ROAD INFRASTRUCTURE READINESS FOR AUTONOMOUS VEHICLES

by

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Dedicated to my uncle Professor Gul Mohammad, my parents, my siblings,
and all my outstanding professors and mentors who
were instrumental in my professional
upbringing and nurturing.

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LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
AV	Autonomous Vehicle
BL	Binomial Lattice
CBD	Central Business District
DCF	Discounted Cash Flow
DfC	Design for Changeability
FHWA	Federal Highway Administration
HDVs	Human-Driven Vehicles
ODD	Operational Design Domain
INDOT	Indiana Department of Transportation
IOOs	Infrastructure Owners and Operators
MaaS	Mobility-as-a-Service
MCS	Monte Carlo Simulation
MP	Market Penetration
NPV	Net Present Value
ROA	Real Options Analysis
SMMA	Small- and Medium-sized Metropolitan Areas
SPM	Stakeholder Participation Model

ABSTRACT

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Contemporary research indicates that the era of autonomous vehicles (AVs) is not only inevitable but may be reached sooner than expected; however, not enough research has been done to address road infrastructure readiness for supporting AV operations. Highway agencies at all levels of governments seek to identify the needed infrastructure changes to facilitate the successful integration of AVs into the existing roadway system. Given multiple sources of uncertainty particularly the market penetration of AVs, agencies find it difficult to justify the substantial investments needed to make these infrastructure changes using traditional value engineering approaches. It is needed to account for these uncertainties by doing a phased retrofitting of road infrastructure to keep up with the AV market penetration. This way, the agency can expand, defer, or scale back the investments at a future time. This dissertation develops a real options analysis (ROA) framework to address these issues while capturing the monetary value of investment timing flexibility. Using key stakeholder feedback, an extensive literature review, and discussions with experts, the needed AV-motivated changes in road infrastructure were identified across two stages of AV operations; the transition phase and the fully-autonomous phase. For a project-level case study of a 66-mile stretch of Indiana's four-six lane Interstate corridor, two potential scenarios of infrastructure retrofitting were established and evaluated using the net present value (NPV) and ROA approaches. The results show that the NPV approach can lead to decisions at the start of the evaluation period but does not address the uncertainty associated with AV market penetration. In contrast, ROA was found to address uncertainty by incorporating investment timing flexibility and capturing its monetary value. Using the dissertation's framework, agencies can identify and analyze a wide range of possible scenarios of AV-oriented infrastructure retrofitting to enhance readiness, at both the project and network levels.

1. INTRODUCTION

1.1 Background

The emerging era in transportation, characterized by new transportation technologies such as autonomous vehicles (AVs), will require significant transformations in infrastructure planning, design, and operations (TRB, 2014; AASHTO, 2018; AVS, 2018; FHWA, 2018). AVs are classified by the National Highway Traffic Safety Administration (NHTSA) as vehicles that operate at an autonomy level of 5 (NHTSA, 2016). These include vehicles that can operate in any operational design domain (ODD) without assistance from a human driver. AVs are expected to revolutionize road transportation (TRB, 2014; Johnson, 2017; FHWA, 2018). However, it is believed that the safety and mobility benefits of AVs will not be realized fully until the road infrastructure is ready to support their operations (Johnson, 2017). There are complexities associated with various operational conditions including driving in different ODDs such as in snow or at night, correctly interpreting traffic signs and control devices that are non-uniform across states, and sensing poor road surface and faded pavement markings for lane keeping. These challenges can be overcome through carefully planned and adequate infrastructure readiness. However, the currently poor state of road infrastructure is not only an impediment but also exacerbated by limited resources and funding uncertainties. Clearly, the existing infrastructure faces serious challenges in terms of its readiness to accommodate AVs (Johnson, 2017; Young, 2017).

The current literature is replete with research related to the impacts of AVs on travel behavior, operations, city planning, emissions, energy use, safety, and land use (Duarte and Ratti, 2018; Soteropoulos et al., 2018; Gandia et al., 2019; Gkartzonikas and Gkritza, 2019). However, the impacts of AV operations on highway infrastructure have not been studied adequately and rigorously (TRB, 2014; Labi et al., 2015; Saeed et al., 2015; Johnson, 2017). As such, transportation agencies at different levels (federal, state, city, and other local jurisdictions) are generally not sufficiently informed or prepared to make the needed investments in their physical infrastructure to accommodate this new technology. However, these agencies must start preparing for the emerging era of autonomous vehicles (Bamonte, 2013). The existing infrastructure is designed and built to meet human driving capabilities and information needs. As they grapple with their infrastructure preparedness for AVs, transportation agencies are struggling with several critical questions:

- Which highway infrastructure changes are required to support AV operations and when are these investments needed?
- Will market penetration drive the infrastructure preparedness? If yes, what is the minimum AV market penetration for initiating the retrofitting of infrastructure?
- What will be the market penetration trends in the future?
- Which infrastructure management practices including the minimum levels of regular roadway maintenance, will be required to promote AV operations?
- To what extent, should human-driven and autonomous vehicles be allowed in the same or different lanes?
- What are the major sources of uncertainty in efforts to prepare infrastructure for AVs?
- Finally and most importantly, how will agency expenditures and revenues change, and what will AV-related infrastructure retrofitting mean in terms of public investment?

Against the background of questions such as mentioned above, there exist varied perceptions regarding the possible impacts of AV operations on highway infrastructure. Silberg et al. (2013) expect AVs to transform the existing highway infrastructure in a way that could save the United States a large portion of the $7.5 billion that it currently spends annually on roads, highways, bridges, and other related infrastructure. The authors argue that such savings will be due to a reduced need for new infrastructure, a considerable reduction in infrastructure monitoring costs due to the road condition assessment and reporting capabilities of sensor-based AV technologies, and reduced need for additional lanes or right-of-way due to increased capacity with AV operations.

Recently there has been increased discussion about the poor readiness of the existing highway infrastructure to accommodate AVs. McFarland (2015), Sage (2016), Tracy (2017) and KPMG (2018) considered infrastructure one of the major hurdles to the deployment of AVs on existing roads. This such poor infrastructure readiness is mainly attributed to the poor condition of the aging road infrastructure. The U.S. Department of Transportation (2016) reports that about 65 percent of U.S. roads are in poor condition, and the U.S. transportation infrastructure system was rated 12th in the World Economic Forum's 2014–2015 global competitiveness report (Schwab and Sala-i-Martin, 2014). The state of U.S. roads is directly relevant to the proper functioning of the AVs' sensor-based technology and this issue received media attention when a driverless car failed a test drive in Los Angeles due to poor lane markings (Sage, 2016). In another incident, a Tesla running on autopilot, deployed on a stretch of concrete road on Interstate 405 in Los Angeles, failed to recognize the lanes because there were two sets of lane markings angled at slightly different directions and the lanes were separated by a seam (McFarland, 2015).

The currently poor state of road markings, inconsistent signage, and the prevailing across-state inconsistencies in the design of the U.S. three million miles of paved roads are considered major hindrances to the AV deployment. The 2018 Autonomous Vehicles Readiness Index compiled by KPMG (2018) rated the United States seventh (of all the developed countries) in terms of its infrastructure readiness to host AVs. These concerns have been echoed by automakers and technology developers as they have found the existing infrastructure to be unsuitable for AV navigation (Sage, 2016). These shortcomings could motivate AV manufacturers and software developers to introduce more sophisticated sensors and maps. These include the 2017 luxury E-Class Mercedes-Benz's steering pilot feature, which has 23 sensors used for detecting barriers, guardrails, and other vehicles, and for keeping the vehicle in its lane even where lane markings do not exist (Thompson, 2017). However, such increased technological sophistication could have major cost implications for vehicle purchasers and could therefore impede market penetration.

1.2 Problem Statement

Research needs regarding the readiness of existing infrastructure to host AVs continue to be identified (TRB, 2014; AASHTO, 2017; Johnson, 2017; AVS, 2018; FHWA, 2018). At the 2014 Automated Vehicles Symposium in San Francisco, "Road infrastructure needs of connected-automated vehicles" was listed as a broad topic with immense research gaps (TRB, 2014). In a report titled "Readiness of the Road Network for Connected and Autonomous Vehicles," Johnson (2017) noted the lack of research efforts on road infrastructure readiness for AVs and commented that "research on the infrastructure requirements of CAVs is in its infancy." He pointed out several important issues related to road infrastructure readiness, including the implications of various AV implementation scenarios for the condition of roadway infrastructure and its maintenance needs; the reciprocal relationship between road infrastructure and AVs and the associated uncertainties of this relationship; the very small likelihood that AVs will reach their full potential if infrastructure is inadequate; and the potential for the greater use of sophisticated technology-based types of infrastructure may lead to a significant increase in maintenance costs, which should be duly considered in future research studies on AV-oriented highway infrastructure investments.

Moreover, the American Association of State Highway and Transportation Officials (AASHTO, 2017) published a research need on infrastructure requirements for AVs, highlighting the urgency to study the preparedness of infrastructure for AVs, the necessary modifications to the existing infrastructure, and the infrastructure challenges associated with a mixed stream of traffic consisting of both AVs and human-driven vehicles (HDVs).

Since very little has been done regarding the preparedness of road infrastructure to accommodate AV operations on roadways, highway agencies at all levels of government (federal, state, and local) seek to understand the infrastructure changes that would be required at different levels of AV market penetration. Many unresolved questions regarding the necessary infrastructure changes are further exacerbated by uncertainties surrounding the pace and state of the technological development of AVs, the rate of user adoption of AVs after their commercial deployment, and the road infrastructure requirements to accommodate AVs.

Given these multiple sources of uncertainty, highway agencies appear to be hesitant to make significant investments pertaining to AV-oriented infrastructure readiness (FHWA, 2018). Their hesitation is understandable, considering the constantly evolving nature of AV technology, the limited resources of highway agencies, and funding uncertainties. Nevertheless, regarding infrastructure preparedness, transportation agencies should rather be proactive. This is mainly because adequate infrastructure modifications could play a critical role in fueling AV market penetration. This AV market penetration will drive agency decisions related to road infrastructure/supply regarding renewing, rightsizing, upgrading, expansion, or modernizing, for example, the addition of a new travel lane in the case of growing AV traffic demand. Infrastructure investments at the agency level are traditionally justified based on user demand.

Based on the aforementioned discussion, the problem statement can be summarized as follows:

1. There is a need to identify AV-related infrastructure changes that may occur during the transition phase (with roads hosting both AVs and HDVs) and the fully autonomous era (roads with AVs only).
2. The AV-oriented infrastructure readiness and related investment decisions should account for the uncertainty associated with AV market penetration and incorporate timing flexibility to facilitate phased infrastructure retrofitting.

In view of the uncertainty surrounding autonomous vehicle operations, AV-related infrastructure investments made for existing roadways today or during the design of new roadway systems should be flexible enough to respond to unforeseen and uncertain futures, particularly, the levels of AV market penetration over time. This timing flexibility should be reflected in all AV-oriented infrastructure investment decisions made by transportation agencies. Traditional value engineering is unlikely to capture and quantify the monetary value of this flexibility and, therefore, may result in decisions that may be optimal at the inception year but not over the lifetime of the infrastructure change. Real options analysis (ROA) identify the latent value of projects, which is not attainable using the traditional economic evaluation approach. By adopting ROA that captures the flexibility and latent value, transportation agencies can make more robust and reliable investment decisions that are optimal over the entire lifecycle of the road infrastructure and ensure that design modifications facilitate AV road operations as need (demand) arises.

1.3 Objectives of the Dissertation

Given the aforementioned problem statement, the objectives of this dissertation are listed below:

1. Identify the types of changes that may be needed for road infrastructure at the two stages of AV operations: the transition phase and the fully autonomous phase;
2. Develop a framework to facilitate phased infrastructure retrofitting, incorporate uncertainty into AV-related infrastructure investment decisions and to capture the monetary value of investment timing flexibility;
    - This framework could function as a planning roadmap that transportation agencies may use as a point of reference for initiating AV-oriented infrastructure investments.
3. Propose policy guidelines for transportation agencies in the context of AV-related readiness.

1.4 Organization of the Dissertation

The dissertation proceeds as follows. Chapter 2 presents a discussion on the key concepts of autonomous vehicle operations, the different stages in the implementation of AV operations, and the complementary roles of the key stakeholders. Chapter 3 identifies various sources of uncertainty associated with AV operations and suggests ways to deal with them. It also contrasts the traditional value engineering approach with ROA, both of which are implemented later in the dissertation. Chapter 4 introduces the main framework of this dissertation for transportation agencies to make AV-oriented infrastructure readiness decisions. Chapter 5 focuses on the first step of the framework, namely how the stakeholder perspectives can be taken into account in the decision-making process. Chapter 6 discusses the changes that road infrastructure may undergo at different points in time during the different stages in AV implementation. Chapter 7 explores and estimates the impacts on road users and agencies of different AV-oriented infrastructure changes during the early transition phase, followed by an overall economic evaluation of these impacts, including the application of ROA approach to capture the value of investment timing flexibility. The economic impact analysis is demonstrated using a case study at the freeway corridor level. Chapter 8 concludes the dissertation with a summary of the major findings, key policy recommendations, main contributions, and recommendations for future work.

2. AUTONOMOUS VEHICLES: KEY CONCEPTS

2.1 Introduction

This chapter explains the key concepts and phenomena related to AV operations. The various levels of vehicle autonomy/automation defined by the International Society of Automotive Engineers (SAE) (2014; revised in 2016) and the NHTSA (2016) are presented in this chapter, followed by a discussion on the different stages of AV operations. Moreover, the key stakeholders and their complementary role in actualizing AV operations are discussed in detail. A Stakeholder Participation Model (SPM) is presented to illustrate how feedback from different stakeholders will inform AV-related infrastructure planning and retrofitting at the agency level. The role of each stakeholder is clearly illustrated.

2.2 Levels of Vehicle Autonomy

In the United States, SAE International (2016) and the NHTSA (2016) have established an official classification system comprising the following six levels of vehicle autonomy/automation:

1. Level 0 (No Automation: “Humans drive it.”) – A human driver completely controls the vehicle at all times.
2. Level 1 (Driver Assistance: “Hands on the wheel.”) – The vehicle is driven and controlled by a human driver; however, an automated feature in the vehicle can assist the human driver in some aspects of the driving task.
3. Level 2 (Partial Automation: “Hands off the wheel, eyes on the road.”) – An automated feature in the vehicle partially performs the driving task while the human driver performs the rest of the tasks and monitors the driving environment.
4. Level 3 (Conditional Automation: “Hands off the wheel, eyes off the road – sometimes.”) – An automated system installed on the vehicle can partially perform the driving task and monitor the driving environment in some instances, but the human driver must be ready to take back control upon the request of the automated system. In certain conditions, the driver can fully cede control of all safety-critical functions to the vehicle; the vehicle senses when conditions require the driver to retake control and provides sufficient time for a comfortable transition.

5. Level 4 (High Automation: “Hands off, eyes off, mind off – sometimes.”) – An automated system can both perform the driving task and monitor the driving environment, and the human rider/driver is not required to take back control, but this automated system operates only in certain environments and under certain conditions.
6. Level 5 (Fully Autonomous: “No steering wheel”) – An automated system in the vehicle performs all driving tasks under all conditions that a human driver can. In this dissertation, the term “autonomous vehicles” refers to vehicles at level 5 automation. The terms “autonomous vehicles,” “driverless vehicles,” and “self-driving vehicles” are synonymously used in this dissertation.

AVs are equipped with sensor-based technology that uses cameras and artificial intelligence-based image detection algorithms to develop (and interpret) in real-time, a three-dimensional characterization of the physical environment within which the vehicles operate. The successful operation of AVs depends partly on the nature and efficacy of vehicle-to-infrastructure (V2I) communication. The potential safety implications of V2I communication include red light violation warning, curve speed warning, stop sign gap assist, reduced speed zone warning, spot weather information warning, stop sign violation warning, railroad crossing violation warning, and oversize vehicle warning (Harding et al., 2016). Other applications include warnings for hazardous situations (such as congestion, accidents, or obstacles), merging assistance, intersection safety, speed management, rail crossing operations, priority assignment for emergency vehicles, traffic jam notification, prior recognition of potential traffic jams, dynamic traffic light control, dynamic traffic control, and connected navigation (ETSI, 2011; Kenney, 2011). The terminal level of this communication protocol is termed vehicle-to-everything (V2X), which is based on the exchange of information with all elements in the vehicle’s surroundings. V2X communication includes vehicle-to-vehicle (V2V), V2I, vehicle-to-pedestrian (V2P), vehicle-to-device (V2D), and vehicle-to-grid (V2G).

V2X is deemed essential and critical for fully autonomous operations. The European Telecommunications Standards Institute (ETSI) and SAE International have identified the early-stage potential applications of this technology (ETSI, 2011; Harding et al., 2011; Kenney, 2011; SAE, 2016). Some of the basic road safety applications of V2X communication include forward collision warning, lane change warning/blind spot warning, emergency electric brake light warning, intersection movement assist, emergency vehicle approaching, road works warning, and platooning. The effectiveness of this technology is not expected to reach its full potential until all vehicles on the roadway are equipped with this technology (Ma et al., 2009; Yoshida, 2013).

2.3 Stages of Autonomous Vehicle Operations

This dissertation defines the two main stages of AV operations as follows:

a. Fully autonomous - All vehicles on the road are at Level 5 autonomy.
b. Transition phase - A mix of vehicles, including traditional (operated by human drivers, i.e., Level 0 autonomy), automated (Level 1 to Level 4 autonomy), and autonomous (Level 5 autonomy), co-habit the roadways.

It is certain that fully autonomous operations (when all vehicles on the road are at autonomy Level 5) will not happen at once but will occur incrementally over some period. This period is called the transition phase (Figure 2.1) and the process is expected to be incremental in terms of technology maturation, infrastructure modifications, and road user adoption. During this transition period, roadways are expected to host a mix of vehicles, including traditional (operated by human drivers, i.e., Level 0 autonomy), automated (Level 1 to Level 4 autonomy), and autonomous (Level 5 autonomy), until a time when all vehicles on the road are fully autonomous (steady-state), i.e., at Level 5 autonomy. The transition from the current non-autonomous phase to fully autonomous operations is expected to take place over a period that may involve near-, mid- and long-term decision-making points with reference to the base state (all vehicles at Level 0 autonomy) of non-autonomous operations. The timing of these infrastructure retrofitting decision-making points will be defined by the user adoption of AVs and hence, the market penetration rates. Figure 2.1 presents a schematic diagram depicting the transition phase (the Y-axis refers to the market penetration of Level 5 vehicles, and each step refers to an incremental increase in the market penetration of AVs over time). As such, the more current times depict the near-term of the transition phase, where the market penetration of Level 5 vehicles is in its infancy. These vehicles are only being tested for commercial use, whereas vehicles at Level 1 and Level 2 autonomy are currently operating on the roadways.

There are different untested hypotheses regarding the length of this transition phase. A study by IHS Automotive (2014) expects the entire global fleet to be fully autonomous by 2050. Litman (2014) suggests restricting human driving after 2060 if the impacts of AVs are beneficial. The CEO of Tesla, an automotive industry giant, suggests prohibiting the use of traditional human-driven vehicles after there is widespread use of AVs and their superiority in terms of safety is evidenced on public roadways (The Guardian, 2015). However, the switch from human-driven to autonomous vehicles cannot be expected to be completed in a short period. Kyriakidis et al. (2015), in a survey of 5,000 respondents from 109 countries, found that 69% of respondents estimate a 50% market share for NHTSA-defined Level 4 vehicles between now and 2050. A study by Saeed et al. (2018) found that during the transition phase, 68% of respondents from small- and medium-sized metropolitan areas would prefer to continue using their traditional vehicles over self-owned, hired, or shared use of AVs.

It is obvious that not all market segments will be willing to give up their traditional vehicles right away. As such, the nature of the shift to AV operations is still uncertain. However, many believe that the transition to steady-state fully autonomous era will be an evolutionary process that is expected to be dynamic and that will lead to increasingly smart vehicles and infrastructure, ultimately resulting in a fully driverless era. An important question that still needs to be answered is the nature of AV market penetration trends. A variety of predictions have been made about the timing of AVs' diffusion into the mainstream market, their initial autonomy levels versus the need to maintain some driver control, and the effects of their introduction and deployment into the current mix of vehicles on the roadways (Advocates for Highway and Auto Safety, 2017).

Currently, it is not obvious whether prospective users of AV technology can fully comprehend the wide range of capabilities that this technology offers for making transportation safer, more efficient, more accessible and responsive, and better able to support mobility needs (Abraham et al., 2016). Prospective users also do not have a clear understanding of the complexity associated with the various levels of autonomy. Moreover, they do not often perceive risk and uncertainty in an unbiased way. The prerequisite for developing trust in technology is the ability to predict its effects, and, to date, it has not been possible for users to predict the actual behavior and performance (both the merits and demerits) of this technology. The outcomes of any perception study conducted in the absence of actual market penetration are highly reliant on the respondents' current perceptions about the state of the technology and anticipated AV operations in the future. However, the results of these studies are expected to change over time as respondents gain more awareness of the technology, its potential, emergence patterns, and expected implementation scenarios and, more importantly, as respondents personally experience the use of AVs once they are available for public use. Potential users' perceptions are likely to be negative whenever news about an AV crash during test deployment is highly publicized. These perceptions will likely become stable with cognizance of the impacts (both positive and negative) that this technology might have based on travelers' personal experiences. User trust is expected to rise over time as users witness AV operations on roadways (The Economist, 2018).

An important question in the context of transportation agencies is what the transition phase means for road infrastructure. Current road infrastructure is designed to serve a traditional (human) driving environment. With increasing AV operations, there will be a need for infrastructure that serves a mixed stream of automated (Level 1 to Level 4 autonomy), autonomous (Level 5 autonomy), and human-operated vehicles and, eventually, infrastructure that serves a fully autonomous vehicle fleet. Given the rate of technological development and its associated uncertainties and the limited resources and funding limitations of transportation agencies, the retrofitting of roadway infrastructure can be expected to be incremental and stepwise. This retrofitting will need to be proactive rather than responsive because it will have implications for consumer acceptance of AVs.

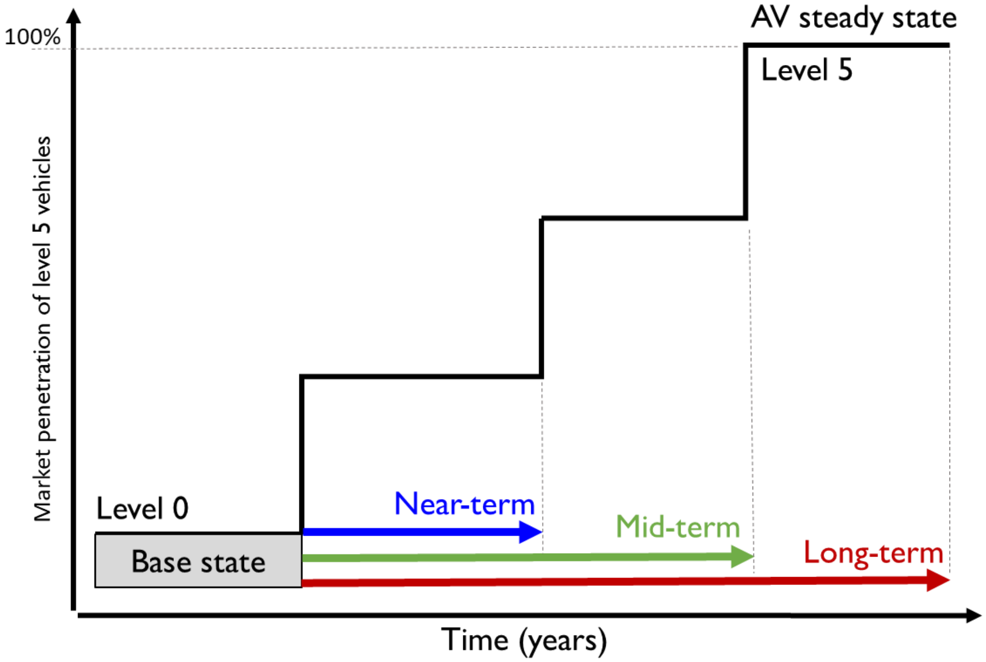


Fig. 2.1 Depiction of transition phase as defined in this study

2.4 Key Stakeholders and their Role

It is expected that the successful development and deployment of AVs will be driven by decisions made by three key stakeholders (Figure 2.2): road users (prospective consumers or users of this technology and those who will drive their traditional vehicles but share the road with AVs), industry (technology developers, vehicle manufacturers, and service providers), and government agencies responsible for infrastructure readiness, regulations, and policy formulation. The roles of all stakeholders are complementary in nature; in other words, their individual efforts are expected to complement one another and, hence, contribute towards the realization of AV operations.

