

Crash Factor	Types of Human Error	% of Fatal Crashes	% of Non-Fatal Crashes
Intoxication	Alcohol, Drugs	37.0%	6.9%
Aggressive Driving	Speeding, driving too fast for curve or conditions, erratic operation, illegal maneuver, other prohibited driver errors	23.1%	17.5%
Distraction & Inattention	Internal and external distraction, inattention	6.1%	15.4%
Judgment Failure	Failure to keep in lane, failure to yield, misjudgment of gap or other's speed, false assumption of other's action	8.3%	6.7%
Performance	Inexperience / over-correction, inadequate surveillance, panic / freezing, sleep, heart attack	2.0%	35.8%
Other Factors	All other crashes	23.5%	16.2%

Figure 17.3 Quantitative Estimates of Safety Impacts

In order to provide a quantitative estimate of the potential safety benefits of CAVs, it is necessary to understand the number, severity, and cost of crashes that Texas experiences on an annual basis (Tables Table 17.3Table 17.4Table 17.5), the shares attributable to various causes (Table 17.9), and the potential for their future reduction through CAV capabilities (Table 17.8). By applying these factors across three levels of market penetration (10%, 50%, and 90%), it is possible to estimate the total potential collision savings for

CAVs as they enter the Texas transportation system. Table 17.10 summarizes the road safety implications and potential of CAVs for non-motorcycle crashes, Table 17.11 summarizes the same for motorcycle collisions (crash reductions here are assumed to be lower, since motorcycles are assumed to be non-automated and only enjoy safety enhancements gained through reduced crash exposure from other vehicles), and Table 17.12 summarizes implications across all road crashes.

Table 17.10 Potential Crash Implications for CAVs, Non-Motorcycle Crashes

Implications	CAV Market Penetration			
	0%	10%	50%	90%
# Crashes	436,975	405,168	248,213	70,450
# Injuries	224,930	208,569	127,794	36,289
# Fatalities	2,905	2,669	1,588	412
Economic Costs (\$M)	\$17,932	\$16,593	\$10,100	\$2,814
Comprehensive Costs (\$M)	\$76,158	\$70,389	\$42,695	\$11,770
Lives Saved	-	236	1,317	2,493
Economic Savings (\$M)		\$1,339	\$7,832	\$15,118
Comprehensive Savings (\$M)	-	\$5,769	\$33,463	\$64,388

Table 17.11 Potential Crash Implications for CAVs, Motorcycle Crashes

Implications	CAV Market Penetration			
	0%	10%	50%	90%
# Crashes	8,854	8,693	7,898	6,998
# Injuries	7,669	7,530	6,841	6,061
# Fatalities	503	494	449	398
Economic Costs (\$M)	\$1,172	\$1,151	\$1,046	\$926
Comprehensive Costs (\$M)	\$7,056	\$6,927	\$6,294	\$5,576
Lives Saved		9	54	105
Economic Savings (\$M)		\$21	\$127	\$246
Comprehensive Savings (\$M)	-	\$128	\$762	\$1,479

Table 17.12 Potential Crash Impacts for CAVs (Not Accounting for VMT Changes)

Implications	CAV Market Penetration			
	0%	10%	50%	90%
# Crashes	445,829	413,861	256,111	77,448
# Injuries	232,599	216,099	134,635	42,350
# Fatalities	3,408	3,162	2,036	810
Economic Costs (\$M)	\$19,104	\$17,744	\$11,146	\$3,741
Comprehensive Costs (\$M)	\$83,214	\$77,316	\$48,989	\$17,347
Lives Saved		246	1,372	2,598
Economic Savings (\$M)	-	\$1,361	\$7,958	\$15,364
Comprehensive Savings (\$M)	-	\$5,898	\$34,225	\$65,867

To these estimates, an added *exposure factor* must be applied, to account for the higher levels of VMT and resulting increased collision risk that will be experienced. As previously mentioned, different VMT changes are expected in rural vs. urban areas, and with differing market penetration levels. While urban areas were projected to experience VMT increases of 3%, 12%, and 26% for 10%, 50%, and 90% of market penetration, respectively, in rural areas these same values were estimated at just 1%, 5%, and 9%. This analysis then assumed that increasing VMT as a measure of exposure is directly proportional to the expected number of collisions. The final collision estimates were then achieved by applying these VMT growth factors to the earlier urban/rural crash split shares and merging them with the potential CAV impacts estimated in Table 17.12. From this, Table 17.13 was generated, which summarizes the total estimated potential impact of CAVs on safety in the state of Texas.

Table 17.13 Potential Statewide Crash Implications for CAVs

Implications	CAV Market Penetration			
	0%	10%	50%	90%
# Crashes	445,829	419,901	266,082	83,475
# Injuries	232,599	222,080	148,993	48,401
# Fatalities	3,408	3,224	2,211	955
Economic Costs (\$M)	\$19,104	\$18,020	\$11,932	\$4,292
Comprehensive Costs (\$M)	\$83,214	\$78,575	\$52,590	\$20,024
Lives Saved	-	184	1,197	2,453
Economic Savings (\$M)	-	\$1,085	\$7,172	\$14,813
Comprehensive Savings (\$M)	-	\$4,639	\$30,624	\$63,190
% Reduced Comprehensive Crash Costs	-	5.6%	36.8%	75.9%

When Tables Table 17.3Table 17.6 are taken together, these results indicate that CAVs could potentially save around 185 lives per year on Texas roads, even at the 10% market penetration level. With 90% market penetration, annual motor vehicle crash fatalities could be cut to almost a quarter of their current levels, leading to comprehensive collision cost savings in excess of \$62 billion. Importantly, motorcyclists are expected to comprise nearly half of the remainder of fatal crashes at this market penetration level, with much of the remainder caused by non-CAVs. CAVs will still likely be responsible for collisions, (or even some fatalities, as projected here), though the key takeaway is the magnitude of the tremendous safety potential that CAVs might bring. As with the estimated congestion impacts, readers should remember that these estimates represent order-of-magnitude projections of potential outcomes, and there remains a great deal of uncertainty surrounding the ultimate improvements in safety that will eventually come to pass.

Productivity and Leisure

As drivers are freed from the task of operating their vehicles, they will gain the ability to focus their attention and efforts elsewhere, through relaxing, working, surfing the internet, or engaging in other activities that were previously not possible to do while driving (at least safely). This should therefore result in added benefits stemming from CAVs, in terms of productivity gains and added leisure time for former drivers.

Here, it is assumed that productivity and leisure gains will be realized by the former driver of each CAV based on the time spent previously driving that is now available for other tasks. On average, 335 hours are spent driving per year per Texan, estimated based on Urban Mobility Scorecard data (TTI 2014). From this dataset we obtained each city's daily travel distance (VMT) by freeway and arterial, as well as Travel Time Index, percentage of congested travel (% of VMT), and number of auto commuters. Additionally, we assumed that free flow speed of freeway and Arterial as 70 mph and 30 mph respectively. Using equation (17-2), we can estimate the yearly travel time per Texan:

$$T_i = \sum_i \sum_j \left(\frac{\left(\frac{FFS_j}{VMT_{ij}} \right) \times TTI_i \times PC_j + \left(\frac{FFS_j}{VMT_{ij}} \right) \times PU_j}{c_i} \right) \times 365 \quad (17-2)$$

Where: T = yearly driving time, FFS = free flow speed, VMT = daily travel distance, TTI = travel time index, PC = percentage of congested trip, PU = percentage of uncongested trip, C = number of auto commuters, i = city, and j = freeway or arterial.

Using USDOT guidance regarding personal travel (Endorf, R. 2015), existing values of travel time were assumed to be equal to half the median wage rate (\$16.18 for Texas, BLS 2014), and gains from productivity and leisure were estimated to be 50% of current travel time valuations, consistent with MacKenzie et al. (2014) and Gucwa (2014). This means that each CAV should deliver approximately \$1,357 per year in monetized time benefits to their users.