Road user acceptance and, hence, demand is critical to the successful deployment of AVs (Heide and Henning, 2006). Among several other challenges associated with automated driving, there is a need to address public perceptions (Howard and Dai, 2014). Dennehy (2018) recommends addressing consumers' concerns and fostering public acceptance before accommodating AVs on existing roadways. The demand for AV technology emanates from road users, and, as such, it is important to understand their individual attitudes regarding this technology. The needs of road users must be met, and their concerns addressed; otherwise, the AV implementation may be delayed, as noted by Fagnant and Kockleman (2015). To address these concerns, investigating user acceptance of this technology at every phase of its development and deployment is critical for at least four reasons: it will ascertain the extent to which users will embrace this technology, thereby defining demand; it will govern agencies' decisions regarding investments and policies toward AV operations; it will determine how technology developers design these systems and make adjustments to capture users' feedback and address their concerns; and finally, it will help define how vehicle manufacturers market AVs.

It is expected that while the stride and scale of AV market growth will be driven by consumer demand, the anticipated societal benefits cannot be reached until a critical mass of consumers accepts and uses this technology. Government agencies may mandate the use of AVs in certain areas, which could accelerate AV market penetration. However, the timing of AV deployment and the state of AV technology are still unclear and uncertain. Moreover, any measures from government agencies, such as promoting the use of AV-oriented ride-hailing or ridesharing services or restricting the use of private cars or banning them from certain areas, could be unpopular (The Economist, 2018). That is why it is important to keep road users involved in the entire process of transitioning to AV operations. In a national dialogue on highway automation held by the Federal Highway Administration (FHWA, 2018), one of the key outcomes was the need to actively involve road users and include their insights into decisions regarding AV-related infrastructure preparedness at the federal level. However, it remains unclear how to proceed in this vein. More direct and closer communication and interaction among all the stakeholders will help overcome the challenges associated with AV operations.

The existing literature is replete with public perceptions regarding AV adoption potential based on several factors, including individuals' behavioral characteristics, travel time, and cost. However, their preferences and intentions regarding AV adoption have not been fully investigated in relation to road infrastructure modifications. If the government does not mandate or proscribe the use of this technology, the rate of AV market penetration is expected to depend on market forces (NAE, 2018). However, the situation is not as simple as it seems. The deployment of AVs involves a complex blend of vehicle technology, information technology, highway users, and infrastructure systems. The lifecycles and investment horizons of these systems and related technologies often differ completely from each other.

Because of the extreme uncertainty surrounding the pace and state of technological development of AVs, the rate of user adoption of AVs after their deployment, and road infrastructure requirements, transportation agencies are hesitant to make significant investments pertaining to AV-oriented infrastructure readiness. This is understandable given the evolving nature of AV technology and the limited resources and funding uncertainties of highway agencies; however, the role of transportation agencies regarding infrastructure preparedness should be proactive. This is mainly because adequate infrastructure modifications will play a critical role in fueling market penetration. As such, rapidly evolving AV technology presents a strong motivation to revitalize infrastructure in the future transportation ecosystem.

Equations (2.1) through (2.4) are presented to illustrate the endogeneity and simultaneity of the roles of key stakeholders. All of the efforts made in the context of readiness for AV operations are expected to be highly interrelated, endogenous and cross-consequential, and will be evidential of the complementary role of the key stakeholders in the realization of AV operations.

Rate of change of road transport system = f (rate of change of road infrastructure, rate of maturation of AV technology, rate of user acceptance of AV technology) (2.1)

Rate of change of road infrastructure = *f* (rate of maturation of AV technology, rate of user acceptance of AV technology) (2.2)

Rate of maturation of AV technology = *f* (rate of change of road infrastructure, rate of user acceptance of AV technology) (2.3)

Rate of user acceptance of AV technology = *f* (rate of change of road infrastructure, rate of maturation of AV technology) (2.4)

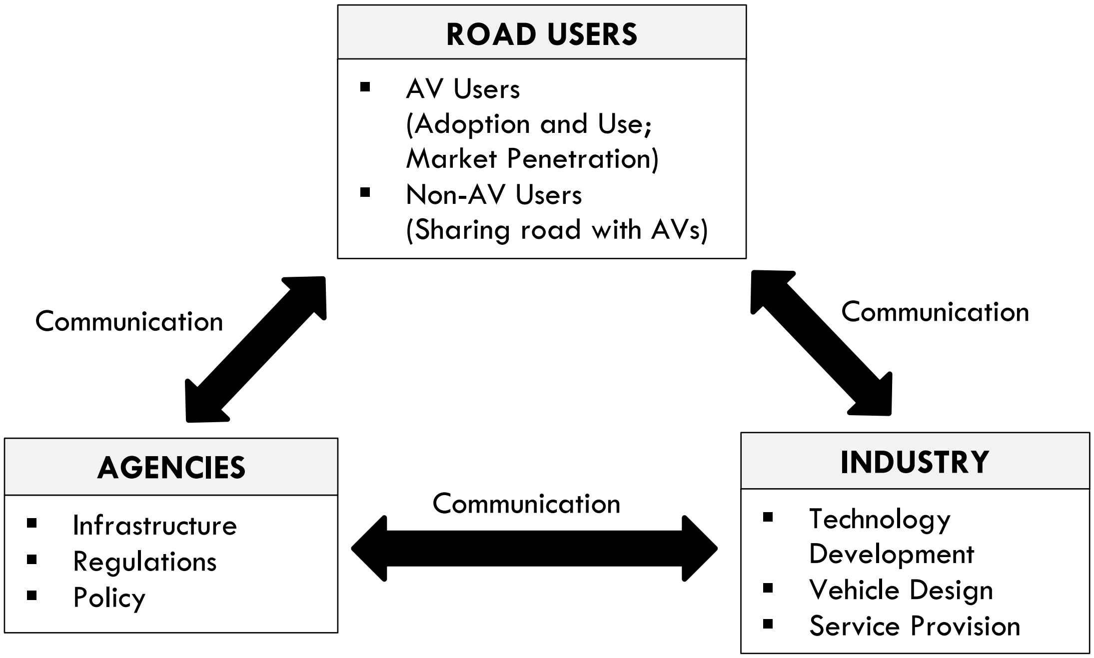


Fig. 2.2 Schematic depiction of key stakeholders and their respective functions

2.5 Stakeholder Participation Model (SPM)

While the complementary roles of key stakeholders in realizing AV operations are described in the previous section, how, when, and what changes should be made to road infrastructure are still open questions. To this end, Figure 2.3 presents the Stakeholder Participation Model (SPM) that conceptualizes the entire process of transitioning to fully autonomous operations while clearly illustrating the role of each stakeholder. The model demonstrates how feedback from different stakeholders will inform AV-related infrastructure retrofitting at the agency level. The SPM necessitates acquiring input from key stakeholders (i.e., road users, infrastructure owners and operators, and technology developers) and sustained information sharing among them to help identify adequate infrastructure needs. The model depicts the complex endogenous and interdependent relationships and multi-directional simultaneous interactions among key stakeholders. Strong feedback effects may arise among functional elements (technology development, policy formulation, user adoption, market penetration, infrastructure modifications, and regulations) during the transition to AV operations.

As Figure 2.3 suggests, the industry is leading the technology development efforts. However, demand is defined by the end-users of this technology. As is traditional for transportation agencies, demand informs agency decisions regarding the development of new and the expansion of existing systems. Therefore, transportation agencies need to keep track of AV demand estimates. Currently, the best available tool to gauge user demand for AVs is a survey questionnaire. For example, if a city agency seeks to know the anticipated level of demand for AV technology, it should collect information on public opinion and potential AV adoption through surveying a representative sample of the city's population, as recently done by the Puget Sound Regional Council (2017) and the California Energy Commission (2017).

Moreover, during the transition phase, there will be two types of road users: those who use AVs in some form (self-owned, hired, or shared) and those who continue to drive their own or to use traditional vehicles in some form. The feedback from both non-AV users and potential early adopters of AVs is important at the current time. While surveying may help establish initial demand estimates by identifying early adopters, the feedback from non-AV users also has obvious consequences for infrastructure modifications. During the transition phase, agencies will seek to develop and maintain a roadway environment that is compatible with and friendly to both types of road users. As such, non-AV users could be surveyed about their comfort level with sharing the road with AVs while driving their traditional vehicles. Their perspectives could be collated for subsequent consideration in agency decisions regarding AV-oriented road infrastructure (for example, whether to separate AVs from other vehicles through an exclusive lane for AVs and whether to protect the AV exclusive lane using barriers or similar devices).

Furthermore, information collected through survey tools can be leveraged to investigate the user acceptance and potential effectiveness of various alternative infrastructure retrofitting strategies under consideration at the agency level. For example, surveys could help investigate how road user comfort level might change across various retrofitting options (e.g., the provision of an exclusive lane for AVs versus the provision of an exclusive lane for automated heavy vehicles). A similar question could be, During the initial deployment of autonomous vehicles on freeways, which of the following roadway design changes would elevate your trust and comfort level regarding a highway operating environment that includes AVs? Possible responses could include (a) a dedicated lane for driverless vehicles; (b) a dedicated lane for automated trucks, with other lanes shared by traditional and autonomous vehicles; and (c) no change is necessary.

Carefully designed and calibrated surveys could serve as useful and effective tools for facilitating agency decision-making related to highway infrastructure modifications. Such tools could help capture the road user insights, thus facilitating their inclusion in the decision-making process. This is considered important and necessary (FHWA, 2018). However, until AVs actually appear on the road in significant numbers and survey respondents have personal experience with the technology, public preferences cannot be captured with certainty. Consequently, surveys should be conducted periodically to feel the market pulse and any fluctuation thereof. As implied in Figure 2.3, it is expected that infrastructure modifications will have implications for the adoption and acceptance of AVs. These infrastructure changes, if adequate, may likely fuel the market penetration of AVs by encouraging their increased use; if inappropriate, these changes could potentially lead to a waste of public funds and also impede AV market penetration. Furthermore, this entire process of transitioning to a new era of infrastructure needs to be regulated through a set of regulations and driven by policies issued by government institutions.

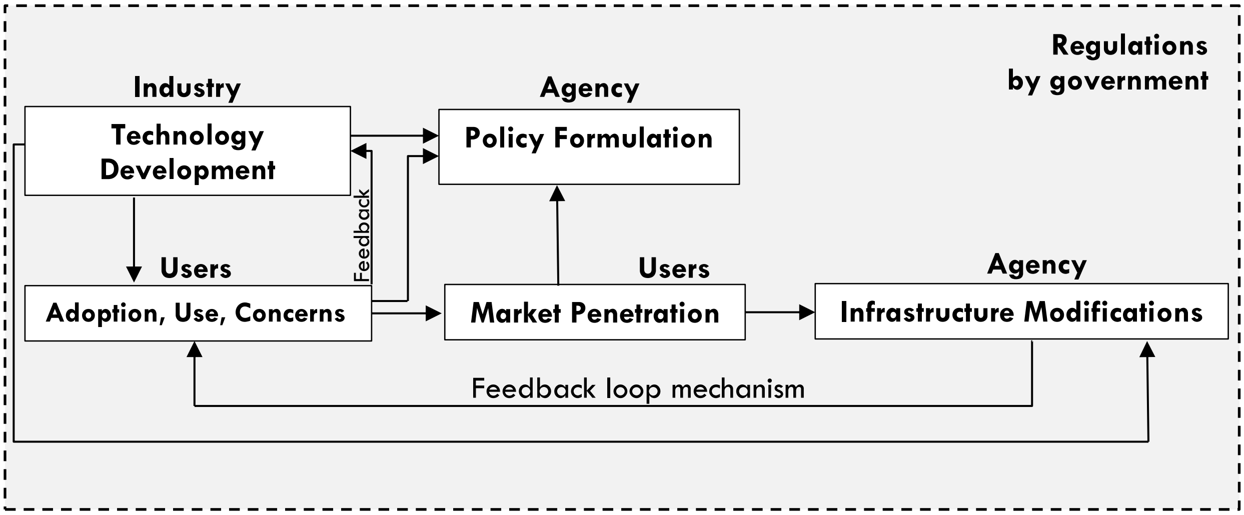


Fig. 2.3 SPM for AV-oriented infrastructure retrofitting

2.6 Chapter Summary

This chapter reviewed the levels of vehicle autonomy and identified two main stages of autonomous vehicle operations: the transition phase and fully autonomous operations. The AV transition phase was deemed to be more critical of the two stages due to the complexity associated with user demand and infrastructure preparations during this era. The key stakeholders and their complementary roles were also reviewed in detail, and prospective mathematical relationships were presented to describe these roles. A Stakeholder Participation Model was introduced to conceptualize the entire process of transitioning to autonomous vehicle operations and clearly explain the role of each stakeholder. The next chapter identifies the major sources of uncertainty associated with AV operations and discusses ways to respond to these uncertainties.

3. ECONOMIC EVALUATION AND ADDRESSING THE UNCERTAINTIES ASSOCIATED WITH AV OPERATIONS

3.1 Introduction

The previous chapter addressed the key concepts, stakeholders, and phenomena related to AV operations. The present chapter identifies the various sources of uncertainty associated with the era of AVs. These uncertainties are then discussed in the context of their implications for the timing and types of AV-oriented infrastructure changes. This chapter also discusses how highway agencies can account for some of these uncertainties in their infrastructure investment decisions. Then the merits, demerits, and applicability of traditional value engineering and real options approaches are discussed in the context of AV-related infrastructure investment decisions made by agencies.

3.2 Sources of Uncertainty

The types of uncertainties associated with AV operations can be broadly categorized as known uncertainties and unknown uncertainties. The first category includes the uncertainties associated with technology maturation rate, the user acceptance rate, and the safety and operational performance of AVs on existing roadways in different operational design domains. Other contributors to the known uncertainties include future changes in economic activity, travel, and demographics. Although the extent to which AVs will increase or decrease the amount of travel is uncertain, it is certain that any increase in the amount of roadway travel is expected to have impacts on pavement quality and asset deterioration rates and hence the agencies' repair schedules and expenditures. Both positive and negative impacts can be expected, but it is more difficult to discern the nature and direction of the net impacts (Labi et al., 2015). More importantly, it is highly uncertain when AVs will become available for public use; how long it will take for its various impacts to take place; and how much it will cost to use it (either self-owned or through a rented or shared service). A large and diverse set of anticipated AV applications, adoption (self-owned, rented, shared), and operations is expected to introduce new sources of uncertainty regarding their deployment/implementation scenarios. Given the road user concerns noted in several past studies, the existing roadway network is expected to continue to host a mixture of manually-driven vehicles and vehicles at varying levels of automation. This mixed driving environment and the resulting interactions are expected to generate new types of uncertainties; and given the convoluted nature of this whole process, it is difficult to discern what the uncertainties will be and how they will emerge. In this section, two major uncertainties are discussed that could have a direct or indirect impact on types and timing of road infrastructure changes.

3.2.1 Technology Development and Adoption Scenarios

Currently, AV technology is undergoing rigorous testing and its performance, under different operational design domains and roadway environments, is being evaluated. Keeney (2018) noted that Waymo, Tesla and Cruise are operating fleets of test AVs and their real road test miles range from millions (for Waymo) to billions (for Tesla). AV technology still needs to undergo evolution in many areas (Forni, 2017), which include (1) accurate sensing for enabling vehicles to perceive their location both situationally and geographically; (2) high-definition internal vehicle maps to pinpoint exact vehicle location in the roadway; and most importantly, (3) artificial intelligence and deep learning algorithms for accurately detecting, predicting, and reacting to the behavior of other road users (e.g., vehicles, animals, pedestrians, and cyclists) and other dynamic roadway events. Sudden and enormous sharp twists and turns in the state of technology, therefore, are expected based on insights from the test deployment of AVs. As such, the real behavior of AV technology is still uncertain as well as its real-world safety and efficiency impacts. The infrastructure requirements necessarily will vary as the technology undergoes evolution so the uncertain state and behavior of AV technology also hinder the road infrastructure readiness process.

Some AV optimists and advocates have predicted that by 2030, AVs will be sufficiently affordable and reliable to replace most human-operated vehicles, providing multiple benefits to both users and society at large, including provision of independent mobility to those who cannot drive otherwise, reduction in driver tedium and stress, and remedies for accidents, congestion, and pollution problems (Johnston and Walker, 2017; Keeney, 2018; Kok et al., 2017). However, there may be some skepticism about such claims mainly due to the realities and limitations of the current technology. Most of the optimistic predictions about the AV market penetration are made by those having financial interests in the AV industry and based on experience with earlier technological innovation including smartphones, cameras, and the Internet (NetworkNewsWire, 2018). In most cases, such analysis seems to be driven by wishful thinking and not by realistic assumptions and therefore often overlooks its significant costs and other obstacles. Many complex technical issues must be resolved before AVs can be operated in all conditions, and AVs must undergo significant testing before they are approved for public use. More importantly, this technology must be affordable and attractive to consumers.

Most of the existing vehicles host Level 1 and 2 technologies, including hazard warning, cruise control, and automated parallel parking. The Autopilot developed by Tesla comes with automated steering and acceleration in restricted circumstances; however, its deployment was delayed after it was involved in a fatal crash in 2016 (Hawkins, 2017). Some companies are carrying out Level 4 pilot projects; and Uber and Waymo released their plans to initiate autonomous taxi services (Bergen, 2017; Lee, 2017). Notwithstanding this advancement, substantial technical developments are needed before AVs are capable of driving under all operational design domains (Simonite, 2016). For example, it has not been determined if the current automated vehicles will operate reliably in snow or heavy rain, on unpaved roads, or in mixed traffic.

Due to the possible frequent interactions encountered in roadway travel with a variety of oft-unpredictable events and objects, including animals, potholes, vehicles, cyclists, and pedestrians, the operation of AVs on public roads could become even more convoluted (Mervis, 2017). AVs would need even more complex software technology to be able to sense these anticipated interactions, and it is perhaps far-fetched at this time to believe that such software technology will be perfect and will never fail.

The proponents of AV technology duly acknowledge the need for substantial technical progress before Level 5 vehicles are tested, approved, and declared reliable (Mervis, 2017). As noted by Truett (2016), the director of the Michigan Mobility Transformation Center anticipates that it will be decades before the technology is reliable enough to allow the vehicle to drive on its own safely on any road at any speed and in any weather. Moreover, the Toyota Research Institute believes that neither the information technology nor the auto manufacturing industry is even close to attaining real Level 5 autonomy (Ackerman, 2017). Similarly, Uber's self-driving vehicle lab director confirmed that a self-driving vehicle technology that is safe and reliable enough to operate everywhere is not available at this point in time and is not expected in the near decades to come (Marowits, 2017). Artificial intelligence experts also see a prevailing underestimation of the magnitude and intensity of the technological progress needed for enabling AVs to anticipate the types of dangerous and unusual situations that can happen in the roadway environment (Marowits, 2017). Ebert (2016) explained the AV technology development process as a replication of the human vehicle driver without replicating the human mistakes (i.e., substituting the human brain through artificial intelligence), which is believed to be far in the future.

Another uncertainty that decision-makers confront is how AVs are likely to be adopted and used by consumers. What are the possible adoption scenarios (self-owned or used as a ride-hailing, transit, or ridesharing service) at the very initial deployment phase? On what roadway types (limited-access freeways or other low-volume roads) and in what locations (urban centers, cities, central business districts, etc.) may these vehicles see their initial operations? There have been various answers to these questions from academia and industry. Several studies foresee an opportunity for the emergence of shared autonomous vehicles (SAVs) as the most prevalent and dominant mode of road transportation (Kornhauser et al., 2013; Bansal et al. 2016; Bischoff and Maciejewski, 2016; Krueger et al., 2016; Fagnant and Kockleman, 2018; Barbour et al., 2019; Menon et al., 2019).

Some researchers expect a great shift from private cars towards on-demand mobility services (Fagnant et al., 2015; Stocker et al., 2016). However, a shift from using more than 270 million registered personally-owned vehicles in the U.S. to everyone riding in SAVs would not happen overnight as noted by Abuelsamid (2018). Some studies, using simulation of different deployment scenarios based on untested and unrealistic assumptions, even reported estimates of potential reduction in the number of personal vehicles (31% to 95%) with the use of SAVs (Burns, 2013; Spieser et al., 2014; Burghout et al., 2015; Fagnant and Kockelman, 2015; Fagnant et al., 2015; Bischoff and Maciejewski, 2016). Bansal et al. (2016) estimated potential adoption rates of SAVs in Austin, Texas under various pricing scenarios; and based on their survey, only 13% of respondents indicated they may be willing to relinquish personal vehicles and rely completely on SAVs at a cost of $1/mile. Using a mixed logit model, Krueger et al. (2016) explored empirically the interests of 435 residents from five major metropolitan areas of Australia regarding three options: SAV without ride-sharing, SAV with ride-sharing, and respondents' current option of public transit only. Haboucha et al. (2017) estimated a nested logit Kernel model for three options offered to 721 respondents across Israel and North America: (1) continue to commute using a regular car that you have in your possession; (2) buy and shift to commuting using a privately-owned AV (PAV); and (3) shift to using a SAV from a fleet of on-demand cars for your commute. Forty-four percent of individuals from both geographical locations together chose regular vehicles;

32% PAVs, and 24% SAVs, whereas, 54% of the North American respondents chose continuing to commute using their regular vehicles. This study also found that only 75% of the survey respondents would be willing to use an SAV service for work- and education-related trips now even if it was completely free of cost. Zmud and Sener (2017) surveyed 556 Austin residents asking about their intent and preference to use and adopt AVs as one of two options: privately-owned or car-sharing (like Uber, taxi, or Zipcar) and found that AV as a self-owned asset (59%) was preferred over its usage as a sharing service (41%). Pakusch et al. (2018) conducted an online survey of 302 respondents in Germany to explore consumer preferences, through a paired comparison, regarding five mobility alternatives: private traditional car, private autonomous car, traditional car-sharing, autonomous car-sharing, and public transport. Their study offered these alternatives to the respondents in different pairs (of two) and not all five alternatives at the same time. The respondents preferred a traditional private car (59.6%; 188 out of 302 participants) over a self-owned AV. In an aggregated paired comparison matrix, the private traditional car was ranked as the first mobility choice by the respondents, followed in order of preference by a private autonomous car, traditional car-sharing, autonomous car-sharing, and public transportation.