17.3 Updated Benefit-Cost Analysis

Assumptions

- Due to the expected increases in vehicle-miles-traveled (VMT) due to eventual Level 4 automation, the method assumed a 20% increase in vehicle-miles traveled (VMT) at the 10% CAV market penetration (MP) level. Likewise, a 15% increase and 10% increase in VMT per CAV are assumed at the 50% and 90% MP levels, respectively.
- Since CAVs are eventually expected to travel with smaller headways, effectively increasing capacity, latent demand from this effective capacity increase is also anticipated. Demand elasticities of 0.4, 0.2, and 0.1 are assumed at the 10%, 50%, and 90% CAV MP levels. These assumptions stem from the 0.74 average demand elasticity with respect to highway miles found by Cervero (2001)'s review of literature. It is not expected that demand elasticities with respect to CAV miles driven will be as high.
- There is much debate about the extent to which shared autonomous vehicles (SAVs) will achieve popularity in the future. SAVs will be Level 4 AVs that are owned by transportation network companies (TNCs) or some other entity. It is assumed that half of all CAV trips will be served by SAVs at the 10%, 50%, and 90% CAV MP levels.
- Expected increases in capacity derive from CAVs' use of CACC, which enables each CAV to communicate with other vehicles on the roadway via dedicated short-range communication (DSRC) so that groups of vehicles form with smaller headways than currently observed with human-driven vehicles. Additionally, the method assumed that conventional vehicles were not equipped with a "Here I am" module, which allows CAVs to communicate with and utilize conventional vehicles in the formation of platoons. Thus, benefits were only derived from CAVs using CACC with other CAVs. A base link capacity of 2100 vehicles/hour/lane was assumed for the base case (0% CAV). Effective lane capacity was assumed to increase to 2,150, 2,425, and 3,435 vehicles per lane at the 10%, 50%, and 90% MP levels, respectively. Assumptions made on the increases in lane capacity at the three market penetration levels due to CACC were consistent with the findings of Shladover et al. (2012).
- A flat 10% reduction in delay on freeways was assumed for all three market penetration scenarios during peak and off-peak. This assumption accounted for the combined congestion impacts of freeway traffic flow smoothing, cooperative speed harmonization (CSH), intelligent ramp metering, and other CAV applications.
- For surface streets, arterials, and collectors, delay reduction of 5%, 10%, and 15% were assumed at the respective 10%, 50%, and 90% MP levels. These estimates were consistent with those made by Fagnant and Kockelman (2015b).

Table 17.14 shows crash reduction factors that were assumed for each of the five crash reduction factors is shown below in Table 17.14. Based on the crash reduction factors (CRFs) assumed at the 10% CAV MP level, the collision rates are assumed to be 50% less at the 50% MP level, and 75% less at the 90% MP level.

Table 17.14 Assumed Crash Reduction Factors for CAVs

Crash Factor	Types of Human Error	CAV Market penetration		
		10%	50%	90%
Intoxication	Alcohol, drugs	99%	99.5%	99.75%
Aggressive Driving	Speeding, driving too fast for curve or conditions, erratic operation, illegal maneuver, other prohibited driver errors	90%	95%	97.5%
Distraction & Inattention	Internal and external distraction, inattention	75%	87.5%	93.8%
Judgment Failure	Failure to keep in lane, failure to yield, misjudgment of gap or other's speed, false assumption of other's action	75%	87.5%	93.8%
Performance	Inexperience / over-correction, inadequate surveillance, panic / freezing, sleep, heart attack	66.7%	83.3%	91.7%
Other Factors	All other crashes	50%	75%	87.5%

Of the five factors, if a crash in the FARS database was attributed to more than one of the five factors, the crash factor with the higher CRF was assumed for that crash. This assumption ensured that crashes were not double-counted.

To account for the expected increase in demand resulting from CAV use, the higher levels of VMT were assumed to increase the expected amount of collisions in a proportional manner from the original collision estimates. The researchers assumed VMT increases of 3%, 12%, and 26% for the three respective MP levels in urban areas. Meanwhile 1%, 5%, and 9% VMT increases were assumed in rural areas at the 10%, 50%, and 90% MP levels.

The value of travel time was assumed to be half of the 2014 median wage rate in Texas, which was \$16.18 per hour according to the U.S. Bureau of Labor Statistics (BLS, 2014)

Benefits from productivity and leisure were assumed to be 50% of the travel time.

- Purchase price costs for adding automation and connectivity capabilities were assumed to be \$10,000, \$5,000, and \$3,000 at the 10%, 50%, and 90% MP levels.
- Texas' existing 23.88 million vehicles was assumed for calculating CAV benefits and costs per vehicle.
- An 11.4-year project life and 10% discount rate were assumed. The relatively high discount rate was used to account for the uncertainty in estimating benefits and costs for CAVs. The project life assumption is based on the average life span of a conventional vehicles.

To further improve the method used to estimate benefits and cost implications of CAV use in Texas, parameter assumptions were updated with the results of autonomous vehicle research by UT-Austin. The updates are organized by the sub-sections listed earlier in Section 17.2.

A flat 10% reduction in delay benefits from CAV use on freeways was assumed in the original methodology. Because of the many factors that impact the amount of delay experienced on roadways, this assumption was made on simplistic grounds due to the lack of data and certainty on how CAVs will impact freeway use. Nonetheless, it is expected that CAV use will reap significant mobility benefits, but the magnitude of the benefits at each respective market penetration level is also uncertain. Here, mixed traffic containing both HVs and CAVs was simulated on several freeway networks in Austin. The links in the networks were simulated

using the cell transmission model (CTM). The researchers assessed the impact of CAVs on two city networks in Austin. When only using traditional signals in their networks instead of new alternative methods of intersection management, there was a 26%, 36%, 45%, and 51% reduction in total travel time at the 25%, 50%, 75%, and 100% market penetration (MP) levels. When integrating CAVs into the simulations, the researchers assumed headways of only 0.5 sec for CAVs, which may not be feasible at the lower CAV MP levels due to concerns about liability. Because of various factors that have not been accounted for in simulations yet, the 10% reduction in delay assumption was made to be conservative. Early simulations as performed in the referenced technical memorandum show that some variation in delay reduction should be experienced as CAV market penetration rises. Additionally, since familiarity with CAVs should grow as more CAVs are adopted on the market, it is reasonable to assume that Texans' comfortableness with smaller headways should increase as well. Thus, it is recommended that the flat reduction in delay on freeways be changed to **10%, 15%, and 20%** at the 10%, 50%, and 90% CAV MP levels. The simulations show much larger reductions in travel times using only signals, which show that the new assumptions maintain conservatism. It is expected that fully realized and optimized autonomous intersection management should reap further reductions in delay.

In Section 17.2, a random survey of Texans was conducted. This survey asked the respondents what their willingness to pay (WTP) to save 15 minutes of travel time. After excluding the respondents who answered \$0 WTP, the average WTP of 1,364 Texans was \$9.50. Scaling this value to an hourly basis, the average VOTT was \$27.20/hour. The original methodology used a VOTT of \$16.18/hour, which was half of the 2014 median wage rate for Texas; according to the U.S. Bureau of Labor Statistics. Since the figure was produced from a random sample of Texans, it is more representative of the opinions of Texans on saving travel time than a proportion of the median wage rate. It is recommended that the ***VOTT used in estimating congestion benefits*** from CAV use be ***increased from \$16.18/hour to \$27.20/hour***. It is anticipated that changing the VOTT parameter will increase the estimated benefits from delay reduction.

17.4 Summary Analysis

Analysis results from prior sections of this book may be drawn from in order to summarize the potential impacts of CAVs on the transportation system, across mobility, safety and productivity/leisure dimensions. This may be used in combination with anticipated future costs of vehicle automation, in order to more fully understand the potential impacts of CAVs in Texas.

Here, added purchase price costs for automation and connectivity capabilities (on top of base vehicle costs) are assumed to be \$10,000 at the 10% market penetration level, \$5,000 with 50% market penetration and just \$3,000 in added cost once CAV market penetration levels reach 90%. These values are consistent with estimates from Southwest Research Institute's Steve Dellenback (2012) and Volvo's Erik Coelingh (ETQ 2012). A 10% discount rate is also assumed, which is higher than the 7% rate required for federal TIGER grant applications, to account for the greater uncertainty surrounding CAVs. These cost and discount rate values are consistent with those used in prior research conducted by Fagnant and Kockelman (2015b).

The benefits from CAV were calculated on a per vehicle basis for comparing the cost of automation and connectivity capabilities. In this research, we assumed a baseline of Texas' existing 23.88 million vehicles to estimate these figures, though the true number of vehicles may likely increase along with Texas' population in future years (TxDOT 2014). An 11.4 year average CAV life span was also assumed for calculating net present value, based on current data for conventional vehicles (USDOT 2014). This noted, it is also possible that a substantial number of CAVs may have shorter lifespans, specifically for SAVs which would be used more intensely during any given year.