Menon et al. (2019) studied the likely effects of SAVs on household vehicle ownership and relinquishment, analyzing responses from target groups comprised of members of the American Automobile Association (AAA) South and associates of the University of South Florida (students, faculty, and staff). Barbour et al. (2019) estimated a random-parameter binary logit model to analyze the consumers’ responses regarding whether they would be willing to use SAVs in any of these six forms: (1) AV car-sharing with car ownership (owning an AV and willing to make it available to others); (2) AV car-sharing without car ownership (obtaining an AV from individual owners or companies that offer car-sharing service via car-sharing platforms such as a web page, smartphone app, etc.); (3) AV ride-sharing with car ownership (owning an AV and willing to share the ride with co-passengers such as colleagues, friends, or someone you might find through ride-sharing web pages or apps); (4) AV ride-sharing without car ownership (sharing the ride with an AV owner such as colleagues, friends, or someone you might find through ride-sharing web pages or apps); (5) AV taxi service; or (6) AV public transit. Of the 782 respondents, 467 (approximately 60%) showed no interest in using an SAV service in any form. Nazari et al. (2018) used a multivariate ordered probit model to investigate the interests of respondents from the Puget Sound region of Washington State regarding four options independently at various ordered choice levels. The respondents were offered to show their interest on the Likert scale in each of these four options in isolation and were restricted from choosing across these four options. They determined their interest as follows: self-owned AV (52.9% not at all interested) and for three SAV services – AV rental (54% not at all interested), AV taxi without a backup driver (50.4% not at all interested), and AV taxi with a backup driver present (44.2% not at all interested). Another study by Payre et al. (2014) investigated consumers' intentions to use a fully automated car on a Likert scale using a mono-modal approach without accounting for the competing alternatives. As noted by Pakusch et al. (2018), there have been several studies related to consumers' acceptance of AVs; however, these studies considered AVs in isolation.

The adoption scenarios during the early transition era of AV operations will have implications for the timing and types of infrastructure changes across road types and across various forms of the built environment (city center, urban, suburban, and rural). For example, if the early adopters prefer to use AVs as a shared service, the provision of a dedicated lane for shared services would probably be enough to support this operation.

3.2.2 Market Penetration (MP)

As discussed earlier in the previous chapters, demand (AV market penetration in this case) is the most critical decision factor that governs agency decisions regarding infrastructure changes and investments. These infrastructure investment decisions are related to the renewal, retrofitting, rightsizing, expansion, or upgrading of infrastructural elements. Highway agencies are responsible for the upkeep of highway infrastructure and traditionally develop time-based or performance-based schedules to facilitate their decisions (Lamptey et al., 2008). These schedules are based on the assumption that an asset-related parameter of volatility will exhibit a peculiar pattern (increasing, decreasing, or otherwise) on the basis of observed historical trends. In the case of AV operations, there are no historical trends available for market penetration. Therefore, the uncertainty surrounding this critical parameter is particularly pronounced during the early transition phase. The yet-to-be-determined safety and efficiency performance of AVs will play a crucial role in defining the direction, magnitude, and rate of market penetration of this technology. During the transition phase, user acceptance of this technology and hence the demand may be expected to be highly susceptible to fluctuation, which in part may be attributed to crash events involving test AVs that are widely publicized. To capture any such fluctuation in the demand, it is important to conduct periodic studies to gauge users' perceptions and potential adoption of this technology (a proxy for potential demand and market penetration) with higher accuracy. AV market penetration is expected to follow a more stable upward trend after a more certain state of the technology is achieved and individual user experience is positive.

For highway agencies to make more informed investment decisions related to AV-oriented infrastructure retrofitting, it is important that they develop estimates of AV market penetration in their respective jurisdictions. The spatial relevance of market penetration trends is also a consideration. The market penetration rates in a given state, region (e.g., urban or city center) or a country in the developed world may not be relevant in another state, region, or country. Therefore, it is important for agencies to rely on their own jurisdictional trends of AV market penetration. Table 3.1 summarizes the forecasts for AV market penetration rates developed by past studies based on rigorous consumer surveys. Some of the similar glowing forecasts reported by earlier studies already have been proven incorrect, mainly because they were based on mere speculations and inaccurate implicit postulates about the timing of AV technology's evolution and maturation as discussed in the previous section. Moreover, most of these optimistic forecasts were made by individuals with financial interests in the AV industry. Such predictions were oriented toward investors and therefore mainly focused on AV's sales potential. Litman (2018) asserted that independent testing and regulatory approval will require additional time even after Level 5 vehicles are fully reliable and functional. In contrast to other technological innovations, AVs will require higher regulation and testing standards due to their potential risk for imposing substantial external costs in terms of road crashes and delays to road users. From an optimistic perspective, the actual testing and approval may only require a few years. However, if AVs are found to be dangerous and unreliable (i.e., if they lead to high-profile crashes), several more years of technology development and testing will necessarily ensue (Bhuiyan, 2017). It is also important to note that different jurisdictions may choose different testing protocols, approvals, and regulations, as is the case with other governing matters, resulting in varying rates of deployment across regions, cities, towns, states, and countries.

In addition to technology development, market deployment and penetration will depend on consumer willingness to pay for this technology. Generally, buying a vehicle is a significant investment for the average person, and not all consumers can afford to purchase new vehicles just for the sake of obtaining new technology so the innovations associated with AV technology may take decades to penetrate markets (Litman, 2018). Some AV advocates believe that some consumers will be willing to prematurely scrap their traditional vehicles given the magnitude and nature of the benefits, but these claims are not necessarily based on realistic assumptions of costs and benefits.

In the recent past, surveys were used heavily to develop reliable market penetration forecasts. These surveys had a smaller margin of error compared to the predictions not based on evidence and therefore provide a more reliable picture of the potential implementation timeline. The findings of these surveys offer more cautious predictions about the speed and scale of AV-driven transformation and its implications across society. These forecasts must be updated constantly, though, due to the rate of change in the evolution of the AV technology. Furthermore, these forecasts may be area-specific and time-specific and thus cannot be generalized for all geographical locations as noted above and their relevance changes over time.

The findings of these surveys have also revealed significant consumer concerns about AV safety and privacy (Schoettle and Sivak, 2014). Most of the responding consumers expressed anxiety about AVs not reaching the desired destination until they are proven reliable in all conditions and operational design domains (Grush, 2017). However, as noted by Wharton (2017), attaining a target of 99% operability (vehicle unable to reach about 1% of desired destinations) under 99.9% of conditions (vehicles unable to make 0.1% of trips) for regulators and consumers is more difficult.

Most importantly, it is critical to duly acknowledge and account for the volatility of market penetration and then make flexible infrastructure investment decisions that can be responsive to the uncertain market penetration rates of the future. As shown in Table 3.1, there is a wide range of predictions regarding the AV market penetration rates and there is no universally agreed value; this clearly signifies the volatility of this parameter. Given the widely-held optimism of stakeholders regarding the safety and efficiency benefits of AV operations, it is reasonable to hypothesize that there will be an upsurge in AV market penetration over time.

Table 3.1 AV market penetration forecasts

Source	**Market penetration forecasts**
IHS Markit (2018)	▪ After personally owned autonomous cars are made available for individual buyers, AV sales are expected to surpass 51,000 units in 2021 globally. Approximately 1 million AVs are likely to get sold in 2025 as self-owned cars and shared fleets. ▪ AV sales are likely to surpass 33 million annually in 2040, corresponding to more than 26 percent of new car sales. ▪ Total U.S. volumes of AVs are expected to reach 7.4 million units per year in 2040.
Litman (2018)	▪ In the 2040s approximately 50% of vehicles sold and 40% of vehicle travel could be autonomous (at level 5). ▪ In the 2050s approximately 80-100% of vehicles sold and 50-80% of vehicle travel could be autonomous (at level 5). ▪ It will be at least 2040 before half of all new vehicles are autonomous, and at least 2050 before half of the vehicle fleet is autonomous. ▪ These forecasts are based on the assumption that Level 4-5 vehicles become commercially available in the 2020s.
Waymo (2018)	Widespread adoption is unlikely before the latter half of the 2020s.
Litman (2018)	▪ 30% and 50% of the vehicle fleet in the U.S. to have Level 4 autonomy in the 2040s and 2050s, respectively. ▪ 40% and 65% of U.S. vehicle travel will be in Level 4 AVs in 2040 and 2050, respectively.
McKinsey and Company (2016)	▪ Fully autonomous vehicles are unlikely to be commercially available before 2020. ▪ 15% of all new passenger vehicles sold in 2030 could be fully autonomous. ▪ 50% market penetration around 2033 ▪ 90% market penetration by 2070
Rowe (2015)	100% of U.S. vehicles will be at Level 4 by 2060
Archambault et al. (2015)	▪ 100% of the North American, European and Japanese vehicle fleet to have Level 4 autonomy by 2050
Goldman Sachs-Cars Forecasts	▪ Level 3 and Level 4 vehicles to be publicly launched first in 2025
Harrop and Das (2015)	The number of self-driving capable cars in the U.S. to reach 8.5 million by 2035
Bierstedt et al. (2014)	25% of U.S. vehicle fleet to be autonomous by 2035
IHS Automotive (2014)	Entire global fleet expected to be fully autonomous by 2050
Hars (2014)	By 2030, car ownership to decline by 20% and 90% of all person-trips in the U.S. will be in Level 4 AVs.
Laslau et al. (2014)	92% and 8% of the global vehicle fleet will comprise of Level 2 and 3 vehicles, respectively, in 2030.
Morgan Stanley (2013)	Nearly 100% of U.S. light-duty vehicles will be Level 3 and 4 vehicles by 2030 and 2055, respectively

3.3 Dealing with Uncertainty in Highway Infrastructure Investment Decisions

3.3.1 Introduction

Although the future of AV operations is not fully known, transportation and infrastructure planning require forecasts of prevailing conditions and needs at future years (Shaheen et al., 2018). Highway agencies, planners, engineers, practitioners, analysts, and decision-makers at all levels seek guidance on how the future of travel and road transportation systems will evolve with the emergence of AV operations; how planning for roads, public transit, and parking will change; and whether public policies should restrict or promote their use (Levinson, 2015; Guerra, 2015; APA, 2016; Kockelman et al., 2016; Milakis et al., 2017; Grush and Niles, 2018). Highway agencies are primarily interested in AV fleet penetration and its travel impacts, which will inform their decision-making processes.

Vehicles use road infrastructure for their operations. The current roadways are designed for human drivers, and to retrofit them for AVs will require significant public investment and planning (Speck, 2017; Papa and Ferreira, 2018). Litman (2018) noted that policy-makers and agencies must investigate and decide (a) when the potential benefits can justify the provision of exclusive AV lanes to support platooning (numerous AVs driving close together with smaller headways and at relatively higher speeds) and (b) how to regulate AV operations.

Substantial investments are needed to prepare existing road infrastructure to support AV operations; however, the traditional value engineering (cost assessment) approaches may not reflect the value of the flexibility associated with the timing of needed infrastructure modifications and related investments for the future AV operations. Therefore, this is an opportunity for highway agencies to adopt value-based evaluation approaches. The cost has been used as a proxy to assess value; however, value is more than just monetary. Value could be associated with the road infrastructure supporting AV operations and ultimately, safety and enhanced mobility. In the recent past, there has been a growing shift towards determining the value of infrastructure development and improvement and not mere financial implications (de Neufville and Scholtes, 2011; Labi, 2014; Athigakunagorn, 2015; Cardin et al., 2015; Mair et al., 2016).

The stakeholders of roadway infrastructure have different objectives and hence they value infrastructure differently. Therefore, the overall value cannot be measured always using the same metrics. This fact recognizes the limitations of traditional cost assessments in representing the actual value of infrastructure. There is no standard adopted approach that is widely used currently for assessing infrastructure value. The departure from the traditional cost-based to value-based approach seems to be the most viable strategy for highway agencies to justify the significant investments for AV-oriented infrastructure modifications at the early stages of the transition phase. This phase is the period when most of the positive and negative impacts of AVs are not known with much certainty.

Recognizing the shortcomings of traditional cost assessment approaches and the anticipated dynamic nature of AV market penetration, the real options analysis (ROA) offers a great alternative to better deal with the uncertain future and account for periodic change and up-grading that road infrastructure design may undergo. ROA represents actual opportunities or choices that can be exercised to add value to infrastructure (Black and Scholes, 1973), for example, decisions about a change in technology or making an early infrastructure intervention/modification for facilitating AV operations. Most of the future decisions related to retrofitting road infrastructure for AVs during the transition phase cannot be predicted today. Therefore, ROA provides an opportunity to incorporate flexibility into the investment decisions, which will make the alternative decision trajectories (e.g., modifying, expanding or abandoning) available for adoption at any point in time, depending on the prevailing conditions (e.g., market penetration or safety and efficiency impacts of AVs). For example, if a highway agency that owns and operates a state highway network is mandated to make infrastructure modifications for accommodating AVs on its network, they can either make system-wide infrastructure changes or begin with a stretch of freeway only, as a pilot project, by providing an AV-exclusive lane until the market penetration and safety and efficiency impacts are completely known. When the market penetration and the safety and efficiency benefits are realized, further investments can be made to facilitate system-wide changes. If the outcome of the AV operations, in terms of safety and efficiency, on the freeway is contrary to expectations, the highway agency can abandon making further AV-oriented infrastructure changes. Clearly, ROA can create value by managing strategic investments and recognizing the pivotal role of flexibility in decisions under uncertainty, such as AV-related roadway retrofitting, to ensure the success of future investments (Amram and Kulatilaka, 1999).

The agencies responsible for the design and operation of highway infrastructure regularly face situations where uncertainties can potentially cause a change in their initial intended actions and plans. This situation continuously and repeatedly arises throughout the lifecycle of highway infrastructure, as noted by Nembhard and Aktan (2010), Labi (2014), and Athigakunagorn (2015).

This potential revisiting and revising over the infrastructure lifecycle can have direct implications for the design parameters (project type, size, etc.) and the value, and hence, the feasibility of the whole system or project. Where there are several infrastructure projects under consideration, using value-based evaluation approach can help decision-makers carry out the prioritization of alternative projects, which is particularly important in the era of AV operations because infrastructure retrofitting investments can involve billions of dollars and agencies must seek prudent spending of taxpayers' money.

Value engineering has been used for many years to assess the appropriateness and feasibility of various actions or interventions to construct, reconstruct, expand, defer, rehabilitate, compact, renew or right-size assets. Most often, the investments made for any of these interventions are not recoverable. Value engineering facilitates the process at the highway agency level by enabling the decision-makers to discern and quantify the effects of alternative decisions/actions in terms of their costs and benefits. It also facilitates the prioritization process across different alternative actions, projects, or decisions to achieve optimal allocation or utilization of resources.

3.3.2 Traditional Value Engineering

At the present time, the most dominant and popular approach for value engineering is discounted cash flow (DCF) analysis. DCF techniques include net present value (NPV), equivalent uniform annual cost (EUAC), internal rate of return (IRR), and payback period. Besides its several known limitations, the payback period method is still frequently used for its simple and quick computation and thus is considered useful for short-term budgeting and high-level reporting (Pogue, 2010). The payback period refers to the number of years from the cumulative benefits to exceed costs. This method aims at determining the period of time required before the investment is recovered; however, it does not consider the time value of money and the cash flow after the payback period (Farris et al., 2010). NPV and IRR help overcome the drawbacks of the payback period approach.

Net Present Value (NPV)

NPV, which is the most commonly used project evaluation method, utilizes the DCF approach to discount future cash flow streams during the analysis period to the base year (the start of the project, in most cases) (Lin and Nagalingam, 2000). In this case, careful selection of the discount rate is required because the project life is often long and face economic risks. As a rule of thumb, public projects use 5% (Sinha and Labi, 2007). The project is considered feasible if its NPV exceeds zero. NPV is also used to prioritize competing projects.

The main shortcoming of the NPV approach is that it is driven by the non-dynamic cash flow. The investments in and out of the project and any decisions in the future must be predefined. Although this approach does not acknowledge the risks and lacks flexibility, it is used in the dissertation as a base case approach for comparing the results with ROA.

Internal Rate of Return (IRR)

For a given cash flow series, IRR refers to the rate that makes the NPV equal to zero (Sinha and Labi, 2007). IRR does not reflect the interest rate in an external market but rather is influenced internally in a sole manner and is calculated by the project's cash flow. The investment decisions are made based on comparing the IRR with the minimum attractive rate of return (MARR); and the project is implemented when the IRR exceeds the MARR (Sinha and Labi, 2007). Considering its simplicity, many agencies use this method to inform their investment decisions. However, some cautions are required while using this method. First, the IRR is meant to favor short-term investments and often neglects the long-term benefits of the project (Hazen, 2003). Moreover, some cash flows may have more than one value for IRR (i.e., cash flow has a negative NPV at the start and the end of the project) or may produce an IRR value that is not a real number. In these cases, the use of IRR as a decision tool could be problematic (Palmer, 2019).

3.3.3 Limitations of the Traditional Value Engineering Approaches

The biggest limitation of DCF is inadequately accounting for uncertainty, for example, by increasing the discount rate to reflect the level of risk and incorporate uncertainty associated with the project as noted by Kodukula and Papudesu (2006). This means that the benefits must exceed the costs to compensate for the risk so that the proposed project remains feasible even after it is discounted heavily. Although the rationale for this method is sound, for projects where the discounted costs overflow the discounted benefits, decision-makers may demur from executing the project, which may turn out to be feasible at a later year. This highlights the fact that traditional value engineering cannot adequately capture and quantify the monetary value of the uncertainty-driven flexibility associated with infrastructure investments.

Although probabilistic discounted cash flow analysis can be employed to explore the effect of volatile parameters (i.e., traffic demand and AV market penetration in this case) on the stochastic distribution of the investment outcome, it cannot be used to estimate the value of uncertainty-driven flexibility and therefore may lead to decisions that are not optimal over the entire lifecycle of the infrastructure investment. Failure to account for the value of flexibility in the infrastructure investment evaluation could lead to executing a project, which in reality, should be deferred or abandoned. This shortcoming can be overcome by identifying the latent value of the AV-oriented infrastructure retrofitting decisions using a real-options approach. As such, highway agencies can make more reliable and informed decisions by considerably reducing the anticipated disruptions caused by uncertain futures (Ford et al., 2002).

The major drawback of traditional value engineering thus is that it forces decision-makers at the agency level to predetermine the decisions over the entire lifecycle of the proposed project, which can lead to underestimation of the project value. However, this limitation can be overcome by leveraging options and inducing flexibility such that the decisions are deferred until the conditions are clearly known and favorable for the investments over the period across the lifecycle. This approach helps mitigate the downside risks and is also why the risk-adjusted discount rate should not be kept constant but rather should be reduced when options are considered. Further, if the entire risk is taken care of through a minimum revenue guarantee or a U.S. Treasury bonds rate, it has the potential to be reduced to a risk-free rate.

3.3.4 Real Options Analysis (ROA)

3.3.4.1 Introduction

In a bid to determine the price of a financial option, Stewart Myer (1977) extended the widely known Black-Scholes equation and proposed the term “real options.” He implemented this concept to assess the upsurge of investments in real assets. By definition, real options indicate a right but not an obligation to exercise options and thereby induce flexibility in terms of expansion, waiting, abandoning, switching, or contracting (Nijssen, 2014). The ROA method accounts for the flexibility inherent in a non-financial asset or project facing an uncertain environment and provides a way to evaluate the actions/options in extra monetary value for the asset (de Neufville and Scholtes, 2011). ROA offers a way to embrace the uncertainty of the asset value and hedge against adverse conditions. For example, if highway agencies seek to retrofit its existing roadways for AV operations, instead of retrofitting the whole roadway environment system-wide with all roadway infrastructure elements across the state, a pilot project could be deployed (e.g., at corridor level) to test the market response to AVs and the changes made to the road infrastructure. ROA can offer guidance to the decision-makers as to the best course of action and to reveal the latent or additional value of the decision actions. This additional value will depict the maximum value of the project or the maximum amount of funds to conduct a market survey or to further increase the scale of the infrastructure changes from corridor level to system level.

As noted by Kodukula and Papudesu (2006), although ROA has numerous advantages, it may not be adequate for all projects. The project should have two features (i.e., decision uncertainty and managerial flexibility) that may enable highway agencies to make a flexible decision in response to an uncertain future or market. In the case of a higher level of uncertainty, as noted by Kodukula and Papudesu (2006), there could be substantial gains from a project where the decision can be adjusted to “profit” from that state. In the case of unfavorable prevailing conditions or market (e.g., lower market penetration of AVs), the decision can be postponed, or the project may be abandoned for a time to avoid a potential loss. Under these circumstances, gathering more information (e.g., updates on AV market penetration) will help make more informed decisions. In the absence of these two features, a proposed project is evaluated in a deterministic manner and thereby traditional approaches are adequate.

Moreover, it is noteworthy that in the case where the NPV of a project is close to zero, ROA is recommended. In the case of a highly positive NPV, the project or investment under consideration is clearly attractive and the value of the option will be low because the chance for exercising an option is small. Conversely, in the case of a highly negative NPV (in comparison to the option values), the option values cannot compensate for the projected loss and hence a reverse decision is suggested.

Although the real options valuation method is derived from the financial options (de Neufville and Scholtes, 2011), they are different from each other in several aspects. In the case of financial options, the underlying assets are securities (e.g., stocks or bonds) with an exact value; and having an exact value makes it easier to quantify or estimate the parameters (i.e., the volatility of the stock). In real options, on the other hand, the underlying assets are tangible ones (e.g., road infrastructure). For such tangible assets, it is rather difficult to find similar projects and extract historical data for determining the asset value, but this can be mitigated by finding the present value of the project and assuming this to be a proxy for the underlying value of the project. In the literature, this has been referred to as the “market asset disclaimer assumption,” as noted by Copeland and Antikarov (2003).

The main assumption in modeling the price of a financial option is that the investor does not have an arbitrage opportunity to buy a security at a lower price and then sell it instantly at a higher price. This assumption is quite plausible in dealing with a financial option; however, because it has already been marketed and therefore can be bought and sold quickly to counter the chances of arbitrage. In the case of real options, no market exists for trading this type of asset because of its less liquid nature. Since real assets do not incorporate the arbitrage assumption, the final option value should account for this through the liquidity discount factor (Kodukula and Papudesu, 2006).

Furthermore, the financial options assume the uncertainty and the price of the asset to be exogenous, meaning that the price, risks, and volatility depend on the market situation, and as such, the decision-makers are unable to control the management decisions or manipulate the price. Conversely, in the case of real options, this may not be possible because the present value of the project can be directly influenced by the managerial decisions. For example, a state highway agency’s decision to build an exclusive lane for AVs instead of just retrofitting the road pavement markings will change the present value of the project. In addition, the decisions made using the real options will have a direct influence on the market situation; for example, choosing to introduce a different item will have a different effect on the existing market and response from competing counterparts and therefore would encounter different levels of risk and uncertainty. On the other hand, for financial options, the price of the options is driven by market value irrespective of whether decision-makers opt for holding, selling, or even buying more of the options. Table 3.2 shows a comparison of the terms and phenomena used across financial and real options.

Table 3.2 Terms used across financial and real options

Financial Option Terms	**Corresponding Terms in Real Options**
Stock price	Current value of asset/project
Strike price	Upfront investment/expenditure required to acquire an asset
Time to maturity	The time before the opportunity expires
Volatility	The riskiness of asset/project
Risk-free rate	Interest rate
Dividends	Cash flows from operations

Due to its similarity to the applications in the financial arena, ROA is widely used for contract management of infrastructure system development and construction. To tackle the uncertainty and risk tied to whether the proposed investment could deliver the intended financial returns, the financial options concept was introduced to assign a value option to contracts. This application motivates the use of ROA in highway infrastructure asset management. To this end, highway asset managers seek to counter the uncertainties associated with asset attributes that potentially may impact the investment decision process. This is one of the several advantages of using ROA in infrastructure management, and it has been widely used for infrastructure management applications (Zhao and Tseng, 2003; Wang and de Neufville, 2005; de Neufville et al., 2006; Cardin and de Neufville, 2009; Athigakunagorn, 2015; Peters, 2016; Swei, 2016). One of the most well-known applications of ROA in the context of infrastructure design and construction is a parking garage case study (Zhao and Tseng, 2003; Wang and de Neufville, 2006; Peters, 2016). The source of uncertainty is the demand for parking spots, which leads to defining the number of floors in the parking garage building and ultimately helps estimate the needed structural capacity of the building's foundation.