Table 17.15 summarizes the various safety and mobility benefits that may be gained across Texas' transportation system, while comparing them to anticipated added CAV costs, from an order-of-magnitude perspective:

Table 17.15 Summary of Anticipated CAV Impacts across Texas

Benefits/Costs		CAV Market Penetration		
		10%	50%	90%
Benefits	Congestion reduction (\$/Veh/Year)	\$318	\$159	\$233
	Economic crash savings (\$/Veh/Year)	\$454	\$601	\$689
	Comprehensive crash savings (\$/Veh/Year)	\$1,943	\$2,565	\$2,941
	Productivity and leisure (\$/Veh/Year)	\$1,357	\$1,357	\$1,357
	Sum of benefits (\$/Veh/Year)	\$3,618	\$4,081	\$4,530
Costs	Price of automation and connectivity capabilities (\$/Veh)	\$10,000	\$5,000	\$3,000
Net Present Values (using comprehensive crash cost savings) (\$/Veh)		\$13,960	\$22,024	\$27,000
Benefit-Cost Ratios (using comprehensive crash cost savings)		2.4	5.4	10.0

These results indicate that the introduction of CAVs may have significant potential for delivering significant benefits to the traveling public. Even at just 10% of market penetration, \$13,960 in net benefits would be realized over the 11.4-year life of the CAV, after the \$10,000 cost of automation and connectivity is removed. At all levels of market penetration, comprehensive crash cost savings represent the largest share of benefits, though if only economic costs are assumed, productivity and leisure benefits become most important. With 90% of market penetration, total lifecycle benefits rise to over 10 times the initial added costs of automation and connectivity. Also of note, not all of these benefits would be realized directly by the CAV owner or user.

Some of the crash benefits would accrue to other road users (through reduced risk), and the benefits from congestion reduction effects would be experienced by all motorists.

CHAPTER 18 OTHER FINDINGS AND RELATED WORK

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18.1 Introduction

This chapter includes summaries of other related work that has been published in peer-reviewed journals and/or presented at industry conferences. At the end of each summary is a website address where to find the publication.

18.2 Forecasting Americans' Long-Term Adoption of Connected and Autonomous Vehicle Technologies (Bansal, Kockelman 2017)

Connected and autonomous vehicle technologies (CAVs) are emerging, and may revolutionize the vehicle market, though the infancy of these technologies creates uncertainty about their future. This uncertainty makes it difficult to accurately predict future adoption of these technologies, and previous studies had failed to consider possible variables. Additionally, previous studies had not adequately addressed adoption of level one and two automations, as well as connected technology.

The study presents a simulation-based framework to forecast Americans' adoption levels of CAV technology from year 2015 to 2045 under scenarios that include 5% and 10% annual technology price reductions, 0%, 5%, and 10% annual increase in willingness to pay, and changes in government regulations. For each yearly time step, the simulation modeled each household's vehicle transaction decision using a multinomial logit, followed by decisions on whether to add connectivity and each level of automation. The simulation mostly neglected each household's demographic changes over time. A survey of 2,167 Americans was conducted, and weighted to represent the U.S. population, to calibrate the simulation. The survey gauged Americans' WTP for each technology, as well as vehicle transaction decisions.

Starting prices for level one and two technologies were estimated by analyzing current packages provided by manufacturers. Starting prices for level three and four technologies, as well as connectivity, were estimated from experts' opinions (see Chapter 2, Identifying CAV Technologies, for descriptions of technology levels).

Survey results reveal a willingness to pay (WTP) of \$110 for connectivity, \$5,551 for level three and \$14,589 for level four automation, all among non-zero respondents. It should be noted that a significant number of respondents indicated zero WTP, over 50% for some of the technologies. Additionally, WTP varies widely among non-zero respondents, and the average WTP is lower than the current price for many of the technologies.

The survey also asked for Americans' opinions concerning CAV technologies. Findings indicate that most Americans like driving and believe that they are good drivers. Americans seem to have mixed feelings on AVs, with a small majority believing they are useful, but with significant percentages having reservations about reliability, viewing them as unrealistic, or simply being scared of AVs. Americans are also revealed to be generally hesitant about their vehicle transmitting information. The respondents also reveal that they trust technology companies more than vehicle manufacturers to design AVs.

The simulation predicts market penetration in the year 2045, for a level four privately-held AV fleet, to be 24.8% under 5% annual price drop and constant WTP, but a 10% annual price drop and 10% annual increase in WTP increases penetration to 87.2%. All level one technologies are predicted to have higher than 90% adoption rates by 2045 with at least 10% annual price reduction or 10% annual WTP increase. It is also worth noting is that survey respondents expect to increase their number of long distance trips after they acquire an AV. Government regulation are shown to have a large impact on technology adoption rates, more than doubling them in some cases, and potentially reaching near-uniform adoption. NHTSA's current and probable regulations are expected to result in 98% of the vehicle fleet having ESC by 2025 and 98% having connectivity by 2030. Under all scenarios, level three automation maintains significantly lower adoption rates than level four automation and increases in rates of WTP and price drops further grow the disparity.

The study concludes that people may become more receptive to the technologies over time as they become more normalized, or alternatively, widespread publicity of problems could set adoption of the technologies back significantly. Also noted is that a change in demographics and built-environment may have a significant effect on WTP over time since WTP is typically dependent on these factors. Analyzing these effects, as well as addressing SAVs are suggested as potential future extensions of the study.

Original publication: *Transportation Research Part A* Vol. 95, 2017.

18.3 Assessing Public Opinions of and Interest in New Vehicle Technologies: An Austin Perspective (Bansal, Kockelman, Singh 2016)

In recent history, CAVs are the biggest technological advancement in personal transport, and their introduction could reduce the burden of auto travel, while improving safety, resulting in significant economic savings. Realizing these benefits will be dependent on the public acceptance and adoption of the technologies is necessary for successful implementation.

For this study, an internet-based survey polled 347 adult Austinites from October to December 2014 concerning their opinions on CAV technologies and strategies. The survey was distributed via Austin neighborhood associations, and the responses were weighted using the 2013 American Community Survey's PUMS data to more accurately represent the population of Austin, TX. It is worth noting that Austinites are generally tech-savvy. The results indicate that respondents view crash reduction as the primary benefit of AVs, but are concerned primarily about equipment failure, interactions with conventional vehicles, and affordability. Average WTP was \$3,300 and \$7,253 for level three and four automations, respectively. Older respondents were shown to generally have a lower WTP. While 30% revealed an interest in using AVs as soon as they are available, about half would prefer to see their peers adopt the technology first. Responses indicate that people are generally not willing to pay more for SAV than current TNC prices, though 41% of respondents would use SAVs at least once per week at \$1 per mile, which is lower than current TNC prices. Respondents with greater familiarity with technology have a higher WTP for connected vehicles.

The survey also explored potential residential shifts associated with AV and SAV adoption, arising from the ease of use and the additional time made available for activities other than driving during the ride. The responses indicate that 74% of households expect to remain at their current location after AVs and SAVs become common. It is also worth noting that people may not be as productive in AVs and SAVs as they could be, as respondents indicated that they are most likely to talk or text with friends and look out the window while riding. Among those who do indicate an intention to move, number of kids, having a bachelor's degree, home distance from workplace, employment and household density of neighborhood, and driving alone to work all correlate positively with an intention to shift farther from downtown once AVs and SAVs are available. Urban residents with more awareness of car-sharing and technology may shift closer to downtown. Respondents are more enthusiastic about riding in autonomous mode on freeways, high-speed highways, and congested traffic, than on city streets.

The study estimates effects of demographics, built environment, and travel characteristics on WTP for the technologies, and estimates adoption rates under \$1, \$2, and \$3 per mile pricing scenarios, as well as how the adoption decisions depend on adoption rates of one's peers. It was found that higher-income people, technology-savvy males, people living in urban areas, those who have experienced more crashes, and those who travel more are more willing to adopt AV and SAV technology. Their adoption decisions are less dependent on those of their peers. Increased distance from a respondent's home and work locations also correlated with increased SAV adoption rates.

Suggestions for future work include conducting similar studies in other locations and expanding them to larger areas. This further research is needed to enable stakeholders, to guide the impending transformation of the transportation system in a more effective and efficient manner, as well as to prepare for the impacts of the coming changes.

Original publication: *Transportation Research Part C* Vol. 67, 2016.

18.4 Are We Ready to Embrace Connected and Self-Driving Vehicles? A Case Study of Texans (Bansal, Kockelman 2017)

Bansal and Kockelman (2017) provide an extensive case study on the acceptance of connected and autonomous vehicle (CAV) technologies by Texans. By asking 93 questions, they tackled key questions, such as Texans' willingness to pay (WTP), concerns and adoption of self-driving technologies. A thorough literature review of the case study reveals the extent to which the public is concerned about AVs, with varying

opinions on who is more likely to adopt these technologies. Previous surveys have not been able to analyze the dependencies between responses and factors characterizing the respondent. However, Bansal and Kockelman have been able to estimate econometric models, such as ordered probit and interval regression models, by developing a multivariate relationship between their survey results and the respondent's demographic characteristics and built-environment factors. The correlation is aimed at helping policymakers and officials make informed decisions regarding AVs and CAVs.

The questionnaire asked questions on an array of topics related to CAVs, including WTP, crash history, interest in existing Level 1 & 2 technologies, adoption of carsharing, and home-location shifting decisions. 1,297 responses were obtained, and a thorough cleaning of the dataset left 1,088 data points for analysis. Data was mapped with respondent location using their IP address if their stated address was found to be unintelligible or incorrect. A population-weighted summary of the data points reflects the exposure of Texans to technology and its influence on adoption of CAV technology. Texans are shown to be average drivers based on crash history and moving violation information. The average Texan's WTP for Level 2, 3 & 4 autonomous technology was found to be 2,910, 4,607 and 7,589 USD respectively and nearly 47% of respondents wanted to wait for their friends to first adopt autonomous technology. Nearly 40% believe they would use an AV at least once a month, with 81.5% not willing to change their home-location. Texans answered similarly to the alternative congestion-pricing policies that were asked. Respondents indicate that while using a Level 4 AV they will primarily spend their riding time talking to other passengers, looking out of the window and eating or drinking. As expected, the most concerning factor with the use of AVs was affordability and equipment failure, while lower congestion, lower emissions and better fuel economy were seen as the greatest benefits.

The multivariate relationship for interest in connected or automation technology was modeled using an ordered probit while WTP for these technologies was estimated using an interval regression model. The results were linked to demographic characteristics such as age, annual vehicle miles travelled (VMT), income, and certain built-environment characteristics, such as population density and distance from home to a transit stop. Similarly, adoption of shared autonomous vehicles (SAVs), shifts in home locations due to AVs and SAVs, and public opinion on tolling policies were also modeled, and a multivariate relationship was established.

The work revealed that experienced licensed drivers were more likely to add connectivity. Older people relied more than other age groups on their friends adopting these technologies before adopting them themselves. Supporters of automated speed enforcement were also found to adopt AV technologies earlier than other groups. People living farther from a city center and owning at least one vehicle were more likely to shift their houses closer to their city center to enjoy the low-cost SAVs. As the public's level of future AV use is still largely undetermined, awareness and appropriate pricing policies will be required to accommodate the possible increase in road users.

Original publication: *Transportation* Vol. 44, 2016.

18.5 Effects of Autonomous Vehicle Behavior on Arterial and Freeway Networks (Patel, Levin and Boyles 2016)

Autonomous vehicles (AVs) bring about the possibility of new traffic behaviors including faster reaction times and new intersection control including the tile-based reservation (TBR) system to replace traditional traffic signals. In this paper, simulations are run using a link-based macro-simulation using conflict region modeling in dynamic traffic assignment (DTA) to observe the effects of AVs and TBR on traffic congestion.

In reservation-based systems, vehicles request to move through an intersection at a certain time wirelessly with an intersection manager (it is assumed that only AVs can use TBR technology in this paper). The intersection manager will accept the vehicle's request if it does not conflict with another reservation, and if it does, the intersection manager uses a priority function such as first-come-first-serve (FCFS) priority to resolve the conflict. When simulating large networks for user equilibrium (UE) using DTA however, this model is not tractable and the conflict region model is used. In this model, the tiles are aggregated into conflict regions with capacity as the limitation. A heuristic is applied to the algorithm to make it more tractable for DTA in larger networks. This simulation also follows a multiclass cell-transmission model (CTM) where capacity

and backwards wave speed change per cell-time to propagate flow in the DTA analyses. It is assumed that all vehicles have the same free flow speed. It is also assumed that speed is limited by free-flow speed, capacity and backwards wave propagation. Next we assume a uniform distribution of class-specific density per cell in our cell discretization; however, the densities may change each time step. Finally, we assume a FCFS priority function with the TBR system.

To analyze the effects of AVs and TBR, two arterial networks, three freeway networks, and one downtown network were simulated using the DTA model. These networks are real networks and are considered to be very congested. Simulations were run using different input parameters such as a percentage of network specific demand, AV proportion, and AV reaction times to output travel times including total system travel time (TSTT) and average travel time per vehicle as a metric to quantify congestion. Three main experiments were run on each network on each of four different demand scenarios (50%, 75%, 85%, and 100%). The first experiment served as a base/reference simulation to simulate normal conditions with a traditional signal system and all human driven vehicles (HVs). The second experiment also used traditional signals but 100% AVs. The third experiment implemented the TBR system with 100% AVs. Lastly, a fourth experiment in which the proportion of AVs was increased from 0-1 (in 0.25 intervals) on each network at 85% demand. It is assumed that AVs have a reaction time of 0.5 seconds and HVs have a reaction time of 1 second.

Results showed that increasing the proportion of AVs in every network tested decreased travel times and congestion. This is because the faster AV reaction time results in closer following headways and increased capacity of the roads. The greatest improvements in travel times were seen on the freeway networks as these networks tend to have little to no intersections, resulting in large benefits from increased capacities. Increasing the proportion of AVs to HVs at 85% demand also always decreased travel times. The downtown city network (Austin, Texas) saw a large 51% decrease in travel times due to an AV proportion of 1 at 100% demand.

Results also showed that reservations improved travel times in some networks tested, with a few exceptions. The reservation-based intersections worked quite well in the larger arterial network tested; however, at higher demand, it failed and had higher travel times than traditional signals with 100% HVs. This is most likely due to the close proximity of the road intersections to one another. The close proximity of the intersections most likely caused FCFS fairness to have a higher local road capacity than signals would allow. The TBR may have also created a large queue spillback onto the arterial road, causing travel times to decrease. Of the freeway networks tested, the network with several signals on the freeway (US 290) improved in traffic congestion with faster travel times due to TBR. However, in the other freeways tested with only merge/diverge ramps, TBR either kept travel times the same or increased congestion slightly, most likely due to the fact that the lack of signal delays on the freeways leads to less potential congestion improvement with TBR. However, at higher demands, TBR began to become more effective, improving travel times. Finally, the downtown city network saw a very substantial improvement in traffic congestion due to TBR, including a 78% reduction in average travel times. Although there are many intersections close in proximity to each other in the network, congested intersections might be avoided by dynamic user equilibrium route choice decisions.

Original publication: *Transportation Research Record: Journal of the Transportation Research Board* No. 2561, 2016.

18.6 On Optimizing Reservation-Based Intersection Controls (Levin, Fritz and Boyles 2017)

Along with the introduction of autonomous vehicles (AVs) comes new possibilities for AV intersection control which have the potential to reduce intersection delays beyond optimized traffic signals. The Tile-based reservation (TBR) intersection control system has this potential, however modeling resolutions to conflicting reservation requests such as First-Come-First-Serve (FCFS) using TBR's microsimulation definition on a large network with user equilibrium routing is not tractable. This paper improves on previous models by creating an integer program (IP) that chooses the optimal subset of vehicles to move every time step, and does so in a more tractable manner through a polynomial-time greedy heuristic.

TBR operates on a grid of tiles in space-time that vehicles can occupy, however the grid is simplified using conflict points. Conflict points occur at some point within the intersection space in which two vehicle paths first intersect. It is assumed that these conflict points are fixed because we assume uniform physical characteristics and acceleration behaviors for all vehicles. It is also assumed that vehicles cannot change lanes within the intersection and that vehicles can propagate through two conflicting turning movements simultaneously if the time step is large enough and spacing is adequate. An IP is then formulated using this conflict point transformation. In most simulation-based dynamic traffic assignment (SBDTA) models, vehicles are assumed to complete the entirety of their turning movements within the same time step, which means that instead of constraining vehicle arrival times at each conflict point, the flow at each point can be constrained (a capacity-based restriction). This shifts TBR towards a more DTA aligned model in which speed decreases as density increases, rather than the microsimulation model in which vehicles decelerate to avoid collisions. Once conflict points have been created and assumed to follow capacity-based restrictions, the points can be aggregated into conflict regions for computational efficiency. Conflict regions are likely to be large enough to contain turning movement intersections within their regions, thus assuming incorrectly modeling a conflict between two non-intersecting turning movements is unlikely. Along with this aggregation, lanes are similarly aggregated into incoming and outgoing links, and for general application, we assume that flow between any path is constrained only by sending and receiving flows in the absence of other flow.

The conflict region algorithm finds a feasible solution to the conflict region IP. At each time step, the algorithm records a list of vehicles that are at the front of their lanes (as not to be blocked from moving by other vehicles), waiting to enter an intersection, S . The algorithm then sorts S by some priority function, $f(\cdot)$ and iterates through S until it finds a vehicle, v that is not obstructed by conflict region saturation or receiving flow in the downstream link and can move through the intersection. The vehicle is moved and the vehicle behind v is added to S , which is again being considered for the next vehicle to be moved. Although solving for the IP on a single intersection is easily done, solving many IPs per simulation and simulating a network many times to solve for UE, such as for DTA, is not computationally feasible. Since IPs are generally non-deterministic polynomial-time hard (NP-hard), theoretical results about the conflict region model were derived which solves the IP for the FCFS objective and admits a polynomial-time greedy heuristic. This heuristic greedily selects the vehicle with the greatest efficiency to enter the intersection if their reservation request does not conflict with another vehicle's.