3.3.4.2 Types of Options

Unlike financial options, which are defined by the time to exercise the option (American, European, Bermuda), real options are categorized based on strategic or managerial decisions/actions, which include call and put options, options to abandon, options to expand, options to contract, options to wait, options to choose, compound options, and rainbow options (Abraham, 2018). These are discussed below.

Call and Put Options

The call option refers to the option of buying security by a predefined date (the expiry date) at a predefined price, which is also termed as the exercise or strike price (e.g., Y). As per the contract (O'Sullivan and Sheffrin, 2003), the buyer of a call acquires the right, however not the obligation, to buy a security (shares) at the predetermined strike price with a non-refundable premium until the date of expiry. The seller of the call (also known as the writer) is under obligation to sell in case the buyer wants to exercise the call option. The call option is acquired under the expectation that the price of the underlying security, S, of the option, will increase beyond the strike price and hence this investment will bring benefit. This is defined as “the option is in the money” where the investor’s profit is the difference between Y and S (Milton, 2018; Mitchell, 2019). Conversely, if the market is not conducive and its price falls below the exercise price ($S < Y$) on the date of expiry, it is logical not to exercise the option but rather let it expire and buy a security at a current value of the market. This is defined as “the option is out of money,” (i.e., the value of the option is zero) (Milton, 2018).

The put option refers to the option of selling a security at a predetermined price until a fixed known expiry date. The buyer of a put option holds the right, though not the obligation, to sell the underlying security (e.g., shares) at the strike price; and if the put owner decides to sell, the put writer is obliged to purchase at the predefined strike price (Kuepper, 2019). The put option is acquired under the anticipation that the price of the underlying security, S, will decrease and as such, a contract is made under a non-refundable premium, which allows the seller to sell a security to the writer (buyer) at the strike price, Y, until a certain time (expiry). This option generates profit when Y is less than S, signifying “the option is in the money” condition as discussed earlier and vice versa. Equations (3.1) and (3.2) can be used to determine the value of the call and the put options, respectively.

$$C = \max[S - Y, 0] \tag{3.1}$$

$$P = \max[Y - S, 0] \tag{3.2}$$

Option to Abandon

The option to abandon refers to the option of closing or ceasing a project or an asset to realize its salvage value (Cruz Rambaud and Sánchez Pérez, 2016; Scott, 2019). Under this option, decision-makers may abandon a project and sell the asset to recover their losses when the market is not in favor or the end-product has not been completely and successfully developed. This is also known as a termination option. The predetermined strike price should not be less than the salvage value.

Option to Expand

The option to expand refers to the option of making an investment or undertaking a project in the future with the intent of expanding an asset or a business (Kagan, 2018). This option prevails where a project is equipped with the managerial ability to expand its operating capacity or to expand into a new market. As noted by Athigakunagorn (2015), this call option is particularly useful for technology-based projects, which fits exactly the case of AV technology in this dissertation. Given the enormous amount of costs associated with such projects, the use of traditional approaches may most likely result in a negative NPV. This negative NPV is unavoidable because traditional value approaches do not incorporate the potential growth and expansion inherently nested in the project. When decision-makers, such as highway agencies in the case of infrastructure retrofitting to support AV operations, realize that such situations exist, some funds/money can be given up as a premium (e.g., by implementing a pilot project of making AV-oriented road infrastructure modifications only on a freeway stretch) to be able to respond to the growing market penetration of AVs and hence retain the option of expansion as future opportunities.

Option to Contract

The option to contract is the option of shutting down a project at some point in the future in the case of unfavorable or infeasible circumstances; for example, a company may suspend its operations in a country due to unstable political conditions (Lyon and Rasmusen, 2004). This put option is contrary to an option to expand and is relevant and valuable for responding to a market where the demand is expected to suffer precipitous changes. Decision-makers thus maintain the right to scale their project, production, or operations to reduced capacity and may sell the resources no longer required.

Option to Wait

The option to wait refers to the option of deferring a decision to the future. The option to wait is also termed as the option to defer (Lensink and Sterken, 2002) and allows decision-makers to wait until the project or the market situations become more favorable. This option is relevant and adequate when the project is facing some sort of hindrance in preserving its value or the intent is to secure the market share from a competitor. Moreover, the life of a project should be predetermined and independent of when the project is initiated. Therefore, no payoff leakage will occur once the investment has completed its life. For example, the construction of a bridge, with a service life of 10 years, is under consideration; if a highway agency decides to delay this project for a period of one additional year, its service life of 10 years remains the same and is not influenced by the amount of time the project is delayed.

Option to Choose

The option to choose refers to the flexibility of deciding or choosing the type of options to exercise from a plethora of alternatives (Labi, 2014; de Neufville, 2016). This option is instrumental in optimizing a project's payoff by allowing decision-makers to abandon, expand, or contract the project at a certain time. Therefore, this option could be either a put or a call option. The option to choose generally carries more value compared to an individual option in isolation because decision-makers have more options to choose from and therefore more flexibility to manage the project over its entire lifecycle. If the individual options are mutually exclusive, the option value will be equal to or less than the joint value of those individual options. In other words, the project cannot be expanded and contracted at the same time, and the option to choose therefore will have a reduced value.

Compound Options

The compound option or the option of an option refers to the situations where the value of an option is dependent on another option and not on the value of an underlying asset (Geske and Johnson, 1984; Fouque and Han, 2004).

The two types of compound options include a sequential compound option and a parallel/simultaneous compound option. The former depicts a condition when the subsequent option arises only when the first/earlier option is exercised successfully. For example, in the case of the asset management cycle and infrastructure development projects, the construction phase occurs only after the completion of the design phase. All the risks, costs, uncertainties, and value of the construction phase are predetermined at the design phase.

In the parallel compound option, both a subsequent option (its value is derived from the underlying option) and an underlying option (its value is derived from an underlying asset) co-exist at the same time. Due to the longer life of the subsequent option, it is discerned first by employing the backward induction method to find the value of the option.

Rainbow Options

The rainbow options facilitate the modeling of multiple sources of uncertainty (Rubinstein, 1991; Chen, 2018). These options are a more realistic and closer depiction of the uncertainties prevailing in the real world, but they are complex to model. Unlike the rainbow options, a simple option is a manifestation of all the sources of uncertainty into a single value.

3.3.4.3 Option Valuation Methods

The three well-known and typical methods of valuing real options include the Black-Scholes equation, the Binomial Lattice (BL) method, and the Monte Carlo simulation.

The Black-Scholes equation, introduced by Black and Scholes (1973) and then extended by Merton (1973), uses a closed-form equation that gives an exact value, but some assumptions accompany it that significantly limit its applicability to specific option types. The major assumptions of this method are as follows: 1) the option can be exercised only on its date of expiry (i.e., can only find a European option); 2) there is no leakage of the value of the option (i.e., changes in the underlying value are not driven by volatility such as royalty fees or dividend payouts). It is almost impossible, from a practical standpoint, to find an option type that meets these assumptions. However, this limitation can be overcome by modifying the equation through a complex process, fundamental to the Ito’s calculus, as noted by Luenberger (1997).

Binomial Lattice (BL) Method

The most commonly used and widely accepted technique is the binomial lattice (BL) method. Its wider application in the literature can be attributed to its transparency and convenience of interpretation from a practical standpoint. Some modifications are needed, however, to deal with complex options.

Unlike the Black-Scholes equation which is a continuous-time model, the BL method, proposed by Cox et al. (1979), is a discrete-time model for valuing the options. Unlike the Monte Carlo simulation, the BL method requires less computational effort and time to formulate the problem, but it also produces an approximate value. This method is based on a no-arbitrage assumption, meaning thereby that the market is efficient, and investments are able to earn the risk-free rate of return.

The BL method is employed to compute the value of an option by first constructing a tree-like framework (i.e. BL), which starts from the existing value of the asset, S_0, as shown in Figure 3.1.

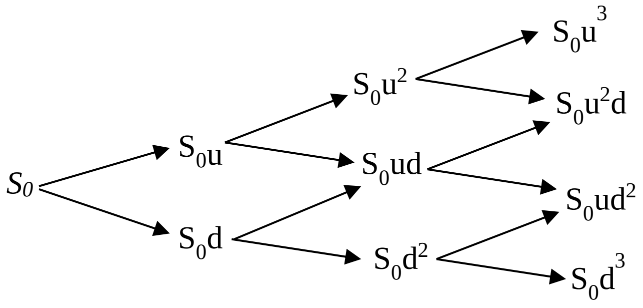


Fig. 3.1 Binomial lattice with three time-step

The lower branches of the lattice indicate the phase when the asset goes down, and the upper branches manifest the upsurge when the underlying asset of the option is going up. The model presented below shows only two possible up and down stages with a constant up and down ratio throughout the lattice. The value of the underlying asset is computed at each node by multiplying the up (u) and down (d) factors wherever adequate until reaching each node. The backward induction is then applied for finding the option value for an intermediate node and back to the start node. The value of the option is identified as the maximum numerical difference between the underlying value at this node and the weighted average of the option value of its ensuing nodes discounted back at a risk-free rate. This weight refers to a risk-neutral probability. Equations (3.3)-(3.5) are employed to compute the up and the down factors and the risk-neutral probability (or the weight), respectively. Equation (3.6) is used for computing the option value.

$$u = e^{(\sigma\sqrt{T})} \tag{3.3}$$

$$d = 1/u \tag{3.4}$$

$$p = \left(\frac{e^{(r_f*\Delta t)} - d}{u - d}\right) \tag{3.5}$$

$$\text{Option Value} = \left(\frac{(p*Option\ value\ at\ upstage) + [(1-p)*Option\ value\ at\ downstage]}{e^{(r_f*\Delta t)}}\right) \tag{3.6}$$

where, T = time to maturity; r_f = risk-free rate; Δt = time step, σ = volatility

Monte Carlo Simulation (MCS) Method

Monte Carlo simulation is the most flexible method for real options valuation. Although it involves a large number of computations, this method can be adapted for any type of option. For real options, the analysis can be done by tracking the expected trajectory of their underlying value. This approximation technique is employed by dividing the option’s life into small time steps. As the time step gets smaller, the option value becomes closer to that attained using the Black-Scholes formula. The simulation in the MCS method can be carried out using Equation (3.7):

$$S_{t+1} = S_t + S_t\ (r_f\ \Delta t + \sigma\ \varepsilon\ \sqrt{\Delta t} \qquad (3.7)$$

where, S_t = value of the underlying asset at time t; S_{t+1} = value of the underlying asset at time $t + 1$; ε = simulated value of the distribution (normal) with mean equal to zero and standard deviation equal to 1; Δt refers to the time step; and other variables are same as defined earlier.

Equation (3.7) is applied repeatedly from the beginning of the option’s life till its termination, with increments of magnitude equal to the time step. Towards the end of the option’s life, it can be exercised if the option’s payoff exceeds a predefined threshold. This is followed by discounting the payoff back to the present value through a risk-free rate. The accuracy of this method relies on the number of simulation trials and time increments. A major disadvantage of the MCS technique is the enormous computational effort, which is required to produce more accurate output. The efficiency of this technique is particularly more pronounced in the case of dealing with a European option, where the exercise date of an option is restricted to its expiry date only. This expiry date is a single pre-determined instance in time, which is not a conducive case for the problem under consideration in this dissertation. In contrast, the American option can be exercised at any point in time before its expiry date, which is the case for the problem being analyzed in this dissertation. In the case of implementing the MCS method for an American option, all possible dates of exercising the option must be simulated to determine the value of the option. However, this process could be extremely inefficient and tedious. Therefore, it is preferred to use the BL method or the Black-Scholes equation and its modified forms where the value of an option can be determined by either one of these two methods. The MCS method is recommended to be used for analyzing options which cannot be evaluated by the other two methods.

3.3.4.4 Limitation of ROA and Potential Remedy

ROA assumes a market monopoly. In other words, ROA postulates that the project value does not decline over time with deferring the proposed investment. Rather this deferment leads to an increase in the investment value due to exercising the option. This presumption may not be the case in many situations particularly in the case of market competition. The integration of Game

Theory with ROA, abbreviated as ROG, has been identified as a remedy to this restriction by Smit (2003). Smit and Trigeorgis (2006) noted that the strategic investment along with the flexibility of the project may be jointly analyzed to determine the NPV, as shown in Equation (3.8).

$$\text{Strategic NPV} = \text{Direct (passive) NPV} + \text{strategic value} + \text{flexibility value} \tag{3.8}$$

The Real Option Games (ROG) approach is useful in finding the optimal investment strategy (Smit, 2003; Smit and Trigeorgie, 2009). A payoff matrix was developed by Ferreira et al. (2009) before identifying the optimal strategy from game theory. The classic NPV failed to realize the value of flexibility and the strategic value of the investment. Therefore, poor outcomes were produced by classic NPV. The authors demonstrated through a case study that the poor outcomes of investment evaluation could be countered through ROA by holding decisions until the resolution of uncertainty and the disclosure of the plans crafted by the competitors. However, the optimal result could not be achieved with ROA as it did not incorporate the benefit of forestalling the competitive market. The authors found it necessary to consider both the strategies (commitments) and the trade-offs for inducing flexibility in the project. As noted by Ferreira et al. (2009), game theory has a major limitation in that it is unable to incorporate flexibility into the payoff matrix, which on the other hand, can be achieved through ROG, which releases the monopoly assumption of ROA as well as improves the performance of game theory by considering uncertainty and flexibility in the analytic framework.

3.3.4.5 ROA Parameters

The value of real options has the following parameters: strike price, underlying asset value, risk-free rate, time increments, options life, and volatility. For ROA, the present value can be an indicator of the value of the underlying asset. The risk-free rate is employed for discerning the value and the return rate of a short-term American bond is used as a proxy for this rate. Moreover, the features of the project and the perspectives of the decision-makers inform the selection of the option’s life, strike price, and time increments. Volatility is the parameter that is relatively challenging to quantify because most projects are often unique, and it therefore can be challenging to find historical data of real projects for valuation. From a practical standpoint, the volatility of the project is estimated after simulating the cash flow of a project by deploying a Monte Carlo simulation. Another way to estimate volatility is to simulate the project cash flow after estimating the distribution, the mean, and the optimistic and pessimistic values of a project based on expert opinion (Mun, 2006).

3.3.4.6 Discussion and Conclusions

The drawbacks of the traditional economic valuation methods were identified and discussed in detail in this section. NPV considers a non-dynamic cash flow (the same discount rate for each period, signifying the same level of risk throughout the entire time horizon of a project investment), which rarely occurs in the real world. Even stochastic NPV does not account for the flexibility value of the project but rather reports the distribution of the possible outcomes (their means and standard deviations). The IRR method uses an internal interest rate and does not relate this to an existing market. Although the decision tree approach can model the dynamic features of a project, the assignment of probability to each chance node is inherently subjective and can greatly influence the outcome.

On the other hand, the ROA approach offers a structured method of integrating flexibility in the value engineering process. This flexibility is a manifestation of the ability to defer, abandon, or proceed with a proposed investment, and more so, to incorporate the value of this flexibility into the decision-making and project evaluation process. For example, deferring the decision (at the current time or at a future specified time) until more conductive conditions start to prevail, such as when new knowledge is available about the proposed investment or reduction in the scale and intensity of uncertainties. According to the ROA method, the decision which maximizes the project value both in terms of the project outcomes and the inherent flexibility is the final recommendation.

Moreover, it is important to note that ROA is not a replacement for any of the DCF techniques. Rather its role is complementary in discerning additional insights about the proposed investment and hence in substantiating the evidence and justification related to these investment decisions. The classic NPV of the project is still needed to be used as a base case scenario for comparison with the ROA method. More importantly, if there is no inherent flexibility associated with a project, the traditional approaches are sufficient to serve the purpose and there is no need to employ the ROA method because the value of the option is zero and the NPV of the project is the same as that reported by the traditional approaches.

3.4 Chapter Summary

This chapter identified and discussed in detail the various sources of uncertainty surrounding the era of AV operations. These uncertainties were discussed in relation to their potential implications for the timing and types of AV-oriented infrastructure changes. The market penetration of AV technology was acknowledged as the main volatility parameter which influences the AV-oriented infrastructure retrofitting and investment decisions at the agency level. Moreover, this chapter also discussed how highway agencies can account for some of these uncertainties in their AV-oriented infrastructure retrofitting projects. The merits, the demerits, the potential applicability, and the relevance of the traditional value and real options approaches were discussed in the context of informing the investment decisions of highway agencies. Moreover, different types of options and their valuation methods were also reviewed in detail. The next chapter presents the main framework of this study.

4. STUDY FRAMEWORK

4.1 Introduction

The previous chapter identified various sources of uncertainty associated with AV operations and discussed how highway agencies could account for some of these uncertainties in their AV-related infrastructure decisions. This chapter presents the main framework used in this dissertation. The key concepts discussed in Chapter 2, the essential complementary roles of stakeholders, and various uncertainties discussed in Chapter 3, led to the development of this framework. The framework presents how a transportation agency could make investment decisions regarding AV-oriented infrastructure changes that account for AV market penetration as a source of significant uncertainty.

4.2 Framework

The study framework implemented in this dissertation is presented in Figure 4.1. The following subsections delineate the tasks and steps contained within the framework.

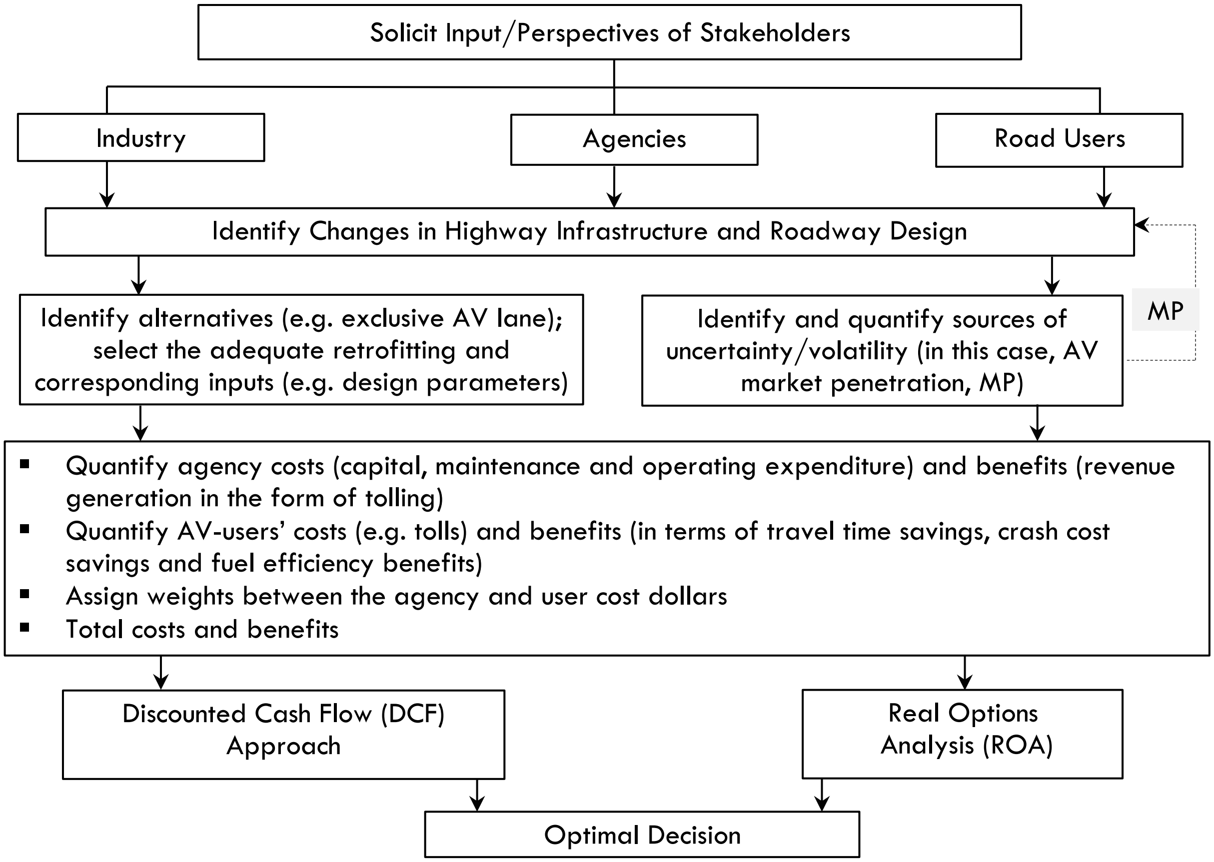


Fig. 4.1 Study framework

4.2.1 Stakeholders' Perspectives

As discussed in Chapter 2 of this dissertation, understanding the complementary and complexly interacting roles of stakeholders is extremely important for promoting AV operations. As such, it is crucial to discern and capture the perspectives of key stakeholders. While the nature of AV technology is expected to shape the types of AV-related infrastructure changes needed to accommodate AVs, the end-users of this technology are expected to drive market penetration and, hence, the need for infrastructure readiness at the agency level. This dissertation uses survey questionnaires as a tool to capture these viewpoints for their consideration in the decision-making process at the agency level.

4.2.2 Road Infrastructure Modifications

Expected changes to road infrastructure and roadway design features are identified at different levels of AV market penetration based on a survey of transportation agency experts, the expectations of technology developers regarding infrastructure readiness for AVs, an extensive literature review, and discussions with experts at different occasions.

4.2.3 User and Agency Impacts

After different infrastructure change scenarios are identified in the previous step, the user and agency impacts associated with each of these scenarios are identified and discussed in detail. The source of volatility is also discerned and used in economic evaluation. After the source of uncertainty along with accompanying flexibility are established, different components of user and agency costs and benefits are quantified for subsequent economic analyses of the proposed scenarios.

4.2.4 Economic Evaluation

For the two scenarios analyzed in this dissertation (i.e., [1] that AVs are deployed in existing lanes on the roadway in a mixed traffic stream and [2] that an exclusive lane is provided for AV operations), all of the costs and benefits identified in the previous step are computed from the perspectives of the road users and the agency. The revenue generated by dedicated AV lanes is an example of agency benefits, whereas the cost of the construction and maintenance of the improvements is an example of agency costs. Meanwhile, changes in the frequency of crash occurrences and changes in travel time are costs and benefits incurred by road users. All of these cost and benefit components are quantified in terms of monetary values to serve as inputs to analyzing the net economic impacts of the potential infrastructure modification investments.

Moreover, it is important to note that a dollar spent by a road user may not always be equal to a dollar spent by an agency (Sinha and Labi, 2007). For example, a road whose pavement is in poor condition, which subjects road users to higher vehicle operating costs due to wear and tear on vehicle tires, increased fuel consumption, and a higher chance of a crash due to distraction may need to be re-paved. In this case, even though the cost to the agency of rehabilitating the pavement is higher than the costs incurred by road users, the relative weight ratio of a dollar of agency cost to a dollar of user cost is low enough to justify the pavement improvement. After all the cost elements are established, project evaluation is carried out to identify the optimal decision. The total project expenditure is one of the possible indicators that can be used to identify the optimal decision using the traditional DCF method. Ideally, the project should be executed at the time when it produces the lowest total project cost.