It then demonstrated, using the conflict region IP, the effects of different objective functions with the goal of decreasing intersection delay. To compare objective functions, simulated total system travel times (TSTT) were found through DTA simulation with sending and receiving flows determined by a multiclass cell-transmission model (CTM), and the conflict region IP determining vehicle movement across intersections on the downtown Austin, Texas network. To make the large city simulation more tractable, the developed heuristic was used. Results show that a more general intersection model called Q^2 , which is an objective function to reduce queue sizes, reduced the TSTT by 17.68% compared to the FCFS function. This can most likely be attributed to vehicles in longer queues being given precedence over others, which shortened queues and reduced link travel times. Finally, the conflict region IP was used to control vehicle movement across intersections using an objective function, called ΔE^4 , to attempt to reduce energy consumption. Results show that ΔE^4 reduced energy consumption with better MPG ratings than both FCFS and Q^2 , however ΔE^4 also outputted significantly higher travel times than FCFS (71.35% higher), most likely due to the function giving precedence to less efficient vehicles due to acceleration-deceleration cycles consuming significant energy.

Original publication: *IEEE Transactions on Intelligent Transportation Systems*, Vol. 18, No. 3, March 2017.

18.7 Paradoxes of Reservation-Based Intersection Controls in Traffic Networks (Levin, Boyles and Patel 2016)

This paper is meant to compliment previous studies regarding the effects of autonomous vehicles (AVs) in a tile-based reservation (TBR) system on traffic congestion; however, presented in this paper are three theoretical situations in which the attributes of the first-come-first-serve (FCFS) policy implemented into a TBR system increases delays. Another two realistic networks were then simulated using TBR and observed

to also be outperformed by traditional signals and/or merge/diverge ramps. Finally, a downtown city network is simulated using reservations; however, it shows a contrasting significant benefit in travel time due to the TBR FCFS system.

To simulate the realistic networks presented in this paper, a link-based macro-simulation solving for dynamic traffic assignment (DTA) is used. To allow for a more tractable simulation to be used in DTA with large networks, a conflict region model is used which aggregates the space-time tiles, laid out by an intersection manager at a reservation-based intersection, into conflict regions. The simulation also uses a multiclass cell-transmission model (CTM) to propagate flow in the DTA analyses. The CTM allows for capacity and backwards wave speed to change per cell-time. The paradoxes presented in the theoretical network analyses are primarily due to the fairness of the FCFS system. It is assumed that priority is given to the vehicle with the highest wait time at the intersection. This fairness does not allow for pre-timed signal progression that is seen on an arterial, for example.

In the first theoretical network, an arterial-local road intersection is presented and it is shown that when FCFS alternates priority between the arterial and local road. This alternating priority increases delay to the vehicles on the arterial road, because although the demand is greater on the arterial road, the vehicles on the local road can claim reservations using the FCFS system as long as they request the reservation early enough. This means that the arterial vehicles are delayed by entire time steps due to a small flow of vehicles coming from the local road. Signals timed for progression or for more green time for the arterial road will move vehicles more efficiently. The same concepts apply to the second theoretical network in which FCFS fairness prioritized vehicles on a local road and accepted their reservation request before a platoon of vehicles on the arterial was able to make a request. This interrupted possible progression on the arterial given by a traditional signal and caused a time step of delay for the arterial platoon. Finally, the third theoretical network presented a situation in which FCFS lowered the expected delay of a local road, making demand prefer to take the lower capacity road with less expected delay, however this causes too much demand to shift to the local road, causing arbitrarily long queue lengths and large delays. This is avoided with the use of artificial delay at the local road, causing demand to flow on the arterial only.

The first realistic network tested is an arterial network in which two arterials intersect with local roads intersecting within close proximity of the main intersection. When simulated TBR did worse than traditional signals in almost all demand scenarios except for very small demands as there is less congestion. Most likely, FCFS allowed for vehicles entering from local roads to make reservations, causing delay for the arterial vehicles. With the close proximity of the intersections, there seemed to be queue spillback issues. The second realistic network was a freeway corridor with only merge and diverge lanes. The merge/diverge lanes consistently outperformed the reservations onto the freeway in all demand scenarios, with an especially large difference in travel times in higher demand scenarios. Traditional merge/diverge lanes add flow to the upstream links based on link capacity, and remaining flow given to saturated approaches. On the other hand, the reservation system adds flow to upstream links by order of requests, lowering flow and travel times across all demand scenarios. Finally, the downtown city network (Austin, Texas) was simulated using TBR assuming a FCFS system; however, the results presented a great benefit to travel times across all demands. At 70% demand, a 58.4% decrease in travel times is seen compared to traditional signals; however, with an increase in demand, travel time tends to not decrease as much due to intersections reaching large capacities in which TBR cannot continue to help at the same rate. This significant decrease in travel times can be attributed to the large number of alternate route choices, fixing problems such as queue spillback found in the first realistic network tested. More testing with reservation systems on asymmetrical intersections as well as testing on large networks such as the downtown city grid with a combination of reservations and signals at strategic locations can be helpful in optimizing the reservation-based intersection control system.

Original publication: *Transportation Research Part A* Vol. 90, 2016.

18.8 A Multiclass Cell Transmission Model for Shared Human and Autonomous Vehicle Roads (Levin and Boyles 2016)

With the emergence of connected and autonomous vehicles and other transportation technologies such as reservation-based intersection control, there is potential to improve link and intersection behavior. Simulation-based modeling becomes increasingly important in studying these behavioral changes. The degree of these changes will depend on the proportion of autonomous vehicles in the network and to model this shared road behavior, Levin and Boyles (2016) develop a multiclass cell transmission model (CTM) that admits variations in capacity and backwards wave speed. The model is then adapted to a simulation-based dynamic traffic assignment (SBDTA) model and tested on a city network to observe shared road conditions.

When developing the multiclass extension of CTM, a few assumptions must be made. We assume that all vehicles travel at the same speed, a uniform distribution of class-specific density per cell, an arbitrary number of vehicle classes and that backwards wave speed is less than or equal to free flow speed. In this multiclass CTM, links are discretized into space time cells with a length allowing a vehicle at free flow speed to traverse one cell in one time-step. Each vehicle class has a class-specific density and a class-specific flow, the latter of which is a function of the speed possible with different class proportions. This speed is limited by free flow speed, capacity, and backwards wave propagation. Levin and Boyles showed that the flow of class m from cell i to $i + 1$ is restricted by three factors: class-specific cell occupancy, proportional share of capacity, and proportional share of congested flow. This transition flow is consistent with hydrodynamic theory.

To compute the cell-time specific capacity and backwards wave speed, a kinematic-based car following model was presented to predict the speed-density relationship as a function of reaction times of multiple classes. Unlike other greatly-simplified car following models used with macroscopic level traffic, this model builds from the collision avoidance theory of Kometani and Sasaki (1959) to predict allowed following headway for a given speed at different reaction times. The inverse relationship gives speed as a function of the headway, determined by density. A triangular fundamental diagram is then produced, displaying the flow-density relationship as a function of reaction time. This car following model predicts how reduced reaction times might increase capacity and backwards wave speed. The car following model is then also expanded for heterogeneous flow with different vehicles having different reaction times by using vehicle class proportions and class-specific densities. With this expanded model, a new fundamental diagram scaling with the proportion of AVs with a certain reaction time is formed and it is seen how with increased proportions of AVs, capacity and backwards wave speeds increase as well.

Because a shared road model is developed and it is desired for mixed classes of traffic such as AVs and HVs to be able to use reservation-based intersection control (TBR). TBR can reduce delay with the presence of 100% AVs, however it is not clear of which control to use for shared roads. To incorporate HVs into the TBR system, in which a vehicle reserves space-time tiles with an intersection manager, the allotted trajectory's safety margins can be increased for HVs to allow them to use the infrastructure. This was proposed by Bento et al. (2013) as the LEMITM policy. To tractably model the TBR system on a large-scale network at the mesoscopic level, Levin and Boyles (2015) previously developed a conflict region model which determines vehicle movement restrictions through an intersection based on the capacity of each conflict region the vehicle passes through during its turning movement. This altered conflict region model requires two modifications to the original control algorithm to accommodate the TBR/LEMITM policy. First, the movement of a non-AV from a sending link to a receiving link requires available capacity for all possible turning movements because the intersection manager does not know the vehicle's destination. Second, when the human driven vehicle's reservation is accepted, space for all possible turning movements from the sending link must be reserved.

Finally, two experiments using the developed multiclass CTM and the TBR/LEMITM policy were conducted using a custom DTA software. The first experiment involves a simple four link, single lane intersection to determine how TBR/LEMITM affects intersection delay as the proportion of AVs increases. Results show that as the AV proportion increased from 0%-60%, the average travel time per vehicle decreased linearly with the proportion of AVs. Results also showed that from 70%-100% AVs, little to no change in travel times was observed. This is due to the increased capacity of the intersection (due to reduced reaction times and closer following headways of AVs) being sufficient enough to handle all demand. In the second experiment, the multiclass CTM and TBR/LEMITM are incorporated into a DTA model to study the predictions of the shared

road model with dynamic user equilibrium (DUE) routing. Convergence was measured using the average excess cost (AEC) measure and computation times of 18 minutes and lower were observed (50 iterations). It was also observed that the larger the proportion of AVs, the faster the computation time because the vehicles exited the network faster than with lower AV proportions. When comparing TBR/LEMITM with traffic signals, it was seen that after 80% AVs, the total travel time of the network was lower with the TBR/LEMITM compared to the signals.

18.9 Effects of Autonomous Vehicle Ownership on Trip, Mode, and Route Choice (Levin and Boyles 2015a)

Because autonomous vehicles (AVs) will most likely significantly change traveler behavior and network congestion with the introduction of ideas such as empty repositioning trips, reduced reaction times and other AV-specific behaviors, it is important to incorporate them into planning models. In this paper, Levin and Boyles (2015) develop a multiclass four-step model including AV repositioning and increased link capacities to model the effect of AVs on demand and route choice. Mode choice involving AVs is analyzed using a nested logit model, and network congestion is analyzed using a static traffic assignment model.

Because there is a lack of AV owner behavior and improvements in network capacity, a few assumptions are made regarding traveler behavior and capacity. These assumptions include using a four-step planning model, AV drivers having the option of parking (with a parking fee) or sending their vehicle back to the origin (repositioning while incurring fuel costs, travelers seeking a minimized generalized cost of time, fuel and tolls/parking fees, and the use of an STA model. In model development, the travel time function that incorporates the reduced headways associated with AVs was based on the well-known BPR function. Because AV reduced headways will increase capacity, a capacity function based on Greenshields' speed-density relationship and an increasing jam density function of the proportion of AVs are developed under reasonable assumptions. Based on Greenshields' relationship, capacity is a linear function of jam density which can be used as the "capacity" in the BPR function, making the BPR function a linear function of jam density as well. The jam density is then assumed to be a function of AV proportion, allowing for the simulation of reduced reaction times and AVs.

A generalized cost function incorporating travel time, fuel consumption, and toll/parking costs is also required for modeling AVs. The value of time (VOT) is important as it converts time traveled to a monetary unit and is different for each traveler, so discrete VOT classes were specified. For an AV, the vehicle can make a one-way trip with parking or a two-way repositioning trip back to its origin. The one-way trip will incur costs of time traveled, parking (and possibly tolls), and fuel consumption. The repositioning trip will incur the costs of the one-way trip without the parking and add on the fuel consumption of the trip back to its origin. A fuel consumption function, found by Gardner et al. 2013 was used and found to be monotone decreasing with speed and therefore monotone increasing with travel time. This was converted into money through an assumed price of gasoline and into a generalized cost per link using the link's length and travel time. Finally, the cost of transit is found using a VOT as well as transit fees.

Static traffic assignment like that in this paper, due to its multi-class nature of AV and non-AV vehicles, has been demonstrated to not always be convex meaning that multiple equilibria can exist. This along with the somewhat arbitrary nature of multiple discrete VOT classes may push the STA formulation towards non-convexity even farther. This issue, however, is common to all multiple discrete VOT class models and later numerical results show that using the Frank-Wolfe algorithm as a heuristic for the formulation's VI converges to an equilibrium. Optimal and unique convergence was not the main focus of this paper.

To incorporate AV round-trips into a planning model, the commonly used four-step model was modified. The AV four-step algorithm assumed the first step of the four-step process, trip generation which outputs productions and attractions between zones, to be known. The next three steps (trip distribution, mode choice, and traffic assignment) were performed in a feedback loop for convergence. Trip distribution outputs total person trips per origin-destination pair and VOT class based on travel costs. Mode choice determines the mode-specific trips per class by splitting the total person trips using a nested logit model on utility of each mode. Constants such as an AV preference constant for benefits such as having a vehicle parked at the destination for immediate departure capabilities are included. Choices include parking with an AV,

repositioning with an AV, and using transit. The traffic assignment model then takes in these outputs and finds routes for all vehicle trips, assuming a user equilibrium (UE) behavior. The trip distribution and mode choice steps can then take in the travel costs from the assignment, update, and then feed back into the traffic assignment step. The method of successive averages (MSA) is used for the four-step feedback loop to improve convergence.

The multiclass four-step model was tested on the Austin downtown sub-network. Bus routes were included for transit options and a walking speed was included per link for travel to bus zones. VOTs ranged from 1.15 to 22, parking costs were estimated at \$5.00 per day, transit costs were \$1.00 and fuel cost was set at \$3.00 per gallon. These unit costs remained fixed, however in reality the transit and parking costs may decrease to compete with the reduction in demand. Because it was assumed that travelers with a higher VOT (higher income) were more able to afford AVs, experiments chose a certain number of VOTs with the highest values to use autonomous vehicles. Empirical results showed that the Frank-Wolfe heuristic method for solving UE converges to an equilibrium. Several effects of AVs increasing roadway capacity and of the introduction of AV round-trips were seen. As the proportion of AVs increased, transit demand decreased due to the reduction in transit utility is primarily due to the lower cost of AVs. When few AVs are present and mostly available to the upper classes (a small portion of the population), transit demand is still high as a majority of low VOT travelers choose transit. However, as AVs become more available to middle-lower classes of VOT, the rate of decrease of transit demand is much greater with the model overall predicting a 61.4% reduction in transit ridership due to lower AV costs for low VOT travelers. Also, AV round-trip demand reached 83% of all personal vehicle demand at full market penetration, contributing a shift of 39592 trips. This shift along with an increase in total demand for any personal vehicle mode from 23500 to 47676 trips presented a total increase of 271.4%. Many of these additional trips were traveling away from downtown, but even with the significant increase in link volumes, average speed decreases were modest, showing that AV increases in capacity substantially offset the increased demand.

18.10 Intersection Auctions and Reservation-Based Control in Dynamic Traffic Assignment (Levin and Boyles 2015b)

Connected and autonomous vehicle (CAV) technology is maturing, and with it, a promising tile-based reservation (TBR) intersection control policy proposed by Dresner and Stone offers a potential improvement to intersection capacity beyond optimized traffic signals. Reservation control also allows for the integration of vehicle movement prioritization such as intersection auctions. TBR has been modeled but only in micro-simulation models, and not under user equilibrium conditions. To model it under UE and further understand TBR vehicle routing behavior, Levin and Boyles implement TBR in dynamic traffic assignment (DTA) using a computationally feasible model for larger city networks.

The TBR system takes advantage of the computer precision and communication abilities of AVs to move vehicles through an intersection. TBR works as such – Vehicles request permission from the intersection controller to move along a specific path in space-time. The intersection controller divides the intersection into a grid of space-time tiles to check whether vehicle paths will collide, accepting or rejecting requests depending on the occupancy of the tiles at a requested time. Different priority functions can be used to organize vehicle requests, the most basic of which is the first-come-first-serve (FCFS) prioritization. Since modeling this control on a large DTA network is computationally infeasible, a conflict region (CR) model is presented.

The CR model divides an intersection into regions which are much larger than TBR's individual tiles and assigns each conflict region a capacity which can change every time step. Each vehicle on its source and destination link path consumes a proportion of the conflict region capacity found by the ratio of conflict region capacity to flow from the source to the destination link. Intersections are divided into conflict regions through the radial division of a circle at the center of the intersection. The circle is divided by radii along incoming and outgoing link angles. The CR model solution method uses an algorithm that first sorts vehicles on each incoming link by when they entered the link. Then, the vehicles at the front of each link's queue (the minimum of the number of lanes or sending flow) are added to a unique set (one per incoming link). These sets are then organized by some priority function, such as FCFS. The highest priority vehicle is chosen in a set and if there is sufficient capacity in all conflict regions along the vehicle's trajectory and if the receiving flow of the destination link is sufficient, move the vehicle. Once the vehicle is moved, the capacities of conflict regions

in the vehicle's path and the receiving flow of the destination link are all reduced. If the sending flow of a link has more vehicles, the earliest arrival time vehicle is added to the unique set of eligible to move vehicles as the moved vehicle is removed from it.