In the cases being studied in this dissertation, the level of market penetration of AVs will greatly impact the value and feasibility of AV-oriented infrastructure modifications. Therefore, the AV market penetration is considered to be the source of uncertainty or the parameter of volatility. In the NPV approach, when the user benefits are found to exceed the agency costs, the optimal decision is to proceed with the proposed infrastructure change. In ROA approach, the instant cost savings (at each year) associated with the proposed infrastructure change (cost savings when the project is executed), are computed and compared with the expected cost savings when the proposed change (the addition of a dedicated lane for AV operations) is deferred. Based on the aforementioned criteria, the optimal decision is determined.

As discussed in Chapter 3 of this dissertation, three commonly used ROA methods could be employed to find the value of an option. In this dissertation, the binomial lattice and Monte Carlo simulation methods are implemented to determine the option’s value; however, the BL method is preferred because it allows an investment’s value to be tracked throughout the analysis period. This is a vital distinction of this approach that is relevant in the context of this dissertation. In addition, it requires less computational effort compared to the Monte Carlo simulation.

4.3 Chapter Summary

This chapter presented and defined the study framework proposed in this dissertation. Within this framework, all of the major steps and tasks required to determine an optimal AV-related infrastructure readiness decision were identified for both the DCF and ROA approaches. The application context of the user/agency cost weight ratio and the two ROA methods were also noted in the study framework. The following chapter implements the first step of the study framework by soliciting the input of three key stakeholders (AV technology developers, highway agencies, and road users) and presenting the outcomes of survey questionnaires designed to retrieve the perspectives, opinions, and preferences of these stakeholders in AV implementation.

5. STAKEHOLDERS’ PERSPECTIVES

5.1 Introduction

This chapter elaborates on the first step of the study framework introduced in the previous chapter. The key stakeholders are AV technology developers, transportation agencies, and road users, including both users of AVs and those sharing the road with AVs while driving or riding traditional vehicles. The established critical roles of these stakeholders towards AV operations have already been described in Chapter 2 of this dissertation. The stakeholder participation model clearly elucidates the major elements and tasks corresponding to these stakeholders with regard to the AV implementation. This chapter demonstrates how some of these elements can be captured for further consideration in the agency decision-making process related to AV-oriented infrastructure readiness. This chapter describes surveys that were used as an effective tool for capturing the perspectives and preferences of the key stakeholders. This chapter also duly recognizes the spatial and temporal limitations of the survey findings and their applicability.

5.2 AV Technology Developers

5.2.1 Introduction

In this dissertation, AV technology developers are defined as the firms and individuals that are involved in developing autonomous vehicle technology. These include vehicle manufacturers, software developers, and experts and companies in other industries that are contributing to innovations and enhancements for all or part of the capabilities and technological components of AVs (for instance, laser sensors, LiDAR, machine vision systems, and artificial intelligence software). The industry is leading the efforts in the development and testing of AV technology. Therefore, it was relevant and appropriate to ask industrial experts instead of transportation agency personnel, to comment on the potential timing of the deployment and commercial availability of AVs for public use. This is also because these experts are fully aware of the current state of the technology, its potential evolution, the plans for improvements to the technology, and the state of the ongoing testing of this technology (and its performance and reliability during testing). The current state and capabilities of AV technology and the timing of commercial deployment are expected to have implications on market penetration. As such, technology developers were also asked how they expect market penetration rates to grow or change.

5.2.2 Survey Questionnaire, Findings and Discussion

The questions that were asked of the technology developers along with the responses are presented in Table 5.1. A total of 83 technology developers were surveyed through either an online survey tool or the distribution of a paper-based questionnaire on different occasions in the year 2018. One such occasion was at the 2018 Automated Vehicle Symposium held in San Francisco, California, where numerous well-known companies involved in the development of AV technology, including Waymo (a self-driving technology development company, formerly the Google self-driving car project), were heavily represented as exhibitors displaying their contributions to the development of AV technology. The survey was concluded in August 2018. The questions asked and the responses recorded are discussed in the following sections.

1. First time of AV availability for public use

As shown in question 1 in Table 5.1, the respondents were asked to comment on the very first time that AVs would be available for public use. Respondents were also allowed to record a response of their own in case they chose not to select any of the options offered. Twenty-nine percent of respondents believed that AVs would be available for public use in 2020, whereas 24% thought it may happen in 2023. In one of the recent reports by Litman (2018), it was stated that Level 4 or 5 vehicles might be commercially available in the 2020s. Thirty-five percent of respondents wrote their own responses. Some of these written responses were as follows: “10 to 15 years minimum,” “8 years,” “level 5 is not expected more than 5 years from now,” “Waymo cars are available now,” “today,” and “technology will develop more quickly; however, the ‘certification’ process for AVs will take much longer, and also the readiness of highway/street infrastructure will delay its public use.”

The last response is particularly interesting. This reflects the notion that the AV technology industry is aware of the fact that the inception of AV operations will depend on road infrastructure readiness, as also noted by Johnson (2017). The former part of the response, related to certification, refers to the development of regulations by governments, and the latter part of the response indicates the need for road infrastructure readiness. As discussed in Chapter 1 in this dissertation, the AV technology industry has expressed serious concerns regarding the non-readiness of the road infrastructure, particularly the poor road surface conditions and markings, which prevents AV technology from adequately sensing the road. Furthermore, one of the responses noted earlier, "Waymo cars are available now," came from a representative of Waymo. While that response was recorded in July 2018, apparently Waymo already had a plan to initiate their commercial service by the end of 2018, which they had not yet unveiled at the time. In December 2018, Waymo started a trial program for a 24-hour commercial driverless taxi service, named Waymo One, in the Phoenix metropolitan area. This service is similar to Uber and other ride-hailing apps; however, it is available only for those riders who participated in the initial stages of the trial program. These riders are allowed to bring along a child and two adults. Moreover, while these Waymo cars are completely self-driving, a human driver will be present initially, not to take control of the car but just for the riders' convenience, trust, and comfort. Moreover, Business Insider Intelligence (2018) revealed the plans of Waymo, Uber, and General Motors to deploy AV fleets to provide on-demand ride services in various U.S. cities.

2. Timing of road infrastructure investments to accommodate AV operations

Another important question that was asked of the technology developers was related to the timing of major AV-related road infrastructure changes in relation to AV market penetration. As the responses to question 2 in Table 5.1 indicate, 41% of the respondents suggested making major infrastructure changes when the vehicular traffic on roadways consists of about 25% AVs. Conversely, 17% of the respondents wrote their own opinion rather than choosing one of the given options. Some of these responses were "the sooner the better; it will accelerate market penetration," "unclear if that will be necessary/feasible," and "between a quarter and a half." The first response demonstrates and validates the stakeholder participation model introduced in Chapter 2 of this dissertation, which posits that the adequacy of infrastructure readiness may have implications for accelerating or hindering market penetration. Adequate infrastructure readiness is expected to address many of the concerns of prospective users who are apprehensive about riding in AVs, and, as such, more people would be expected to adopt the technology. One such example of infrastructure readiness could be the provision of protected, exclusive lanes for AVs, which could elevate AV users' comfort levels and reduce their anxieties by minimizing the chances of conflicts or interactions with traditional vehicles in the traffic stream. The second written-in response, "unclear if that will be necessary/feasible," depicts the lack of consensus on this question; the respondent questioned whether road infrastructure accommodations for AVs would be necessary or even feasible in the first place. The opinions of some infrastructure experts align with this response. This is mainly because making substantial changes to the existing infrastructure may require a significant amount of funds, which is a rather difficult challenge to meet. Moreover, this response can also be attributed to the uncertain length of the transition period for AV operations. During a meeting of the National Governors Association, the CEO of Waymo asked the governors not to cease their current infrastructure investments just yet, mainly because a very long period of overlap between personally owned HDVs and AVs on the roadways is expected (Abuelsamid, 2018).

3. Freeway readiness for AV operations

Another important question that was asked of the technology developers was related to the road infrastructure modifications needed to support AV operations on freeways (the Interstate highway system in the United States) in the early stages of AV deployment. Forty-one percent of respondents suggested the provision of a dedicated lane for AV operations. However, 53% of respondents deemed it unnecessary to make any changes during the period of the initial deployment of AVs. This split in responses from technology developers provided the two scenarios that are analyzed for their economic implications in subsequent chapters of this dissertation: (a) no changes are made to freeway corridors, but only the basic requirement of all-weather-visible and tractable pavement markings that can easily be sensed by AVs is met and (b) a dedicated lane for AV operations on freeways is provided.

4. Likely locations for initial AV deployment

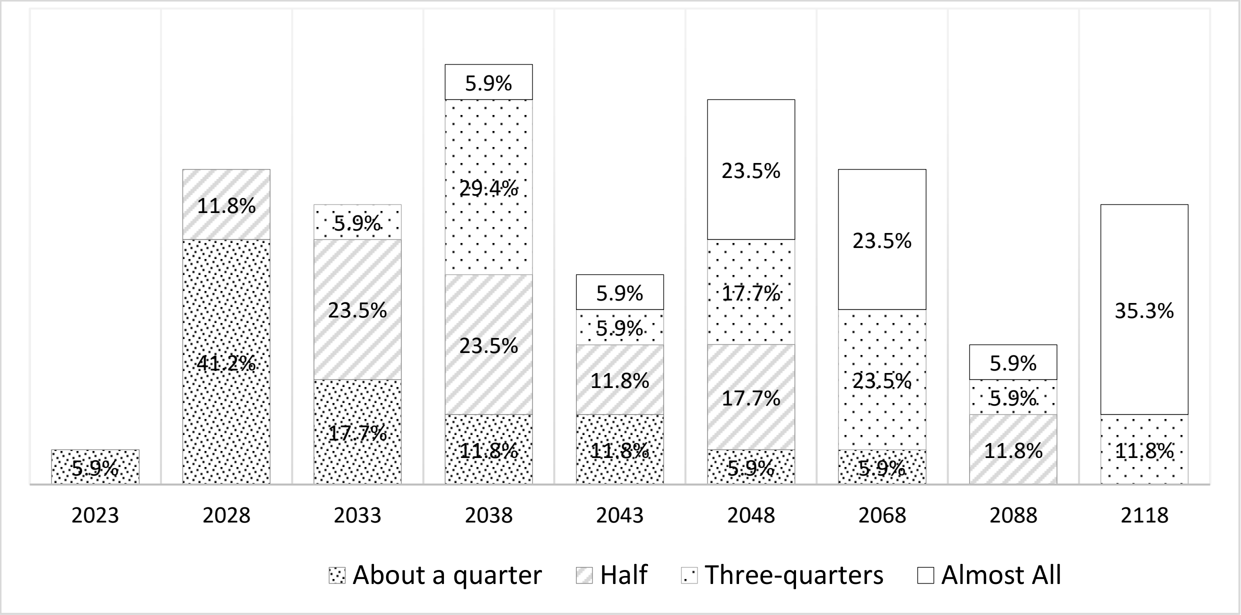
The fourth question asked of the technology developers was regarding the most conducive or favorable location for the first or early deployment of AVs. A majority of the respondents (53%) favored high-speed roadways (freeways) for the very early deployment of AVs, followed by central business districts (18%), restricted residential neighborhoods (12%), and rural roadways (6%). In addition to the options provided in the survey, respondents were allowed to write in their own responses. Some of these responses included non-open road venues and private campus environments. Overall, the responses to this question provide additional evidence that freeway retrofitting should be done first to support AV operations; a case study on this topic is presented in Chapter 7 of this dissertation.

Table 5.1 Responses of technology developers

No.	Questions	Responses	Percent
1	In your opinion, about how many years from now will driverless cars be FIRST available for public use?	Next 2 years	29%
		Next 3 years	6%
		Next 4 years	6%
		Next 5 years	24%
		Other (please specify)	35%
2	In your opinion, at which the minimum level of market penetration of driverless vehicles, should MAJOR changes be made in roadway design? (for example, reconfiguring the lane width)?	When about a quarter of vehicles on roads are driverless	41%
		When half of the vehicles on roads are driverless	24%
		When three-quarter vehicles on roads are driverless	18%
		Other (please specify)	17%
3	At the INITIAL deployment of driverless vehicles on a FREEWAY, which of the following design changes would you suggest?	A dedicated/ separate/ exclusive lane for driverless vehicles	41%
		A dedicated lane for trucks and other lane(s) for driverless and traditional automobiles.	6%
		No change is necessary	53%
4	In your opinion, which of the following locations should be the first for deploying driverless vehicles?	High-speed roadways (freeways, expressways)	53%
		Urban highways	0%
		Central business districts	18%
		Restricted residential neighborhoods	12%
		Rural roadways	6%
		Other (please specify)	11%

5.2.3 Market Penetration Trends

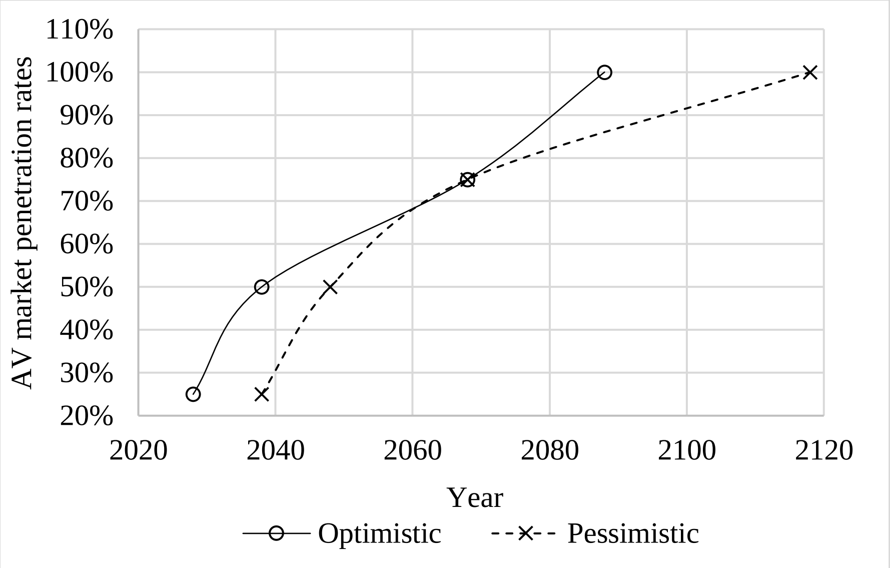
Another question asked of the technology developers was related to the emergence of AV market penetration rates over time (years). Respondents were asked to provide the times (years) when they believed AVs would constitute the following specific fractions of the vehicle stream on roads: about a quarter, about half, about three-quarters, almost all. For each fraction, the possible responses were within 5 years, within 10 years, within 15 years, within 20 years, within 25 years, within 30 years, within 50 years, within 60 to 70 years, and within 80 to 100 years. The survey was conducted in the summer of 2018. The responses are presented in Figure 5.1 and clearly depict quite disparate opinions about the market penetration rates of AVs. This signifies the uncertainty and volatility surrounding market penetration rates. The market penetration trends predicted by the respondents are presented in Figure 5.1(b). Though the actual market penetration rates will depend on customers' adoption and use of AV technology, nevertheless these responses from the technology developers could be a proxy of the industry's expectations regarding the timing of user adoption of its technology. Additionally, these responses could be an implicit indication of how soon the industry expects to achieve certain levels of market penetration based on its efforts in technological advancement and testing. Two trends of market penetration rates were established based on the survey responses, as shown in Figure 5.2(b). One trend suggests 25% market penetration by the year 2028 (the optimistic trend), whereas the other trend indicates that this market penetration is expected to occur by the year 2038 (the pessimistic trend). The optimistic trend expects to attain 100% market penetration by the year 2088, while the pessimistic trend predicts this market penetration happening by the year 2118.



(a)

Fig. 5.1 Market Penetration Trends

Fig. 5.1 continued



(b)

5.3 Highway Agencies

5.3.1 Introduction

As the stewards of road infrastructure, highway agencies are responsible for developing new road facilities and for the expansion, retrofitting, rightsizing, modernizing, maintenance, rehabilitation, and reconstruction of the existing facilities. The critical role of highway agencies in AV implementation in the context of road infrastructure readiness is discussed in Chapter 2 of this dissertation.

For this chapter, highway agencies (state and local) were surveyed to capture their perspectives and opinions regarding the emergence of AVs and their implications for the current and the future road infrastructure and design features. The questions that were asked of the agency respondents along with their responses are presented in Table 5.2. A total of 39 agency responses across the United States were collected through an online survey distributed by the American Association of State Highway and Transportation Officials (AASHTO). AASHTO is a nonprofit association representing highway and transportation departments in the 50 states, the District of Columbia, and Puerto Rico. It also develops and publishes guidelines used in highway geometric design and construction across the country. The questions asked and the responses provided are discussed in the remainder of this section.

5.3.2 Survey Questionnaire, Findings and Discussion

Fifteen major questions were asked of the highway agencies. In addition to selecting one of the responses offered by the survey, respondents were provided an opportunity to note the reasons for their choice or other important thoughts related to the selection of an option from the pool of choices for a given question. It is clearly noticeable from the quality and comprehensiveness of the written responses that the agency personnel responded in a very careful and responsible manner, which is an indication of their keen interest, curiosity, and thoughtfulness regarding AV-related infrastructure readiness. Valuable insights were derived from these responses, which are discussed below.

1. <u>Timing of road infrastructure readiness to accommodate AV operations</u>

When agencies were asked about the level of AV market penetration at which AV-related infrastructure retrofits and related investments would be appropriate, 20% of respondents felt that such investments would be appropriate at 25% market penetration, 20% chose 75% market penetration, and 8% chose 50% market penetration. However, 52% of respondents recorded their own independent thoughts rather than selecting an option from the given choices. These responses are discussed in the following paragraphs.

One response emphasized the need for AV-related road infrastructure immediately without any delay because the respondent noted, it is not possible to stop the future from coming; if agencies are not planning ahead now, they will fall behind quickly. One response indicated high expectations regarding AV technology, noting that no infrastructure accommodation is needed for AVs; rather, AVs should be capable of navigating any road (including gravel roads) in any weather with limited pavement markings or signage. AV technology can be developed to be sophisticated enough to do so, but such sophistication may lead to higher costs for consumers, which may impede market penetration. Other respondents indicated that infrastructure retrofitting and investments should be made at the half-way point when it is clear and certain that AV technology is sufficiently developed and the automotive industry in the U.S. is heading towards AVs. This type of response shows that some agencies want to wait and see how the technology progresses before making any infrastructure changes.

Another response noted that AV-related infrastructure planning should be initiated when the first AV is deployed. Still another response remarked that the AV industry is designing vehicles to drive on existing facilities; there will always be a need to design road facilities for human drivers, and public transportation and infrastructure facilities must accommodate all users. One of the respondents noted that the road infrastructure should be updated as soon as any deployed AVs encounter problems using existing infrastructure, such as that in work zones. If any safety issues arise that could be improved through updating infrastructure, the infrastructure updates should then commence (given that the volume of AVs will only rapidly increase). Another response suggested that infrastructure improvements should be made when it is understood with some reasonable degree of certainty what infrastructure changes would be required for and/or beneficial to AVs, while the needs of vehicles driven by humans should continue to be met.

One of the responses noted that even at a 10% market penetration rate, cooperative adaptive cruise control will start showing improvements in throughput. Infrastructure owners and operators (IOOs) should start gearing up now to engage private industry and inquire what improvements are needed. Once the needs are identified, IOOs should start implementing them.

Another respondent noted that infrastructure improvements should be made when AVs become imminent, as it will likely take some time to prepare the infrastructure to meet the needs of driverless vehicles. Another agency respondent noted that improvements should be made now as a proactive measure to avoid delays in the implementation of AVs.

Another detailed response stated that “determining infrastructure needs for AVs is an ongoing iterative process that has already started and will parallel development and deployment of the technology. The State of California has recently adopted new striping standards that improve contrast and visibility for all drivers, including automated driving systems. Right now, there is a lack of clarity in terms of exactly what agencies will need to do to accommodate AVs. The respondent further noted that some auto manufacturers have taken the stance that their vehicles must function safely regardless of infrastructure deficiencies such as poor pavement or marking condition, and they cannot rely on specific infrastructure requirements. However, as automated vehicles develop further, it seems likely that there will be a better understanding of the infrastructure changes that will be conducive to recognition by machine vision systems, and standards or best practices for machine-readable infrastructure will likely emerge, possibly through the Federal Highway Administration’s Manual on Uniform Traffic Control Devices (MUTCD). The respondent continued to note that there is sometimes speculation about the ways that AVs could change infrastructure requirements. For example, in the future, all lanes could be made narrower because AVs are expected to operate safely at closer distances/headways, and they are expected not to wander from their tracks. However, this conjecture is premature because a mixed environment of AVs and human drivers is expected to last for decades at least. The infrastructure design changes should not be defined and planned based on the predicted characteristics of future vehicles.

Obviously, from the aforementioned responses, there is a strong realization of the infrastructure changes needed to accommodate AVs on the roadways. However, there is a lack of clarity regarding exactly what agencies will need to do and when changes must be implemented. One thing that is obvious, however, is that identifying infrastructure needs and then retrofitting to support AV operations is an ongoing, iterative process that will occur in parallel to the development and deployment of the technology.

2. Likely locations for initial AV deployment

When respondents were asked for their opinions regarding the likely roadway environments for the very first deployment of AVs (the second question in Table 5.2), 32% of respondents chose high-speed roadways (freeways, expressways), followed by central business districts as the next most preferable option (24%); however, 28% noted their independent thoughts. These are discussed in the following paragraphs.

One of the responses noted that AVs are expected to operate on all types of roadways very soon; it will be difficult to keep them on only one type of roadway. This is a plausible response, particularly given the fact that discussions regarding the deployment locations of AVs often do not account for the realistic situation that roadways of different classes and in different areas of the built environment (city center, urban, suburban, and rural) together constitute an integrated network, and therefore AVs cannot be constrained to drive on one particular type of roadway. However, high-speed roadways are usually cited as the top preference for initial AV deployment, especially during the early transition phase when the safety and efficiency of AVs in the actual driving environment are not completely known. On high-speed roadways that have controlled access, there are fewer chances of encounters and interactions compared to other road types. Moreover, the efficiency benefits can be more easily investigated on these road types.

Two similar responses suggested the initial deployment of AVs in multiple locations: (a) “There could be multiple deployment scenarios such as AV bus rapid transit in urban areas, shuttles in suburban environments, or shuttles that can be in a controlled setting (e.g., airports, hospitals, shopping centers, military installations).” and (b) “Perhaps a combination of locations - where the technology may be perfected and where there is the highest likelihood of success for the AVs and the highway environment. One would envision this being any one of the following: high-speed roadways (due to their greater degree of uniformity), urban highways, and central business districts (CBDs). A key component could be placing a geo-fence around areas where AVs may be allowed to operate given there is adequate infrastructure to support AV operations.”

Another two respondents offered similar suggestions that emphasized the deployment of AVs in protected dedicated lanes: (a) “High Occupancy Vehicle (HOV) lanes are the first candidates where AVs can be implemented. This will provide some separation of AVs, in the initial phases of deployment, from the non-automated traffic.” and (b) “Express lanes, HOV lanes, etc. that are separated from general use lanes by concrete barriers.” The emphasis on the provision of protection, even in the form of exclusive lanes, depicts a strong realization at the agency level that trust issues exist both for those who plan to use AVs and for those who will drive their traditional vehicles but share the road with AVs.