To validate the use of such a CR model, a single intersection experiment was conducted using the new model to be compared with micro-simulation model results from Fajardo et al. 2011 . The intersection tested was a simple four approach, symmetric intersection with four square conflict regions with a 10 second time step. Results from a maximum demand with mostly through traffic experiment showed an average delay of 0 seconds (all vehicles that reached the end of the intersection moved through in the next time step) compared to the 0.67 second delay per vehicle in the micro-simulation. The same was seen from the left-turn experiment where most demand was involved in left turns. The CR model reported a delay of 0 seconds compared to the 0.69 second delay from the Fajardo et al. 2011 micro-simulation experiment. Since this model is built on capacity-restricted tiles and capacity is determined by incoming and outgoing links, it is a reasonable approximation of TBR.

The CR model was then implemented into a link transmission model SBDDTA with a 10-second time step to analyze the impact of auctions on travel time under user equilibrium behavior. The goal of the paper was to show the benefits of a simple first-price auction scheme and how they occur using the user equilibrium principle and a larger network. The auction scheme worked by prioritizing bidding vehicles based on the highest bid, in which a vehicle would choose a bid for itself once it reached the front of its lane (and vehicles behind the first vehicle choose bids for that front vehicle when subsidized bidding is permitted). Bids were assumed to be each vehicle's value of time (VOT) which were chosen from the Dagum model of 2008 U.S. income distribution with mean \$22.02 and with intervals of \$5. Because higher-VOT vehicles may experience lower delays, VOT was included in a modified shortest path algorithm. The method of successive averages (MSA) algorithm was used to solve user equilibrium so exhibit the computational tractability of SBDDTA with the CR model. Results show that, after running the downtown Austin, Texas network, an average of 18.5 seconds per iteration (for 50 total iterations) was required, indicating being solved in a reasonable amount of time. The auction scheme was then tested using the mentioned models on the Sioux Falls, South Dakota network. Little benefit was observed for auctions with subsidies, in which vehicles could bid for vehicles queued ahead. Without subsidies, auctions greatly reduced time spent traveling (on average 495.9 seconds of reduced travel time) in contrast to FCFS because it reduced queue lengths and congestion on the links. FCFS resulted in a congestions queue, on average, of 58.1 vehicles and auctions reduced that to 30.2 vehicles. Auctions did not provide much benefit, however, to favoring high-bidding vehicles but reduced travel times similarly for all vehicles. This CR model can be used for other, more elaborate testing involving for instance, the effects of TBR vs. traffic signals under UE behavior.

18.11 Economic Effects of Autonomous Vehicles (Clements and Kockelman 2017)

Autonomous vehicles (AVs) are becoming increasingly viable as a widespread technology and may soon dominate the automotive industry. Once the technology is sufficiently reliable and affordable, it will gain greater market penetration, generating a significant economic ripple effect throughout many industries. This chapter synthesizes and expands upon analysis from multiple reports on the economic effects of AVs across 13 different industries and the overall economy. Industries include automotive, technology, freight movement, personal transport, auto repair, medical care, insurance, law, infrastructure, land development, digital media, police, and oil and gas. AVs will also generate significant time and safety savings, which will benefit citizens everywhere.

AVs will be central to the automotive industry, with software making up a greater percentage of vehicle value and hardware percentage value falling, an effect that technology companies will capitalize on. Additionally, vehicles purchased could be decreased by vehicle sharing within families or shared transport systems but could also be increased by the new market of children, elderly, and disabled independent occupants. The freight transportation will likely be the first to implement AV technology, and could gain \$100-500 billion annually due to increased efficiency with conveying, decreased need for drivers, and increased overall drive time while any occupant is free to complete other activities. Personal transport could see a large shift to shared

autonomous vehicle fleets (SAV), threatening the business of taxis, buses, and other forms of public transportation.

Fewer collisions due to smarter vehicle operations will lower demand for auto repairs, medical, insurance, and legal services because over 90% of crashes are caused by human error, which AVs would not commit. The U.S. collision repair industry could lose \$15 billion annually, while the medical industry could lose \$12 billion annually. Personal insurance policies will become more limited while corporate policies for auto manufacturers and vehicle software providers will become more important. The auto insurance business could shrink as much as 60%, representing a \$108 billion decrease in a \$180 billion industry. A decrease in personal claims could result in \$3 billion in losses for the legal profession, but this could be counterbalanced by an increase in tort claims.

Traffic police are likely to become less needed, and this could reduce ticket revenues for municipalities. Infrastructure provision increases in effective roadway capacity could cause a 10% reduction in infrastructure investment, saving around \$7.5 billion per year, but more advanced infrastructure will be needed. AVs and SAVs can reduce parking demand, saving up to \$45 billion in freed land, which could be repurposed for housing, office buildings, or parks, possibly increasing urban density. However, the easing of commutes by decreasing of congestion and by the available free time in as an occupant in an AV could increase urban sprawl. Additionally, with occupants as a captive audience, digital media may generate as much as \$14 billion in additional revenue if just 5% of commute times are spent on the internet.

The decrease in crashes and increase in efficiency with the connection of AVs will work to reduce traffic congestion, while a potential increase in VMT could work to counter to this. Estimates from the Center for Urban Transportation range from 22% to 80% increases in highway capacity, based on 50-100% market penetration of fully automated vehicles. However, VMT is expected to increase by around 10% due to an increase in accessibility for children, elderly, and disabled citizens and greater repositioning distance traveled by SAVs. Additionally, the increase in productivity due to the ability to work in the car during commutes could save over 2.7 billion unproductive hours, generating savings of \$447.1 billion per year. Additional possible savings from AVs include \$488 billion from collision costs, due to the value of physical damage and lives saved. The total economic value of the 13 major industries affected along with safety and time savings adds up to approximately \$1.2 billion. Change is coming, and we must be prepared to adapt in order to thrive in the developing economic landscape. Table 18.1 summarizes economic impacts on safety and industry sectors.

Table 18.1 Summary of Economic Effects (Industry and Economy-Wide)

Economy-Wide Effects				
Savings	-	Dollar Change in Industry (billions)	-	\$/Capita
Productivity	-	\$448	-	\$1,404
Collisions	-	\$488	-	\$1,530
Economy-Wide Total	-	\$936	-	\$2,934
Industry-Specific Effects				
Industry	Size of Industry (billions)	Dollar Change in Industry (billions)	Percent Change in Industry	\$/Capita
Insurance	\$180	\$108	60%	\$339
Freight Transportation	\$604	\$100	17%	\$313
Land Development	\$931	\$45	5%	\$142
Automotive	\$570	\$42	7%	\$132
Personal Transportation	\$86	\$27	31%	\$83
Electronics & Software Technology	\$203	\$26	13%	\$83
Auto Repair	\$58	\$15	26%	\$47
Digital Media	\$42	\$14	33%	\$44
Oil and Gas	\$284	\$14	5%	\$44
Medical	\$1,067	\$12	1%	\$36
Construction/Infrastructure	\$169	\$8	4%	\$24
Traffic Police	\$10	\$5	50%	\$16
Legal Profession	\$277	\$3	1%	\$10
Industry-Specific Total	\$4,480	\$418	9%	\$1,312
Collision Value Overlap	N/A	\$138	N/A	\$432
Overall Total	N/A	\$1,217	N/A	\$3,814

Note: Green = Industry Gain Red = Industry Loss \$/per capita and Total: All values added due net economic/consumer benefit

18.12 Summary

In this chapter, an overview of current research has been discussed, including topics such as opinions on CAVs and new vehicle technologies in America, Texas, and Austin; the effects of autonomous vehicle behavior on arterial and freeway networks; optimization and paradoxes of reservation-based intersection controls; a multiclass cell transmission model for SAV and AV roads; effects of AV ownership on trip, mode, and route

choice; intersection auctions and reservation-based control in dynamic traffic assignment; and economic effects of AVs.

CHAPTER 19 RECOMMENDATIONS AND BEST PRACTICES

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19.1 Introduction

Smart-driving technologies are changing the landscape of transportation. Significant mobility, safety and environmental benefits are anticipated from these technologies, which enable safer and more comfortable driving in general. However, in order to realize the maximum potential benefits for regional, statewide, and national transportation systems, these technologies alone are not enough. Rather, policymaking and innovation in infrastructure and operations strategies, become crucial.

A series of conclusions and recommendations were developed and presented across preceding chapters, which go deeply into the traffic and safety impacts of C/AVs. In addition, a series of specific recommendations for transportation stakeholders were developed based on legal analyses, and crash and safety assessments made.

Research presented here provides ideas and equipment for more efficient intersection, ramp, and weaving section operations for CAV operations, alongside a suite of behavioral and traffic-flow forecasts for regions and networks under a variety of vehicle mixes (smart plus conventional, semi-autonomous versus fully autonomous, connected but not automated). One chapter provides rigorous benefit-cost assessments of multiple strategies that transportation agencies may pursue to bring smarter, safer, more connected, and more sustainable ground transportation systems to regions, states and nations, in concert with auto manufacturers, technologists, and the traveling public. Such efforts support proactive policymaking on vehicle and occupant licensing, liability, and privacy standards, as technologies become available and travel behaviors change.