Another detailed response tied the location of AV deployment to the business case for AVs: “AVs will be deployed where private companies can justify a business case for them. Automated freight and automated taxi services have been offered as possible examples of profitable applications but are predicated on the maturation of the technology. There are widely varying opinions on how close the technology is to maturity and how difficult it will be to overcome the remaining engineering challenges. That makes it possible that a lower-risk technology—such as a low-speed shuttle—might actually be ready for safe deployment sooner. Is the question of what technology ‘should’ be deployed first based on achieving a sufficiently safe roadway operation? No one knows who will do that, or when, so that question is unanswerable.”

Additionally, many respondents offered comments to provide additional thoughts or reasons for the selection of their choices, such as the following:

- A respondent chose urban highways because he witnessed AV testing on freeways in Arizona.
- A respondent selected CBDs because it is believed that these areas will have the most action for an AV to react to. Moreover, it is easier to finance technology in busy areas. By

deploying AVs in these areas, one could investigate the vehicles' reaction times in busy environments to a variety of objects.

Respondents who chose high-speed freeways as candidates for the initial deployment of AVs stated that they did so for the following reasons:

- The high-density environment offers better support and fewer chances for the fatal crashes that Uber's and Tesla's automated vehicles experienced.
- Such roads are the easiest for AVs to handle.
- There is limited access.
- AVs are easier to implement on these roads.
- Higher levels of automation are likely to start in constrained ODDs. Limited access roadways will likely be the first location for the deployment of AVs. This has already been seen for low levels of automation, like General Motors's Supercruise and Tesla's Autopilot. However, some limited AV deployments can also be done in urban areas using low-speed automated shuttle and mobility-as-a-service (MaaS) providers working in specific geofenced locations;
- High-speed limited access facilities are the most predictable environments for vehicles. They also seem like a "rational place" for drivers to switch to the autonomous mode for long road trips.
- Agencies are more likely to be able to maintain freeways/expressways in a condition that would support driverless vehicles.

Respondents who chose restricted residential neighborhoods as likely locations for initial AV deployment stated that they did so for the following reasons:

- These roads offer a more controlled lower speed environment where vehicles making repeated short-distance trips can be monitored.
- The investment is very valuable to village centers.
- The systems infrastructure (WiFi, etc.) will likely be more highly developed in urban areas, and the public living and working in central districts will likely gain more from AV operations. By "gain more", the respondent meant that residents and workers would benefit from no parking fees, reduced congestion, improved safety, etc.

Some respondents indicated that they chose rural roadways as the location for the initial deployment of AVs mainly because AVs' actual performance in real-world roadway environments should first be evaluated on low-volume open roads for safety reasons and then on more urbanized roads after there is greater confidence in the software/hardware.

Other responses included the following:

- The first locations should be places where challenges can be safely met and can benefit the ongoing refinement of issues and technologies.
- One respondent noted that limiting deployment to a single classification of roadways would not help overcome the challenges posed by each roadway type. In order for testing to be effective and to expedite the development of the technologies, AVs should be deployed in a variety of conditions and on a variety of roadway types.
- The testing and performance evaluation of AV technology should be undertaken at different locations and in different settings. This and the previous response were the most plausible and realistic responses.

3. <u>Freeway readiness for AV operations</u>

When asked explicitly about the likely design changes that would be necessary to support AV operations on freeways during the transition phase, 44% of respondents suggested providing a dedicated/separate/exclusive lane for AVs. Respondents stated that they selected this choice based on the following reasons:

- To enhance safety
- To prove the effectiveness and efficiency of AVs first
- Testing should occur in a controlled environment prior to a situation with mixed traffic (motorized vehicles, bicycles, and pedestrians).
- Initially, AVs should be segregated from mixed-flow traffic to ensure that the technology is safe and error-free. In addition, it will take some time for drivers to get used to mixing with AVs, so the integration of such vehicles into general traffic should be phased in.
- High-occupancy vehicle (HOV) and high-occupancy toll (HOT) lanes are the best candidates for implementation of all levels of automation. HOV/HOT lanes will not only

provide separation from non-automated traffic but will also let agencies determine whether automated technologies are providing any improvement in safety and mobility.

- To minimize conflicts between driverless and traditional vehicles, it is a good idea to have a dedicated lane for driverless vehicles until a significant saturation of AVs occurs.

All of the aforementioned viewpoints indicate the realization at the agency level that not only AV users but also the users of traditional vehicles are duly regarded in the decision-making process. Highway agencies want to assure a roadway infrastructure environment that is equally friendly for both AV and non-AV users.

Twenty-four percent of respondents suggested providing a dedicated lane for trucks with other lanes for autonomous and traditional passenger vehicles. For choosing this option, the respondents gave reasons such as (unedited here):

- This way one knows where the trucks are in snowstorms.
- Due to the increased demand in freight traffic and driver shortages, the trucking industry has a financial incentive to adopt automation faster. As a result, not only will there be platooning but also unmanned operations. To address initial public safety concerns, trucks should get dedicated lanes. Leading up to this, the lanes could be used for traditional trucks (similar to what Georgia is doing).
- This will facilitate platooning and, hence, fuel efficiency.

In response to this question, 32% of respondents did not choose an option from the given choices but rather recorded their own opinion. One respondent did not envision dedicated lanes to begin during the initial AV deployment for two reasons: this would represent too much infrastructure dedicated to too few users, and human drivers would not comply with the road markings unless the lanes are protected. Another respondent did not see any need for a dedicated lane for AVs or a dedicated lane for heavy vehicles. Still another respondent doubted whether his/her state agency would be able to devote lanes for AVs or trucks and concluded that the agency would likely have mixed lanes for foreseeable future. Another respondent from a state agency foresaw a need only for improved pavement markings and signage. A particularly important response from a state agency respondent was that there is no rational basis for speculating about future highway design changes with almost zero data about AV capabilities at deployment or considerations related to interaction with human drivers. If at deployment a pattern emerges where collisions between AVs and traditional vehicles are significantly more common than collisions between AVs or between traditional vehicles, that pattern might provide a justification for creating a separate lane for AVs. However, AV manufacturers are currently designing their technology with the intention that it can interact with and respond to all road users, including human drivers.

The last few responses above reflect one of the scenarios analyzed in this dissertation, namely that no major changes are made to freeway corridors except the provision of enhanced or more visible pavement markings that can easily be sensed by AV machine vision systems under all weather conditions.

4. Minimum MP rates for making major roadway design changes

When asked about the minimum level of AV market penetration needed to make major roadway design modifications (for instance, reconfiguration of lane widths), 28% of respondents indicated that this should be done even before AVs are deployed, 16% indicated that this should be done when a quarter of vehicles on the road are AVs, 16% suggested doing so when 75% of vehicles are AVs, 4% of respondents suggested doing so when 50% of vehicles are AVs, and 36% of respondents provided their own responses, which are summarized below.

One agency respondent noted that during or near the end of “testing” on a separate right-of-way, it would make sense to prepare draft roadway specifications. Once the technology is “proven,” then final specifications should be prepared. So, design modifications should be considered sometime between “even before AVs are deployed” and “when about a quarter of vehicles are AVs.”

One respondent suggested making changes to roadway design and infrastructure only in response to the issues experienced by AVs upon their first deployment. Another agency respondent did not anticipate any change for the foreseeable future because currently there are no real-world data available to determine the exact impacts and infrastructure needs of AVs. Another respondent called infrastructure modifications a “bootstrap process” and suggested that both the infrastructure preparation and the AV market penetration should occur simultaneously. In other words, private industry and IOOs should work hand in hand to implement AVs on the roadways. Lastly, one agency respondent stated that commenting on roadway design is premature speculation, noting, “If a human driver needs a 12-foot lane to drive safely, it does not matter if 3/4 of the vehicles are

AVs and require less space. Either the lane must remain 12 ft in width or the narrower lane must be restricted to only those vehicles which can navigate it safely. In any case, this conversation is premature, and highway agencies do not make infrastructure decisions based on predicted capabilities of future vehicles." The same was noted in FHWA (2018) that highway agencies cannot make huge investments to retrofit road infrastructure until the state of AV technology and the infrastructure needs are clear and certain.

5. Changes in the amount of vehicle travel

When asked about the expected changes in the amount of vehicle travel or vehicle miles traveled (VMT) with the increased use of AVs during the transition phase, 42% of respondents expect an increase, for the following reasons (stated here unedited):

- If an AV is used as a MaaS (Mobility-as-a-Service) vehicle, the amount of travel for that vehicle will increase as the vehicle is driven more when used for a service than when driven by one person.
- If AVs are not parked, they may be cruising around looking for passengers or goods to serve. To offset the costs to the owners of the vehicles, AVs will need to keep moving to make money.
- Driverless vehicles will provide transportation options not currently available for the elderly and disabled. In addition, if subscription services begin to replace car ownership, there is a strong likelihood that AVs will travel empty on roadways as they transit to pick up a subscriber requiring transportation.
- No matter what and definitely in more rural areas, there may be an increase in mileage of empty vehicles. This may be to get to remote parking, or it may be to facilitate remote pick-ups.
- AV MaaS providers will look to increase their footprint and attract younger people that currently do not have a license or a car. Similarly, more mobility options may emerge for the elderly and disabled with the use of AVs. As such, VMT is expected to increase. Moreover, low-speed shuttles are expected to address first/last mile travel issues, potentially reducing pedestrian and bike traffic.
- Trip making requires a driver. Currently, a lot of trips do not happen due to the lack of a driver. With AVs, it will be possible to make driverless trips (e.g., for the elderly, young

children, etc.). In some extreme cases, it might be possible to let the car drive without a driver just because parking is not available or might be expensive (e.g., in New York or San Francisco). As such, VMT is expected to see a definite increase.

- VMT will increase due to the increase in the number of trips made by driverless vehicles picking people up and dropping them off.
- Automation is predicted to lower the cost of transportation due to historical evidence that declining transportation costs induce additional vehicle travel. Theoretically, a high degree of sharing or the use of high-capacity modes could outweigh induced demand, but in preliminary studies of the interaction between new modes and transit, there does not exist any evidence for this.

Only 21% of respondents expect a decrease in VMT with the use of AVs, mainly because the availability of AVs will result in increased use of these vehicles as a shared service and thus a reduction in VMT. Twenty percent of agency respondents expect VMT to remain the same.

Seventeen percent of agency respondents were unsure about the changes in VMT, mainly due to the following reasons (stated here unedited):

- It is hard to believe that a change in transportation technology will determine a change in travel demand. Travel demand is generated by other factors not related to transportation technology, such as the local economy and housing prices. A reduction in the use of mass transit (e.g., shuttles, buses, or rail systems) can be envisioned; however, the net change in vehicle travel is uncertain at this time, and the results will likely vary by location.
- The ways in which possibly longer commute times will interact with and offset the impact of shared vehicles (e.g., Uber) is completely speculative at this point.

6. <u>Change in the amount of passenger travel</u>

When asked about the expected change in the amount of passenger travel or passenger miles traveled (PMT) with the increased use of AVs during the transition phase, 50% of respondents expect an increase for the following reasons (stated here unedited):

- More opportunities will be available for younger, disabled, and older people to take trips.

- Passenger travel may increase slightly because driverless vehicles will allow for those who cannot drive themselves (e.g., the young, elderly, or disabled) to be transported more easily and more frequently.
- Traveling from point A to point B and not having to worry about driving will be an asset; being able to get projects complete en route will benefit time management.

Moreover, 29% of agency respondents expect PMT to stay the same, mainly for two reasons. First, travel needs will not increase much, except for the possibility of additional long vacation trips. Second, travel demand to desired destinations should stay the same, though the means of travel will change. These two reasons and some others given to support this response regarding PMT are not rational and logical, which shows that these agency respondents were not able to effectively comprehend the nature of PMT in the era of AVs. Transportation agencies were probably not the right subjects for this question; the question should rather be posed to transport service providers based on their proposed business models in the era of AV operations.

In addition, 13% of the respondents were unsure about the emerging trends of PMT with the increased use of AVs. One of the most plausible reasons offered for this response is that it is difficult to discern how AVs will be used in the future by the public, families, and businesses.

7. Infrastructure funding needs

When asked about the highway infrastructure funding needs to accommodate AVs, 63% of agency respondents expect an increase for the following reasons (stated here unedited):

- Infrastructure is so "behind the times" in many states already, and the government will need to step up and fund more projects to facilitate AV deployment through infrastructure retrofitting and related investments.
- Communications infrastructure (internet and WiFi) will need to be expanded in rural areas lacking connectivity in order to fully support AV operations.
- Funding needs always increase when new innovations are brought forth.
- There are many reasons, but primarily system requirements such as advanced signals, enhanced lane markings, and compatible signs.
- Since all roads (urban, suburban, and rural) are not set up for AVs, something has to new on the street level that does not exist today; that could be cyber-physical infrastructure.

- While talking to all of the original equipment manufacturers (OEMs), the standard response for what AVs need from the departments of transportation (DOTs) is “smooth roads and clear pavement markings.” There will be a strong push to improve pavement conditions. Right now, some roads are not re-striped for two years. This may not be an option in the future.
- It is a serious challenge – how driverless vehicles will be able to detect and navigate potholes and other roadway obstructions.
- There are serious doubts that current funding levels are adequate to maintain the system to adequately accommodate driverless vehicles.
- Existing facilities are not ready for driverless technologies at all. With every agency in need of improvements, there will be a heavy demand for funding. An additional question is where that funding will come from. The public will be resistant to additional taxes, fees, and surcharges.
- While the magnitude of additional investment is highly uncertain, state agencies expect that there will be some new requirements for data backhaul, processing, and dissemination, and potentially infrastructure changes to ensure machine readability. It is even less certain whether infrastructure investment benefits, such as less money spent repairing infrastructure following crashes, could help to offset these costs.

Only 8% of agency respondents foresee a decrease in highway infrastructure funding needs to accommodate driverless vehicles. The most plausible response noted was that with an increase in travel, IOOs will have to implement a usage-based model for infrastructure funding. The funding will have to be increased based on higher usage. As such, the amount of usage will define the needs.

Furthermore, 17% of respondents expect funding to stay the same primarily because of limited resources or limitations in the ability to change the amount of resources. Another reason provided was that roadway projects can maintain the same costs while simply using modified designs to handle the needs of AVs. The respondents commenting on the resources did not quite seem to understand the question, which asked about “needs that could arise” and not “resources.”

Moreover, 12% of respondents were unsure about the infrastructure funding needs, attributing this uncertainty to the many unknowns at this time and the possibility that funding may increase due to expanding equipment needs but may decrease if AVs are able to increase throughput using existing lanes or even decrease the number of lanes needed.

8. Overall parking needs

When asked about the overall parking infrastructure needs with increased AV operations at higher levels of market penetration, 65% of respondents expect these needs to decrease for the following reasons (stated here unedited):

- If AVs are used as part of a MaaS operation, then AVs would not be parking but in continuous motion.
- In order to offset the costs of vehicle purchase and upkeep, owners will need to keep their vehicles moving goods and people.
- Parking needs should decrease as the efficiency/use of road vehicles may increase and it would be unnecessary to park all day or all night in one location.
- Parking will no longer be the issue. Curb space will be a big focus. Vehicle ownership is envisioned to stay the same or decrease, even with an increase in the vehicle use. These shared models will decrease the need for centrally located parking.
- Fewer people driving their own vehicles means no need to park, just like the Uber model.
- Autonomous taxi services will result in less parking need.
- AVs could take several passengers to their destination, and then return home to wait until the next travel request.
- There will be a need for increased passenger loading/unloading zones and less need for parking.

Seventeen percent of respondents were unsure about the overall parking needs with increased AV operations, citing the following reasons (stated here unedited):

- Many people may not want to use a vehicle that is available for public use.
- Many people may not want to wait for the AV to arrive on time to pick them up for their drive. They would rather use a self-owned vehicle—with all their comforts—and they will want it in a timely manner.
- The issue is too complicated to determine at this point in time. For example, one would need to know whether a driverless vehicle ever needs to park.

Moreover, 9% of agency respondents thought that overall parking needs may increase due to the continuing rise in population and the resulting need for additional parking, despite the prospective increase in ridesharing. Conversely, 9% of respondents thought that overall parking needs may stay the same because (a) whether one is driving or riding, the car still will need to park, and (b) while parking at airports, downtowns, event locations, and residences may be reduced, vehicles will need to be parked somewhere. None of the agency respondents thought that parking infrastructure would be eliminated completely in the AV era.

9. Shoulder widths on arterials and freeways

When asked about the expected change in the shoulder widths on arterials and freeways with increased AV operations, 13% of agency respondents expect that shoulder widths will increase, mainly because shoulders are needed for refuge, emergency responders, evacuation routes, human drivers, etc. With AV operations, it is likely that shoulders will be needed more than ever so that vehicles experiencing software or hardware failures can have a safe refuge.

However, 35% of respondents expect shoulder widths to decrease with AV operations for the following reasons:

- Driverless vehicles are projected to handle road conditions better; therefore, the need for a shoulder on a road may decrease.
- Driverless vehicles drive more precisely.
- Shoulders are predominately used for people with vehicle issues, people who need to check on something, or people making a call. Since an AV functions as a driver, one may not have to pull over to make a call or check on, for example, a screaming child. One can just take his/her eyes off of the vehicle’s operations and deal with the issue. Additionally, due to an increase in sensors in the vehicle, it will sometimes be possible to diagnose issues immediately or before they happen. This will reduce the need to stop the vehicle.

Thirty-nine percent of the agency respondents thought that shoulder widths will stay the same as they are today for the following reasons (stated here unedited):

- Shoulders are for safety and mechanical breakdowns, which are expected to occur from time to time. The number of disabled vehicles is likely to increase since even minor malfunctions could force the vehicles to stop in a fail-safe mode.

- “I am not convinced we will ever get to 100% market penetration, so it will stay the same for safety reasons. If 100% market penetration is reached, widths may decrease, but there may be unanticipated reasons to use the shoulders (parking, system breakdowns, additional pedestrian/bike traffic, etc.).”
- Shoulder widths should stay about the same because bicycles and other similar transportation devices (e.g., e-bikes) may still need to use shoulder space.
- The vehicles are not changing size. It always helps to have additional pavement space for emergencies.
- The need for shoulders will remain. AVs will break down as frequently as vehicles with drivers or possibly even more due to software failures. In addition, there will still be a need for bypassing (emergencies, etc.), so the need for shoulders will not change.
- No change in shoulder widths is expected because the emergency vehicles will always be using shoulders to reach emergency locations on the highways.

Furthermore, 13% of respondents were unsure whether shoulder widths would change with increased AV operations. The most plausible explanation provided was as follows: On the one hand, shoulder widths could possibly decrease, but the transportation community will not have the inputs necessary to make this decision until far in the future. On the other hand, shoulder widths may stay the same because there may still be vehicular breakdowns, and space will be needed to clear the main travel way.

10. Superelevation for new roadways with AV operations only

When asked about the expected change in superelevation for new roads containing only AVs, 70% of respondents thought that superelevation will stay the same for the following reasons (stated here unedited):

- “I don't envision that the road curvature on, say, new mountain roads will change all that much.”
- Vehicles will be designed to match existing designs. There is no push from industry to change this.
- The physics of the cars will not change.

- Horizontal curve design is based on speed, which should not change much with driverless vehicles.
- Roads are designed based on vehicle dynamics. Automation may improve the way vehicles handle themselves on the road. The roadway will have to be designed to accommodate both extremes of the vehicles; HDVs and AVs.
- Vehicles will have better capability to negotiate curves, but passenger comfort should not be compromised.

Twenty-one percent of agency respondents were not sure whether superelevation would change because they were unsure whether vehicle designs and dynamics would change over time. However, they did note that riders' comfort and expectations should not be comprised. Riders' comfort will continue to drive the geometric design of highways.

11. Radius of horizontal curves for new roadways with AV operations only

When asked about the expected radius of horizontal curves for new roadways containing only AVs, 74% of respondents did not foresee any change occurring for the following reasons (presented here unedited):

- Automation cannot change vehicle dynamics as the laws of physics remain the same for all vehicles.
- Horizontal curve design is based on speed, which should not change much with driverless vehicles. Also, the comfort of vehicle occupants is critical.
- Shorter radii will make passengers uncomfortable. It is unlikely that people will tolerate tighter curves.
- Larger vehicles (like buses and trucks), albeit driverless, will still be on the roads.
- During the transition phase, human drivers must be accommodated; vehicle speed and rider comfort parameters should not change.
- Roads must be designed for the comfort of the passenger at given design speed.
- Vehicle performance and safety will not change, so horizontal curves will not change.

In addition, 17% of respondents thought that the radii of horizontal curves may decrease due to the increased precision of AVs and because AVs will be smaller and more efficient than human-driven vehicles. These arguments are not as plausible as the ones provided above in support of the claim that the radii of horizontal curves will stay the same.

12. Gradient of vertical curves for new roadways with AV operations only

When asked about the expected change in the gradient of vertical curves for new roads containing only AVs, 65% of agency respondents expect that gradients will stay the same. Respondents expect AVs to react similarly to human-driven vehicles due to the former's artificial intelligence capabilities. Additionally, one respondent commented that in the case of extreme weather, AV occupants may tolerate steeper vertical curves, but it is more difficult for vehicles to navigate such curves during snow and heavy rainfall. Moreover, respondents noted that the comfort of human occupants is of primary importance. As such, any change that may cause discomfort to human riders is not expected to occur.

Twenty-two percent of agency respondents were not sure whether the gradient of vertical curves would change, primarily for two reasons. First, vertical curve design is at least partially governed by sight distance in the case of human drivers; this factor may change, but it is uncertain. Second, changes to vertical curve gradients may depend on the design criteria of new AVs (the size and physics of these vehicles). Thirteen percent of respondents expect a decrease in this feature because while the vertical curve gradient impacts human drivers, AVs will be more aware of obstacles and other vehicles on a vertical curve.

13. Need for real-time monitoring of traffic and cyber-physical infrastructure

When asked whether there would be a need for real-time monitoring of traffic and cyber-physical infrastructure, all agency respondents unanimously responded "yes." The reason for this response is quite intuitive. Since roadways are expected to be equipped with high-tech infrastructure to support AV operations, this infrastructure may necessitate real-time monitoring to quickly identify technology/hardware breakdowns. Real-time monitoring will help ensure that extended disruptions in road operations are avoided in the case of a critical vehicle breakdown.

14. Speed limits during the transition phase

When asked about speed limits on roadways that host both traditional and autonomous vehicles, 91% of agency respondents expect speed limits to stay the same for the following reasons (presented here unedited):

- Safety will continue to be the top priority, and speed limits are defined to ensure safe road operations.
- Speed limits help manage fuel consumption.
- Speed limits should be based on 85th percentile operations, the same as current guidelines.
- There is a need to maintain driver/rider expectations and safety during the period when the traffic stream contains a mix of AVs and HDVs.
- Speed limits are (in part) decided by geometric features and topography. This may not change when roads host both AVs and HDVs.
- Mixed traffic will still include human drivers and their limited cognitive and physical abilities, so the safety factor will not be reduced much.
- With mixed traffic or a market penetration for AVs of under 100 percent, no change in the speed patterns of traffic is expected because one of the factors governing vehicular speed is tire/roadway resistance. Moreover, throughput in certain cases increases at lower-than-posted speeds.
- Driverless vehicles should conform to the same speed limits as traditional vehicles during the transition phase.

In contrast, only 9% of respondents expect a decrease in speed limits in the AV area, mainly due to the potential for a greater number of conflicts if traditional and autonomous vehicles are allowed to have mixed operations during the transition phase.

15. Speed limits during fully autonomous phase

When asked about speed limits on roadways hosting only AVs, 57% of agency respondents expect speed limits to increase for the following reasons (presented here unedited):

- AVs will take the “human” factor out of the equation.
- With the availability of higher levels of technological sophistication, speed limits should increase because the safety capabilities of AVs will be greater than those of HDVs.

- The efficiency and effectiveness associated with AVs will eliminate human error.
- Assuming human judgment is removed but the topographic features of the road are the same, some increase in speed limits can be envisioned, but (perhaps) not all that much. On flat roads with no human judgment involved, average speeds may increase.
- AVs may be able to drive more efficiently and, unlike human drivers, adjust to changes in real-time. This will allow vehicles to travel at faster speeds. However, speeds in urban areas may not change to account for the concerns of pedestrians and other vulnerable road users.
- When only driverless vehicles operate on the roads, vehicles may travel faster because human limitations will be eliminated, and the primary safety factor will be the capabilities and reliability of vehicle technologies and mechanics.
- Vehicle behavior will be less unpredictable.

However, 22% of respondents thought that speed limits will remain the same. A plausible response noted that under fully autonomous road operations, speeds will increase in some cases, for instance, on rural highway stretches with low levels of average annual daily traffic (AADT). Otherwise, speeds will remain the same mainly due to mechanical limitations. Additionally, IOOs may enforce lower speeds in order to increase throughput at heavy-traffic urban highway segments. Eight percent of respondents were not sure about changes to speed limits.

16. Changes across arterials, collectors and local roads for AV operations

In addition to providing their responses to the questions above regarding expected changes in road infrastructure and design, agency respondents were offered opportunities to offer any additional comments and insights regarding AV-related infrastructure and design retrofitting that they might expect across arterials, collectors, and local roads in both urban and rural settings.

Respondents emphasized a need for the following:

- A similar level of implementation of infrastructure retrofitting and information technology nationwide, for instance, WiFi and other internet access technology, across all types of built environments and all types of roadways.
- Greater uniformity of traffic control devices;
- More roadside infrastructure; and

- Real-time work zone traffic control updates for AVs.

Respondents also mentioned the following possibilities:

- The elimination of traffic signals;
- The elimination of most, if not all, signs;
- Smart infrastructure;
- New types of pavement markings;
- Minor changes to right-of-way configurations;
- Narrower lanes and more access control;
- Arterials will become more efficient and safer as progress is made towards 100% market penetration of AVs. The number of controlled intersections may be reduced, and these intersections will be safer and more efficient.
- Travel demand will be lower for urban areas because fewer vehicles will carry multiple passengers to their destinations.

Regarding the collector roadways, agency respondents indicated a need for the following:

- Bicycle and pedestrian accommodations;
- More roadside infrastructure;
- Smart infrastructure;
- New types of pavement markings;
- Real-time work zone traffic control updates for AVs;
- Installation of signalized intersection communication devices;
- Greater uniformity and consistency in roadway infrastructure installations; and
- Narrower lanes.

Regarding local roads, agency respondents expected a need for the following:

- Extensive signage and markings, which are currently missing on most low-volume local roads;
- Modernization of these roadways, in terms of installing roadside infrastructure and information technology devices, on a footing similar to that of arterials and collectors; and
- Traffic control devices that traditionally have been omitted from these road types.

Table 5.2 Responses of highway agency respondents

#	Questions	Possible Responses	Percent
1	In your view, when during the transition phase should agencies start re-orienting their infrastructure to accommodate driverless vehicles?	When about a quarter of vehicles on roads are driverless	20%
		When half of the vehicles on roads are driverless	8%
		When three-quarter vehicles on roads are driverless	20%
		Other (please specify)	52%
2	In your view, which of the following locations should be the first for deploying driverless vehicles?	High-speed roadways (freeways, expressways)	32%
		Urban highways	8%
		Rural roadways	8%
		Central business districts	24%
		Selected residential neighborhoods	0%
		Other (please share your thoughts)	28%
3	In your opinion, during the transition phase, which of the following is the most likely initial design change to accommodate driverless vehicles on a FREEWAY?	A dedicated/separate/exclusive lane for driverless vehicles	44%
		A dedicated lane for trucks whereas other lane(s) for driverless and traditional automobiles.	24%
		Other (please specify)	32%
4	In your opinion, at which minimum level of market penetration of driverless vehicles, should major changes be made in roadway design (for example, reconfiguration of lane width)?	Even before AVs are deployed	28%
		When about a quarter of vehicles on roads are driverless	16%
		When half of the vehicles on roads are driverless	4%
		When three-quarter vehicles on roads are driverless	16%
		Other (please specify)	36%
5	How do you think the total amount of vehicle travel will change with the increasing use of driverless vehicles during the transition phase?	It will increase	42%
		It will decrease	21%
		It will stay the same	20%
		Unsure	17%
6	How do you think the total amount of passenger travel will change with the increasing use of driverless vehicles during the transition phase?	It will increase	50%
		It will decrease	8%
		It will stay the same	29%
		Unsure	13%

Table 5.2 continued

7	What do you expect to be the impact on infrastructure funding needs to accommodate driverless vehicles on roads?	It will increase	63%
		It will decrease	8%
		It will stay the same	17%
		Unsure	12%
8	In your opinion, how will overall parking needs change with the increased operations (say, 80-100% market penetration) of driverless vehicles?	It will increase	9%
		It will decrease	65%
		It will stay the same	9%
		It will be eliminated completely	0%
		Unsure	17%
9	How do you expect shoulder width of arterials and freeways to change with the increased operations (say, 80-100% market penetration) of driverless vehicles on roads?	It will increase	13%
		It will decrease	35%
		It will stay the same	39%
		Unsure	13%
10	In your opinion, how will superelevation on horizontal curve change for NEW roads containing only driverless vehicles?	It will increase	0%
		It will decrease	9%
		It will stay the same	70%
		Unsure	21%
11	In your opinion, how will the radius of horizontal curves change for NEW roads containing only driverless vehicles?	It will increase	0%
		It will decrease	17%
		It will stay the same	74%
		Unsure	9%
12	In your opinion, how will the gradient of vertical curves change for NEW roads containing only driverless vehicles?	It will increase	0%
		It will decrease	13%
		It will stay the same	65%
		Unsure	22%
13	Do you think there will be a need for real-time monitoring of traffic (using drones, for example) and cyber-physical infrastructure (for example, DSRC technology) in the era of driverless vehicle operations?	Yes	100%
		No	0%
		Unsure	0%
14	How do you expect speed limits to change when roads will host both traditional and driverless vehicles?	they will increase	0%
		they will decrease	9%
		they will stay the same	91%
		Unsure	0%

Table 5.2 continued

15	How do you expect speed limits to change when ONLY driverless vehicles will be operating on roads?	they will increase	57%
		they will decrease	13%
		they will stay the same	22%
		they will no more be required	0%
		Unsure	8%
16	Agency	State	90%
		Local	10%

5.4 Road Users

5.4.1 Introduction

As discussed earlier in Chapter 2 of this dissertation, accounting for the feedback of road users in this whole process of transitioning to AV operations is inevitable. The Federal Highway Administration (2018) held a national dialogue on highway automation where it was duly emphasized that including road user insights into the technical guidelines (relating to policy, regulations, and infrastructure readiness) of AV-related infrastructure preparedness at the agency level is extremely important and much needed. In the context of this dissertation, there are two classes of road users: those who will use AVs in some form (self-owned, hired, or shared) and those who will continue to use or drive traditional vehicles. The input of both classes of road users is equally pivotal to the successful implementation of this envisioned smart future of AVs. Therefore, the survey of road users presented in this dissertation demonstrates the relevance of the input and how the survey outcomes may be used to inform the decision-making process at the agency level. Different state agencies can develop and conduct similar surveys in their respective jurisdictions to capture the road users' perspectives for subsequent consideration in AV-related infrastructure decisions.

The business models of the industry may initially define the deployment scenarios of AVs (discussed earlier in Chapter 2), this uncertainty will continue to prevail until it is clearly known how the end-users of this technology want to adopt and use it (e.g., self-owned, shared, or hired). Therefore, the perspectives, preferences, and opinions of the potential consumers of this technology regarding its adoption are very important. Moreover, the transition phase is expected to span decades; therefore, the perspectives of road users who will continue to drive their traditional vehicles and share roads with AVs are equally important as the AV users. Public transportation agencies will continue to weigh both groups of road users equally in their decision-making process, as also noted by one of the agency respondents in the previous section.

One of the important questions in this dissertation is how the preferences and perspectives of these road users can be captured. At the current time where no historical data is available in the aforementioned context, a questionnaire survey was chosen as a tool to collect this information either at a state level (for state DOTs) or all other administrative jurisdictions (local agencies, city-level agencies). In this dissertation, a nationwide survey was conducted in small and medium-sized metropolitan areas (SMMAs) of the U.S. with a population of 450,000 or less. Of the 382 metropolitan areas in the country, 273 met this population criterion (US Census Bureau, 2018). As such, they represent the pulse of approximately three-quarters of the people in the country (75%).

5.4.2 Data Collection and Description

A web-based survey was used to collect data from a nationally representative sample, across age and gender. There were 1,922 respondents from SMMAs of the U.S. with a population of 450,000 or less. Various attention filters, consistency checks and response time rates were used to evaluate the overall quality of the responses, which included: (1) noting the time taken by each respondent in responding to the whole survey and (2) asking about the same item in two different sections to investigate the attention paid by each respondent while filling out the survey. Hence, the quality of the individual responses could be verified and validated. To maintain a strict check on the quality of the responses, the amount of time spent by each respondent in responding to each section in the survey was also recorded, which helped in quickly discerning potentially bad. This recording of time was an additional validation tool for the response-quality check. For example, if a respondent spent only one-minute responding to the complete survey, that observation was excluded from the analysis. The survey was expected to take about 10 minutes based on feedback from 125 test respondents in a pilot survey. Moreover, the observations that had conflicting/different answers to the same question asked in different sections were discarded. The responses reporting more children or workers than the household size were also excluded from the analysis.

Before the actual dissemination of the survey, it was distributed twice to a group of over 100 test respondents from different age groups, educational attainment levels, and professions. However, 50% of them were from a university campus; and of these, 25% were studying transportation engineering and the remaining 75% were not. The university respondents were at two different education attainment levels: undergraduate and graduate degrees. This pilot survey was carried out with the intent to assess the total time spent in taking the survey and to obtain feedback regarding the level of the respondents' fatigue in completing the survey and the complexity and interpretability of each question in terms of the technical terminology. Based on this feedback, the survey questions were revised to make them simpler, less technical, and self-explanatory for respondents from all education levels. The number of questions was kept low (37) but enough to study the key phenomena. There was a concern that an overly long survey likely would affect the quality of the responses due to responder fatigue based on the pre-survey feedback. The questionnaire was checked for comprehensibility in pretests and revised accordingly. After satisfactory feedback from all the respondents, it was then sent out for response collection. Moreover, the survey briefly described the AV technology and their potential benefits to respondents as: "in an AV, all driving tasks are completely autonomous, and you only need to tell the vehicle where to go. Theoretically, AVs do not crash. You can do things like work, sleep, read, watch TV, and maybe even exercise while the vehicle takes you to your destination. You might either ride a driverless vehicle alone or hire a shared driverless vehicle for carpooling (like Uber) that may pick up other passengers during the trip."

Respondents were required to be at least 18 years old and to own, lease or have access to a vehicle or use a vehicle, either as a driver or a passenger, to go to work or school. The respondents were asked to provide the time and distance of their current trip to work or school. The information collected included travel behavior characteristics, socio-demographic features, technology, and new-travel-options awareness factors, household characteristics, psychological factors, and built environment features. In this dissertation, the built environment refers to the "activity space" within which the household members consume goods and services in addition to executing their daily activities (Banerjee and Baer, 1984; Horton and Reynolds, 1971). The four main forms of the built environment were defined as the city center, urban, suburban, and rural, based upon the dwelling density.

Table 5.3 presents a summary of the responses used to create a large set of explanatory variables investigated in this dissertation. The data presented here were used to create many new derived variables, interaction terms, and indicators for evaluation in the econometric analysis. The survey sample included responses from 43% male (compared to 49.2% nationally) and 57% female respondents. With regard to the educational attainment, 51% of the respondents had some college degree or higher compared to 31% nationwide. In terms of the household annual income, 58% of the respondents belong to the households with an annual income greater than or equal to $50,000, compared to 56.2% nationwide. Regarding awareness, it is interesting to note that 84% of the respondents had heard about AVs, but only 40% had heard about connected vehicles (CVs). Only 9% of the respondents were not familiar with AVs, but 38% of them were not familiar with CVs. This relatively higher awareness about AVs could be attributed to the fact that the media discuss this technology more often compared to CVs.

Table 5.3 Summary of road user responses

Questions	Responses	Percent
Respondents		
	Drivers	91
	Passengers	9
Distance to workplace/school		
	≤ 1 mile	4
	≤ 5 miles	30
	≤ 10 miles	54
	≤ 15 miles	68
	≤ 20 miles	77
	≤ 25 miles	83
	≤ 50 miles	94
	≥ 50 miles	7
Awareness about		
	Ridesharing Service	95
	Carsharing Service	44
	Smartphone use	86
Enjoy Driving		
	Yes, a lot	41
	Yes, a little	33
	Neutral	15
	No, not really	9
	No, I really dislike driving	2
Awareness about CVs		
	Yes	40
	No	38
	Uncertain	22
Awareness about AVs		
	Yes	84
	No	9
	Uncertain	7

Table 5.3 continued

Gender		
	Male	43
	Female	57
Employment status		
	Employed full-time	51
	Employed part-time	21
	Not currently employed	8
	Retired	16
	Student	3
Work location		
	At home	11
	Not at home	66
	N/A (retired, not currently employed or full-time student)	22
Respondents' Age		
	Between 18 and 24 years old	6
	Between 25 and 34 years old	11
	Between 35 and 44 years old	14
	Between 45 and 54 years old	18
	Between 55 and 64 years old	28
	More than 65 years old	23
Number in the household including respondent		
	1 person	24
	2 persons	42
	3 persons	16
	4 persons	13
	> 4 persons	5
Number of household members aged less than 16 years		
	0 person	77
	1 person	12
	2 persons	8
	3 persons	2
	> 3 persons	1
Highest education level		
	Less than high school	1
	High school (included equivalency)	17
	Some college	32
	Bachelor's degree	30
	Professional school degree	3
	Master's degree	15
	Doctorate degree	3

Table 5.3 continued

Annual income of the respondent's household		
	Less than $24,999	12
	Between $25,000 and $49,999	25
	Between $50,000 and $74,999	22
	Between $75,000 and $99,999	16
	Between $100,000 and $199,999	17
	$200,000 or more	3
	Prefer not to answer	4

Table 5.4 presents the summary statistics for key explanatory variables. The first key question analyzed in this study was related to mobility preferences for making daily trips with four options: 1) continue using a self-owned traditional vehicle, 2) using a self-owned AV, 3) using a hired AV service (like Zipcar or Car2Go), and 4) using a shared AV service with other passengers (like Uber and Lyft). Sixty-eight percent of the respondents preferred to continue using their self-owned traditional vehicle for making daily trips when they were asked to choose from these four options. As shown in Figure 5.2, there is very little interest in using AV-based car-sharing (3%) and ride-sharing services (2%) in SMMAs. This result suggests that the use of a traditional vehicle is the most preferred whereas the use of SAV service is the least preferred option. This result also does not validate the widely held perception and the oft-propagated untested hypothesis that with the introduction of AVs, vehicle ownership will become an obsolete choice by consumers and that SAVs will emerge as a dominant mode. Instead, it confirms that private (self-owned) vehicles, whether conventional or autonomous, will remain the preferred travel choice, which is not surprising because people are more comfortable with things they already know. As noted earlier by Bamberg et al. (2003), habits and routines discourage consumers from opting for an alternative transport means. This continued higher level of interest in the traditional vehicle mode could be attributed as well to anchoring effects (obligation to initial opinions) or confirmation bias (supporting their initial opinion by processing information in a selective manner to confirm their initial opinion) as discussed by Sheela and Mannering (2019) in the context of AV adoption. The widely reported (on media) AV-involved collisions (e.g., in Arizona, California, and New York) during test deployment activities on existing roadways could have led to selective processing of information (confirmation bias regarding "the uncertain, unreliable, and unknown state of this

technology”). The initial opinion developed by consumers based on input from the media could have been that the state of AV technology is uncertain and unreliable from the safety standpoint. Therefore, the consumers might choose only selective information (e.g., only collision events) to support their initial opinion from the upcoming new set of information on media. As such, they may prefer to stay with their conventional mode (relatively more certain and reliable). This result indeed appears realistic and reasonable for the early stage of the transition period that will be characterized by a mixed-traffic roadway environment of HDVs and AVs.

Table 5.4 Descriptive statistics of key variables

Variable Description	**Mean**	**Standard Deviation**
Socio-demographic factors		
Older age indicator (1 if respondent is aged more than 55 years, 0 otherwise)	0.485	0.500
Gender indicator (1 if respondent is a female, 0 otherwise)	0.579	0.494
Highest education indicator (1 if respondent's highest educational qualification is Bachelor or higher, 0 otherwise)	0.476	0.499
Younger age indicator (1 if respondent is aged between 18 and 24 years, 0 otherwise)	0.067	0.250
Retired indicator (1 if respondent is living a retired life, 0 otherwise)	0.155	0.362
Household Characteristics		
Number of members in households	2.381	1.236
Household members aged less than 16 years indicator (1 if respondent's household has either 1 or more members aged less than 16 years, 0 otherwise)	0.238	0.426
Travel behavior		
Commute mile indicator (1 if respondent's one-way commute distance is greater than 2.5 miles, 0 otherwise)	0.892	0.310
Awareness factors		
Autonomous vehicle awareness indicator (1 if respondent has heard about autonomous vehicle, 0 otherwise)	0.841	0.366
Carsharing awareness indicator (1 if respondent is aware of carsharing service, 0 otherwise)	0.443	0.497
Built Environment		
Suburban residence indicator (1 if respondent's place of living is a suburban location, 0 otherwise)	0.530	0.499
City center residence indicator (1 if respondent's place of living is a city center, 0 otherwise)	0.089	0.285
Urban residence indicator (1 if respondent's place of living is an urban location, 0 otherwise)	0.198	0.398
Psychological factors		
Enjoy driving indicator (1 if respondent enjoys driving, 0 otherwise)	0.739	0.439
Road-sharing comfort level indicator (1 if respondent does not feel comfortable driving a regular car and sharing road with autonomous vehicles)	0.294	0.456

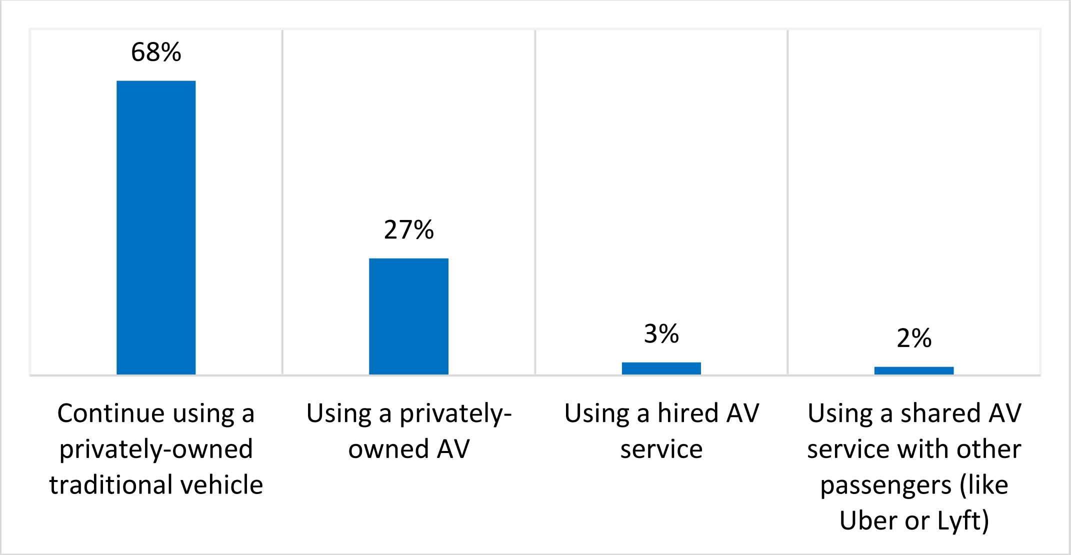


Fig. 5.2 Prospective consumer mobility preferences

Table 5.5 presents the consumers' mobility preferences across the built environment during the transition phase. There is even a decreased propensity for AV use in the rural areas of SMMAs. This current state of mobility preferences during the transition phase of AV operations with roadways hosting both HDVs and AVs seems quite intuitive considering the current infant and uncertain state of AV technology development, infrastructure readiness, regulations, and policy design. The technology is still evolving; road infrastructure is still not ready to host this technology, and few concrete steps have been taken towards the development of regulations and policy formulation. This is probably due to the evolutionary nature of technological advancement and uncertainty surrounding consumer acceptance or demand (Federal Highway Administration, 2018). Car-sharing with AVs is portrayed as a more accessible and affordable option that offers flexible mobility and a potential alternative to private car ownership by avoiding the obligations associated with a private vehicle (fees incurred by insurance, maintenance, fuel, registration, etc.). That said, there was very little interest in an AV car-sharing service by the survey respondents. Moreover, there was little interest in using an SAV service which could be attributed to the privacy, security, and on-time performance (or travel time reliability) concerns of respondents. However, the levels of these responses may change over time as potential users learn more about the technology, especially during actual AV deployment on roadways; therefore, transport planners and vehicle manufacturers should conduct periodic surveys to stay aware of the latest consumer perspectives.

Table 5.5 Prospective consumer mobility preferences across the built environment

Alternatives	**City Center**	**Urban**	**Suburban**	**Rural**
Continue using a privately-owned traditional vehicle	64%	67%	68%	72%
Using a privately-owned AV	27%	27%	28%	26%
Using a hired AV service	4%	5%	2%	1%
Using a shared AV service with other passengers (like Uber or Lyft)	5%	1%	2%	1%

The second key question asked in the survey was: If there were AVs in traffic, how comfortable would you feel about driving your own traditional vehicle? Possible responses to this question were ordered on a Likert scale: very comfortable, moderately comfortable, neutral, moderately uncomfortable, and very uncomfortable. As shown in Figure 5.3, 24% of the respondents chose very comfortable while 29%, 17%, 21%, and 8% of respondents, respectively, chose moderately comfortable, neutral, moderately uncomfortable, and very uncomfortable. Approximately 53% of the respondents indicated that they would feel comfortable driving their vehicles while sharing a road with AVs, and 29% noted otherwise.