Chapter 4's results suggest that advanced CAV technologies may reduce current U.S. annual crash costs, by over \$390 billion per year, including pain and suffering damages, and other non-economic costs. These U.S.-based results rely on the three different effectiveness scenarios with a 100% market penetration rate of all CV- and AV-based safety technologies.

Of the eleven safety applications discussed in Chapter 4, the one with the greatest potential to avoid or mitigate crashes, but not yet on the market, is *full automation* of one's vehicle. A currently available technology, automatic emergency braking (AEB), also offers substantial safety rewards, with an estimated economic savings of \$23.5 to \$100 billion each year, assuming full adoption across the U.S., along with and current crash counts. Among the CV-based safety applications, cooperative intersection collision avoidance systems (CICAS) is estimated to offer the greatest economic and comprehensive cost savings. Overall, AV-based technologies are expected to offer far more safety benefits than CV-based technologies, as expected, since automation proactively avoids human errors during travel, rather than simply warning human drivers about possible conflicts.

There is little doubt that various CAV technologies will offer significant safety benefits to transportation system users. However, the actual effectiveness of these technologies will not be known until sufficient real-world data have been collected and analyzed.

Chapter 14 notes that parking provision is a principal factor in shaping the form and character of downtowns everywhere. Although a major goal of many cities is to create sustainable, pedestrian-oriented downtown districts, the lack of many well-connected, frequent, and popular transit routes and transit-supportive land use patterns across cities like Austin, Texas require that adequate levels of automobile parking continue to be provided in this particular case study until there are more viable alternatives. SAVs may be the breakthrough that cities like Austin seek, though their overall impacts (on travel distances, location choices, and traffic congestion) remain to be seen.

Chapter 17 suggests a balanced perspective regarding investment prioritization for intelligent transport strategy to ultimately yield the best and most equitably distributed safety, mobility and other socially beneficial outcomes. Local needs and anticipated potential for improvement should drive the project application selection process, while also considering funding availability. Finally, pilot roll-outs for these applications may be used to better understand the actual benefits that may be realized before more broad-based applications are implemented, while also helping local transportation agencies to understand the pitfalls and keys to future deployment success.

As Chapter 18 concludes, AVs will eventually become pervasive, or at least hold a large share of the automotive market, it is assured that they will have a strong economic impact, potentially as much as \$1.3 trillion or more. In order to prepare for this revolution, we must be aware of the potential effects so that we can alter our established systems to accommodate these changes. Change is coming, and we must be prepared to adapt.

19.2 Specific Recommendations for Transportation Agency Headquarters and Divisions

Shaping Legislative Policy on CAVs

There is a great deal of uncertainty regarding the current position of state and federal laws concerning CAV use. Various organizations and OEMs (original equipment manufacturers) are researching and developing CAV technologies, but there is little oversight on the extent to which CAVs can be tested and operated for private use on roadways. Though taking no legislative action is a possible option, being proactive in shaping policy will help reap the potential safety and operational benefits expected of CAVs to a greater extent and at a faster pace. Some of the legislative policies that departments of transportation (DOTs) should urge their legislatures to address include:

Creating a single agency point person, situated within each DOT, who has authority and credibility to coordinate among various state and local agencies. This point person should have a minimum respectable number of years of experience at a transportation agency, preferably at division or district deputy level. Such persons assist in ‘preparing government’ for the transition to this new driving paradigm. The agency should have department attorneys or general counselors appoint a staffer to assist these point persons, and to provide a liaising link to the Attorney General’s office for clarification on any state- or federal-level legal issues.

Other recommendations include: ensuring that the legal definition of “operator” is commonly understood based on established legislation, setting standards for testing and development of CAVs, establishing rules for intensive use of truck platooning, addressing privacy and security questions stemming from CAV use, answering liability questions that arise from CAV adoption, and advancing broader public goals in CAV innovation.

The following are short-term, mid-term, and long-term practices recommended to governing agencies in preparing for all levels of CAV adoption. While short-term practices are immediately relevant, the process of considering mid- and long-term practice adoption should also begin preemptively in order to maximize positive outcomes on transportation system safety and efficiency.

Short-Term Practices (within the next 3 years)

Appoint a CAV point person, who has authority and credibility as the agency's point person on CAV issues, challenges, outreach and education.

Establish a working group to: coordinate and provide to the Legislature technical advice as well as recommendations for legislative policymaking and legislative changes; oversee continuing research and testing needed to assess the technically feasible and economically reasonable steps for the DOT to pursue over time, with emphasis on those actions that will encourage early CAV market penetration. This working group should create and update annually a CAV policy statement and plan; and coordinate CAV issues with AASHTO, other states, Transportation Research Board (TRB) committees, the Department of Motor Vehicles, and the Department of Public Safety.

Stakeholders should establish and lead a team to: oversee research and testing on additional or changed traffic control devices and signage that will enhance the operations of CAVs and reduce liability issues; coordinate with industry in the short term on basic items that are proving challenging in CAV development and deployment, such as sensor-compatible lane striping, road buttons, and machine-readable signage. This team should monitor and oversee development of cooperative intersection collision avoidance system technology and assist in test deployments on highways and major arterial roads as well as cooperative-adaptive cruise control and emergency stop device deployment and assess what steps the transportation agency will need to take to assist in extending and translating this technology into throughput, such as improved platooning on trunk routes.

Stakeholders should establish and lead a team to:

Develop and continuously maintain a working plan for facilitating early adaptors of CAV technology, in particular the freight and public transportation industries. This group should identify and begin planning with MPOs for the impacts of expected additional VMT driven by CAV adoption, particularly for assessing impacts on conformity demonstrations in non-attainment areas of the state; Finally, begin assessment for and development of a series of the DOT-recommended VMT management and control incentives for responding to the likely CAV-induced VMT increases; and monitor and assess the impacts of SAVs on the department.

Mid-Term Practices (within the next 13 years)

The department-wide working group should continue to:

Develop and maintain the plan for non-CAV vehicle support and the CAV policy plan. Simultaneously, the team should annually update any operations during the transition to CAVs; coordinating CAV issues with AASHTO, other states, TRB committees, the Department of Motor Vehicles, and the Department of Public Safety; and provide to the Legislature technical advice as well as recommendations for legislative policy.

Stakeholders should:

Continue research and testing for CAV-enabled smart intersections, expanding from off-road test facilities to actual intersections; Initiate research and testing for CAV-appropriate lane management operations, initially for platooning and CAV-only lanes. Also, stakeholders should expand CAV-compatible traffic control device research and testing specific to construction zone, detour, and nighttime operations; and begin updating the various transportation manuals that will be impacted by CAVs.

Following this, they should:

- Research, test, and recommend incentives (for example, micro-tolling, time of day operations restrictions, etc.) for the control of congestion as well as increased VMT induced by CAVs;

- In coordination with PTN and local governments, assess the impact of CAVs in public transportation operations, leading to recommendations appropriate to the Department's goal of congestion relief; and
- Begin research and testing of area-wide traffic demand management operations made possible by CAV technology.

Long-Term Practices

Regional transportation agencies should continue to:

Create and annually update the CAV policy statement and plan and the plan for non-CAV vehicle support and operations during the transition to CAVs. Also, agencies should coordinate CAV issues with AASHTO, other states, TRB committees, the Department of Motor Vehicles, and the Department of Public Safety and provide to local governing bodies technical advice as well as recommendations for legislative policy making. Finally, transportation stakeholders should continue steps needed to identify the optimal traffic demand management strategies that are economically feasible and environmentally compliant, giving particular thought to centralized and automated allocation of routing and timing, as well as required use of SAVs operated to minimize VMT.

While smart-driving technologies have the power to change and enhance transportation, proper levels of government involvement now and into the future are needed to realize a greater potential for benefits. Benefits not only extend to operational safety and efficiency, but they also bear significant economic implications. Involvement of governing agencies, including legislative and transportation departments, comes in the form of policies and innovations in infrastructure. Economic implications include the private development and marketing of in-vehicle technologies, reductions in safety liability, changes in freight transportation costs, and improved personal productivity. As the future emerges, data should be collected internationally on all of these aspects to better inform ongoing policy and operational decision making in efforts to achieve continued benefits.

Summary

This chapter has explored a number short, mid, and long-term legally-focused recommendations regarding implementation of connected and autonomous vehicles. Transportation stakeholders, including local transportation agencies will play a large role in the acceptance and usage of automated vehicle technology. We hope that the insights supplied in this chapter and others may prove useful.

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