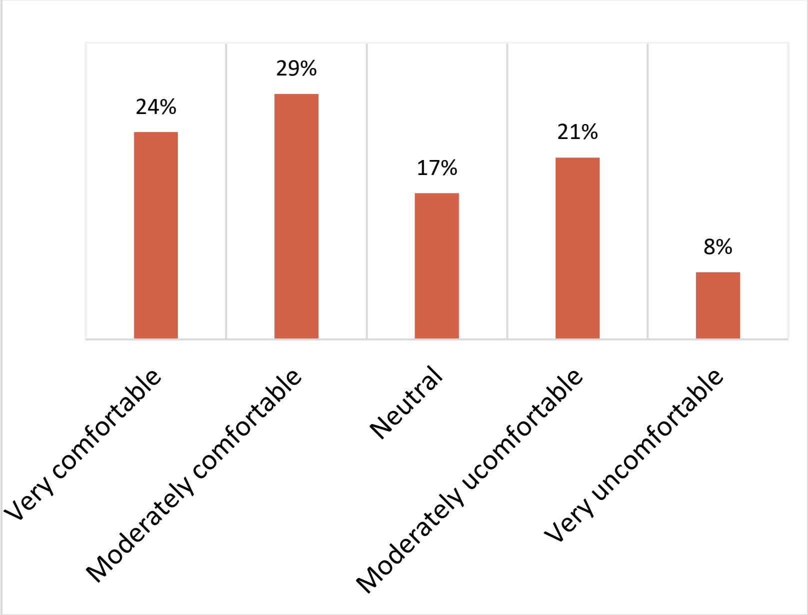


Fig. 5.3 Responses to comfort levels in sharing roads with AVs

5.4.3 AV Adoption Potential

5.4.3.1 Introduction

With a revolutionary transformation in the vehicle technology in the form of connected and autonomous transportation, new mobility services and modes are expected to emerge. It is broadly envisioned that private ownership of vehicles may not be required in the fully autonomous era. However, AVs must be considered in the context of a wider transportation system with competing alternatives, and one should be mindful of the tradeoffs (e.g., comfort, convenience, safety, reliability, security, privacy, and dependability, among several others) as noted by Baroff et al., 1982) that people would consider in their mobility choice decisions, especially during the time when both traditional and AVs may share the road. AVs have the potential to free people from congestion, parking, driving, and pollution, which may come at the cost of freedoms such as taking their own vehicles anytime and anywhere. In addition to the enthusiasm they generate, AVs generate attendant fundamental concerns about personal autonomy, privacy, and freedom of choice and mobility. As such, it is hard to envision future mobility trends with much accuracy due to many known and unknown uncertainties. The key to understanding the future facets of road mobility lies in gathering the opinions and preferences of the end-users (consumers).

There is substantial interest in understanding consumer preferences and opinions related to AV adoption in the context of general interest and attitudes (Nair et al., 2018; Saeed, 2018; Soteropoulos et al., 2018; Gkartzonikas and Gkritza, 2019). Some researchers have investigated the likely adoption of AVs into the market based on vehicle ownership and diffusion models (Lavasani et al., 2016; Daziano et al., 2017; Talebian and Mishra, 2018). Conversely, some studies have used a direct and open-ended expression of willingness to pay for AVs or ride-hailing AV trips (Bansal and Kockelman, 2018 and Laidlaw et al., 2018); however, the findings of these and other similar studies may be debatable because the responses to open-ended questions, in the context of willingness to pay, have been declared biased and invalid by the market research experts and economists, as noted in the frequently cited Arrow et al. (1993). Rather, the choice experiments and studies focusing on consumer attitudes and preferences without an explicit willingness to pay are considered more suitable (see Nair et al., 2018; Saeed, 2018; Weiss et al., 2019).

A recent study by Weiss et al. (2019) offered seven alternatives to 1,897 respondents from the largest urban metropolis in Canada, the Greater Toronto Area: (a) your current observed mode; (b) ride in your AV alone; (c) ride in your own AV with another passenger (carpool/ride-hail); (d) ridehail in an AV and travel alone; (e) ridehail in an AV and travel with other passengers (carpool); (f) ridehail in a conventionally driven vehicle (with a driver) and travel alone; and (g) ridehail in a conventionally driven vehicle (with a driver) with other passengers (carpool). This large number of choices rather added to the complexity of the questionnaire, which could make it even harder for respondents to comprehend correctly, particularly in the absence of technology and respondents' personal experience with it.

The past studies do not address one or more of the following points. (a) Their target population or geographical coverage is mostly localized in nature. The studies were done on a small scale in different cities or geographical locations, mainly urban centers. Most of these studies were based on the notion that AVs will be deployed first in one particular region (a central business district or an urban center) but do not recognize the fact that AVs are expected to drive across different forms of the built environment. The preferences of consumers from all forms of the built environment, therefore, are important and must be captured. (b) The stated alternatives included only AV-related options and lacked an option for a conventional vehicle. These studies were motivated by an implicit or explicit assumption, which was erroneous, that with the introduction of AVs, all the conventional vehicles on the road will be immediately replaced by AVs. Again, this model does not seem plausible. (c) Consumer interest in different AV-related options was investigated in isolation at a Likert scale and not in relation to other modes (e.g., Nair et al., 2018 and Nazari et al., 2018). Therefore, the outcomes of these studies do not provide any concrete and useful insights for policy-making processes. (d) They did not explore the preferences of consumers from various forms of the built environment (city center, urban, suburban and rural), rather they suggested that element for future work (Abraham et al., 2017). (e) Some studies just reported basic descriptive statistics and did not conduct an in-depth econometric analysis. (f) Finally, and most importantly, most of these studies are not representative in terms of their sample size (e.g., Haboucha et al. (2017) study of only 721 individuals living across Israel and North America and Pakusch et al. (2018) study relying on only 320 responses from across Germany).

To address these gaps in the literature, this dissertation explored the mobility preferences of prospective future consumers of AVs, who were asked to choose from a set of four options: continue using a self-owned regular vehicle; using a self-owned AV; using a hired AV service (Zipcar or Car2Go); and using a shared AV service with other passengers (Uber or Lyft). The preferences of a representative sample (in terms of age and gender) with consumers living in all settings of the built environment were studied. Moreover, this dissertation explored consumers' preferences using a multimodal analysis that considered the conventional and AV-related modes in relation to each other and not in isolation as often done in the previous studies (Nazari et al., 2018). While duly recognizing the zero-market penetration and inexperience of the users with this technology, this inventory of travel-choice alternatives was intentionally kept limited to avoid the complexity of the questionnaire and problems surrounding respondents' fatigue. Failure to account for these two important considerations can affect the quality of the responses and thus make any inferences drawn potentially questionable. However, this dissertation did not include the modes related to public transport and AV-transit integration in the choices, which is suggested for future research.

It is a commonly held perception that there would be increased use and adoption of AVs as a shared service where multiple travelers use the same AV concomitantly (Kornhauser et al., 2013; Bansal et al. 2016; Bischoff and Maciejewski, 2016; Krueger et al., 2016; Fagnant and Kockleman, 2018; Barbour et al., 2019; Menon et al., 2019). It is further believed that vehicle ownership will become less prevalent in the future. However, there is a lack of empirical evidence in the literature to support that hypothesis. As such, this dissertation tested this hypothesis using empirical data from the questionnaire survey.

Another most important and contributory consideration of this dissertation is its focus on small- and medium-sized cities, with a population less than or equal to 450,000, which form approximately 75% of the U.S. metropolitan areas (283 of the 382 metropolitan areas) (US Census Bureau, 2018). Personal vehicle ownership is generally high in these areas and hence the findings of this study will have significant implications for travel-mode choices and vehicle ownership in the future during the transition phase. Second, in most of these areas, the major drivers of economic activity are the university campuses and most of these campuses are undergoing a realignment of their master plans to prepare for the new paradigm shifts in residential location decisions expected to emerge with the next-generation transportation technology (one such example is Texas A&M University per Sinha, 2018). As such, to support the retrofitting of master plans of university campuses, this study is very timely and relevant. Moreover, due to wider regional coverage of the nation's pulse related to the mobility preferences, the results of this dissertation could be extrapolated to support the national efforts of policy development relating to the readiness for the era of AVs in the transition phase.

Moreover, it is known with certainty that the fully AV operations will not happen all at once, but it is expected to occur over some period of time through an incremental process. As such, it is important to first explore the public acceptance of the AV modes in relation to the conventional mode available during the transition phase. In this dissertation, important insights are provided regarding the consumers' potential adoption and usage of these modes, which could be indicative of future mobility trends in SMMAs during the transition phase.

Additionally, a random-parameters logit model was estimated to further investigate the consumers' mobility preferences in the context of their travel behavior characteristics, socio-demographic features, their awareness about AV technology and new travel choices, household characteristics, psychological factors, and built environment features.

5.4.3.2 Model Specification

Due to the non-ordinal discrete nature of the response variable, a random-parameter logit model was estimated to identify and quantify the characteristics that may potentially influence the given mobility preferences. While there is a possibility of variation of parameters across observations, a random-parameter or mixed logit model is a suitable framework to use (Washington et al., 2011). Using the framework discussed in McFadden and Train (2000) and Train (2003):

$$Z_{mn} = \beta_m X_{mn} + \varepsilon_{mn} \tag{5.1}$$

where, Z_{mn} is a utility function that determines the probability of respondent *n* selecting response *m* (among the four options of the mobility preferences), β_m is a vector of estimable coefficients for discrete outcome m, X_{mn} is a vector of exogenous variables (observable characteristics) that corresponds to discrete outcomes m for observation *n*. The outcome probabilities for a random-parameters logit model are then defined as (Washington et al., 2011):

$$P_n(m|\varphi) = \int_X \frac{EXP\,[\beta_m X_{mn}]}{\sum_M EXP[\beta_m X_{Mn}]}\, f(\beta|\varphi) d\beta \tag{5.2}$$

$P_n(m|\varphi)$ are mixed logit probabilities which are the weighted average of the standard multinomial probabilities wherein weights are found by the density function $f(\beta|\varphi)$. More specifically, these probabilities are a weighted average of different β values across observations where some elements of the coefficient vector β are random and some are fixed. This dissertation uses a continuous form of the density function, $f(\beta|\varphi)$, i.e., a normal distribution based on the best statistical fit, after investigating multiple distributions (log-normal, uniform, and exponential) for statistical significance. φ is a vector of parameters, that describes the variance and mean of the density function. For estimating random parameters, a simulated maximum likelihood approach is implemented using 1,000 Halton draws for the simulation.

Furthermore, the marginal effects were estimated for the explanatory variables to determine their individual effects on response probabilities. The marginal effect of a predictor variable gives the effect that a one-unit increase in that variable has on the response probabilities. For the indicator variables, the marginal effects show the effect of a predictor moving from zero to one (Washington et al., 2011). Each respondent had an individual marginal effect; the marginal effects averaged over all respondents is presented in this dissertation.

5.4.3.3 Discussion of Model Estimation Results

Table 5.6 presents the results of the random-parameter logit model (including parameter estimates, and z-statistics) that was estimated to explore the respondents' mobility preferences. This framework accounts for unobserved heterogeneity in the data and the possibility of variation of the parameter estimates across the observations. All the random parameters identified in the final model were found to follow a normal distribution. Other distributions (lognormal, uniform, exponential and Weibull) also were tested for significance but did not perform statistically superior to their normal distribution counterparts. Moreover, the average marginal effects are presented in Table 5.7 and visually illustrated in Figure 5.4 for comparison.

The indicator for the joy associated with driving a vehicle produces a normally-distributed random parameter which suggests that 67% of the respondents who enjoy driving, were more likely to continue using a privately-owned traditional vehicle and 33% of the respondents were less likely to do so. To many, driving can be fun, accompanied by feelings of freedom, personal autonomy, privacy, control, independence, and security. Other studies also noted that in terms of driving control and pleasure, consumers find an advantage in the traditional vehicle compared to the AV (Nordhoff, 2014; Eimler and Geisler, 2015). Haboucha et al. (2014) found that individuals who enjoy driving are more likely to prefer their regular vehicle; however, this dissertation found a heterogeneous effect of this attribute across the observations. In this respect, it is noted that driving is not always enjoyable and convenient, particularly in the case of exceedingly long trips or recreation trips with family, wherein time could be spent on entertainment with family rather than on driving. The normally-distributed random parameter for this variable indicates that the respondents who enjoy driving do not behave in a homogeneous way (as in the case of a fixed parameter), which is quite intuitive.

The coefficient for the older age indicator suggests that the respondents more than 55 years old were highly likely to choose the continued use of a privately-owned traditional vehicle (a 0.0438 higher probability as indicated by the average marginal effect in Table 5.7). This result could be due to people in this age group generally being less technology savvy or less flexible/adaptive/welcoming to transformative transportation technologies. They may be less open to attempting new technologies that could cause a disruption in their already-set way of life. As such, they may prefer the status quo and opt-out for the enthusiasm and thrill associated with AV technology. However, older individuals who can no longer drive may welcome AV technologies to regain their mobility with increased trust in AV operations over time.

The female respondents were more likely to continue using a regular vehicle during the transition phase of a mixed-traffic stream of HDVs and AVs (a 0.0369 higher probability as indicated by the marginal effect value in Table 5.7 and Figure 5.4). The female respondents indicated less tendency towards using AV-oriented modalities. This result could be attributable to the uncertain state of AV technology, no individual consumer experience with this technology, lack of confidence in the technology, and a higher risk aversion on the part of females. This is consistent with findings of the past studies, which reported men to be more likely to adopt AVs as compared to women (Yvkoff, 2012; Casley et al., 2013; Megens, 2014; Missel, 2014; Payre et al., 2014). Past studies found that women had more worries and concerns about full vehicle automation and were less willing to pay extra/more for automation (Kyriakidis et al., 2013); whereas, men were more likely to use and buy AVs as compared to women (Payre et al., 2014). The respondents whose highest educational qualification level was a bachelor’s degree or higher (MS/MA/Ph.D.) were less likely to continue using a privately-owned traditional vehicle. This result could be due to these respondents being well aware of the potential benefits of AV technology. As noted by Agrawal and Prasad (1999), individuals at higher levels of educational attainment are generally more receptive and broad-minded about technical innovations. Another study found a substantially higher preference for private traditional cars over automated modes among people without a high school degree (Pakusch et al., 2018). These results are in agreement with the findings of Haboucha et al. (2017), who found that female, older, and less educated individuals were more likely to continue using their regular car in comparison to PAVs and SAVs, and less willing to let AVs drive them.

The AV familiarity indicator had a positive coefficient, which implies that the respondents who have heard about AVs were more likely to choose using a self-owned AV over other options (a 0.1164 higher probability as indicated by the average marginal effect in Table 5.7 and Figure 5.4). This result could be due to these respondents being more aware of the envisioned benefits of AVs that are frequently highlighted in the media; and as a result, they would like to use a self-owned AV. The positive sign for the number of members in a household suggests that the probability of using a self-owned AV increases as the number of members in a household increase. Rather than relying on other modes that are comparatively less flexible, a privately-owned AV could be a more efficient and less costly option for larger households if used as a shared vehicle by household members for the commute, shopping, religious, grocery or other trips of overlapping interests. They would not have to deal with the concerns about privacy, security, and travel time reliability that could otherwise exist when using a commercial ride-hailing service. The respondents whose daily commute distance was more than 2.5 miles away were more likely to use a self-owned AV during the transition phase of AV operations. This result could be due to respondents in SMMAs not wanting to continue driving their regular vehicles in a mixed-stream traffic environment for a longer distance every day or to use a shared AV service with strangers for a longer period of time.

The car-sharing service familiarity indicator had a positive sign, implying that people who are familiar with car-sharing services will prefer to use an AV car-sharing service to other alternatives. These respondents probably had a good understanding of how car-sharing works and were aware of its merits. The respondents whose households had one or more members less than 16 years old were more likely to use a car-sharing AV service. Having many household members below the driving age could be a liability for those with a driving license, who are responsible for pick and drop rides to the younger members. A car-sharing AV service could be a great solution, which will offer flexibility and independence to all the household members traveling around freely without reliance on each other. A past study found an increase in the likelihood of using SAVs by individuals whose households had more than one child (Haboucha et al., 2017). There was conformity in the results in terms of preferring the use of an AV shared service with an increase in the number of very young household members. However, Haboucha et al (2017) did not have

AV car-sharing service as an option in their stated preferences question but just SAV in addition to a regular car and a PAV.

The female respondents were less likely to use a car-sharing AV service (a -0.0081 lower probability as indicated by the average marginal effect in Table 5.7 and Figure 5.4), which could be attributed to the uncertain state of AV technology at the current time and possible concerns associated with the AV-related mode. The younger respondents, between 18 and 24 years old, were more likely to use car-sharing and ride-sharing AV services, which is consistent with the past studies (Krueger et al., 2016). Moreover, this seems highly intuitive mainly because that age group is the least inclined towards vehicle ownership and prefers to opt for modes (ride-hailing, ride-sharing, public transit) that could keep their hands free for other things, including the use of smartphones or laptops (Cottam, 2017). In past studies, millennials have been found to be more interested in using AVs; however, the results in this dissertation indicate how they might prefer to use it (car-sharing or ride-sharing). Individuals who live in urban environments were more likely to use an AV car-sharing service. There is widespread and frequent coverage of car-sharing options in the urban areas, which makes it a popular mode choice. With multiple options of mobility available in urban settings, there is generally less tendency towards personal vehicle ownership and AV car-sharing service thus may be preferred. In addition, this could be due to people preferring to avoid the fatigue associated with driving on urban roads.

Respondents whose current place of living was either suburban or a city center were more likely to use an SAV service. People prefer to opt for SAVs with the intent to avoid congestion on roads in the city center and hence experience better on-time performance. Less congested roads, which are expected to emerge as SAV services grow, could help enhance travel time reliability, which is most often a matter of concern for users (Barbour et al., 2019). However, an important finding is the interest of consumers from suburban locations of SMMAs in the use of an SAV service, which could help the potential AV ride-hailing firms in identifying their future market in these areas. The respondents who were retired from full-time employment were more likely to use an SAV service, which is quite intuitive. Lastly, the road-users who were likely to feel uncomfortable driving a regular vehicle in a mixed-traffic stream of HDVs and AVs were more likely to use an SAV service during the transition phase of AV operations. Having other passengers on board in an SAV service could help dilute the intensity of the discomfort and anxiety of being in a mixed-traffic stream.

Table 5.6 Model estimation results for mode preferences

Explanatory Variables*	**Parameter Estimates**	**z-stat**	**Std. Error**	**p-value**	**95% Confidence Interval**	
Constant [A]	-1.746	-4.59	0.380	0.000	-2.492	-1.001
Constant [H]	-3.086	-8.26	0.374	0.000	-3.819	-2.354
Constant [S]	-4.382	-8.63	0.508	0.000	-5.378	-3.387
Socio-demographic factors						
Older age indicator (1 if respondent is aged more than 55 years, 0 otherwise) [R]	0.823	4.69	0.175	0.000	0.479	1.167
Gender indicator (1 if respondent is a female, 0 otherwise) [R]	0.524	2.95	0.178	0.003	0.177	0.872
Highest education indicator (1 if respondent's highest educational qualification is Bachelor or higher, 0 otherwise) [R]	-0.347	-2.09	0.166	0.037	-0.672	-0.022
Gender indicator (1 if respondent is a female, 0 otherwise) [H]	-1.013	-3.15	0.321	0.002	-1.642	-0.383
Younger age indicator (1 if respondent is aged between 18 and 24 years, 0 otherwise) [H]	0.697	1.52	0.458	0.128	-0.200	1.594
Retired indicator (1 if respondent is living a retired life, 0 otherwise) [S]	1.062	2.52	0.421	0.012	0.237	1.888
Younger age indicator (1 if respondent is aged between 18 and 24 years, 0 otherwise) [S]	1.410	3.07	0.460	0.002	0.509	2.311
Household characteristics						
Household members aged less than 16 years indicator (1 if respondent's household has either 1 or more than 1 member aged less than 16 years, 0 otherwise) [H]	1.157	3.68	0.314	0.000	0.541	1.773
Number of household members [A]	0.134	2.20	0.061	0.028	0.014	0.254
Travel behavior						
Commute mile indicator (1 if respondent's one-way commute distance is greater than 2.5 miles, 0 otherwise) [A]	0.461	1.91	0.241	0.056	-0.011	0.933
Awareness factors						
Autonomous vehicle awareness indicator (1 if respondent has heard about autonomous vehicle, 0 otherwise) [A]	1.065	4.77	0.223	0.000	0.627	1.502
Carsharing awareness indicator (1 if respondent is aware of carsharing service, 0 otherwise) [H]	0.679	2.20	0.309	0.028	0.074	1.285
Built environment						
Urban residence indicator (1 if respondent's place of living is an urban location, 0 otherwise) [H]	0.858	2.7	0.318	0.007	0.236	1.481
City center residence indicator (1 if respondent's place of living is a city center, 0 otherwise) [S]	1.753	3.15	0.557	0.002	0.662	2.844
Suburban residence indicator (1 if respondent's place of living is a suburban location, 0 otherwise) [S]	1.120	2.38	0.470	0.017	0.199	2.041

Table 5.6 continued

Psychological factors						
Road-sharing comfort level indicator (1 if respondent doesn't feel comfortable driving a regular car and sharing road with autonomous vehicles) [S]	1.03	2.96	0.348	0.003	0.349	1.711
Enjoy driving indicator (1 if respondent enjoys driving, 0 otherwise) [R]	1.587	3.06	0.512	0.002	0.569	2.604
	(3.566)	(3.33)	(1.07)	(0.0009)	(1.468)	(5.664)
McFadden Pseudo R-squared Adjusted	0.454					
Log likelihood function (at convergence)	-1448.801					
Log-likelihood at zero	-1527.85					
AIC	2939.60					

*[R] continue using a privately-owned traditional vehicle; [A] using a privately-owned AV; [H] using a hired AV service; [S] using a shared AV service

Table 5.7 Average marginal effects for mobility preferences

Explanatory Variables*	**Using a traditional vehicle**	**Using a self-owned AV**	**Using a hired AV service**	**Using a shared AV service**
Socio-demographic factors				
Older age indicator (1 if respondent is aged more than 55 years, 0 otherwise) [R]	0.0438	-0.038	-0.0026	-0.0032
Gender indicator (1 if respondent is a female, 0 otherwise) [R]	0.0369	-0.0323	-0.0018	-0.0027
Highest education indicator (1 if respondent's highest educational qualification is Bachelor or higher, 0 otherwise) [R]	-0.0207	0.0179	0.0015	0.0013
Gender indicator (1 if respondent is a female, 0 otherwise) [H]	0.0035	0.0043	-0.0081	0.0003
Younger age indicator (1 if respondent is aged between 18 and 24 years, 0 otherwise) [H]	-0.0008	-0.001	0.0019	-0.0002
Retired indicator (1 if respondent is living a retired life, 0 otherwise) [S]	-0.0023	-0.0025	-0.0002	0.0049
Younger age indicator (1 if respondent is aged between 18 and 24 years, 0 otherwise) [S]	-0.002	-0.0024	-0.0003	0.0047
Household characteristics				
Household members aged less than 16 years indicator (1 if the respondent's household has either 1 or more than 1 member aged less than 16 years, 0 otherwise) [H]	-0.0044	-0.0068	0.0116	-0.0004
Number of household members [A]	-0.0332	0.0411	-0.0047	-0.0032
Travel behavior				
Commute mile indicator (1 if respondent's one-way commute distance is greater than 2.5 miles, 0 otherwise) [A]	-0.0425	0.0521	-0.0055	-0.0041
Awareness factors				
Autonomous vehicle awareness indicator (1 if respondent has heard about autonomous vehicle, 0 otherwise) [A]	-0.0955	0.1164	-0.012	-0.0089
Carsharing awareness indicator (1 if respondent is aware of carsharing service, 0 otherwise) [H]	-0.0035	-0.0054	0.0092	-0.0003
Built environment				
Urban residence indicator (1 if respondent's place of living is an urban location, 0 otherwise) [H]	-0.0028	-0.0041	0.007	-0.0001
City center residence indicator (1 if respondent's place of living is a city center, 0 otherwise) [S]	-0.0033	-0.0034	-0.0004	0.0071
Suburban residence indicator (1 if respondent's place of living is a suburban location, 0 otherwise) [S]	-0.0058	-0.0072	-0.0005	0.0135
Psychological factors				
Road-sharing comfort level indicator (1 if the respondent does not feel comfortable driving a regular car and sharing road with autonomous vehicles) [S]	-0.0045	-0.0048	-0.0004	0.0097
Enjoy driving indicator (1 if respondent enjoys driving, 0 otherwise) [R]	-0.0013	0.0014	-0.0007	0.0006

*[R] continue using a privately-owned traditional vehicle; [A] using a privately-owned AV; [H] using a hired AV service; [S] using a shared AV service

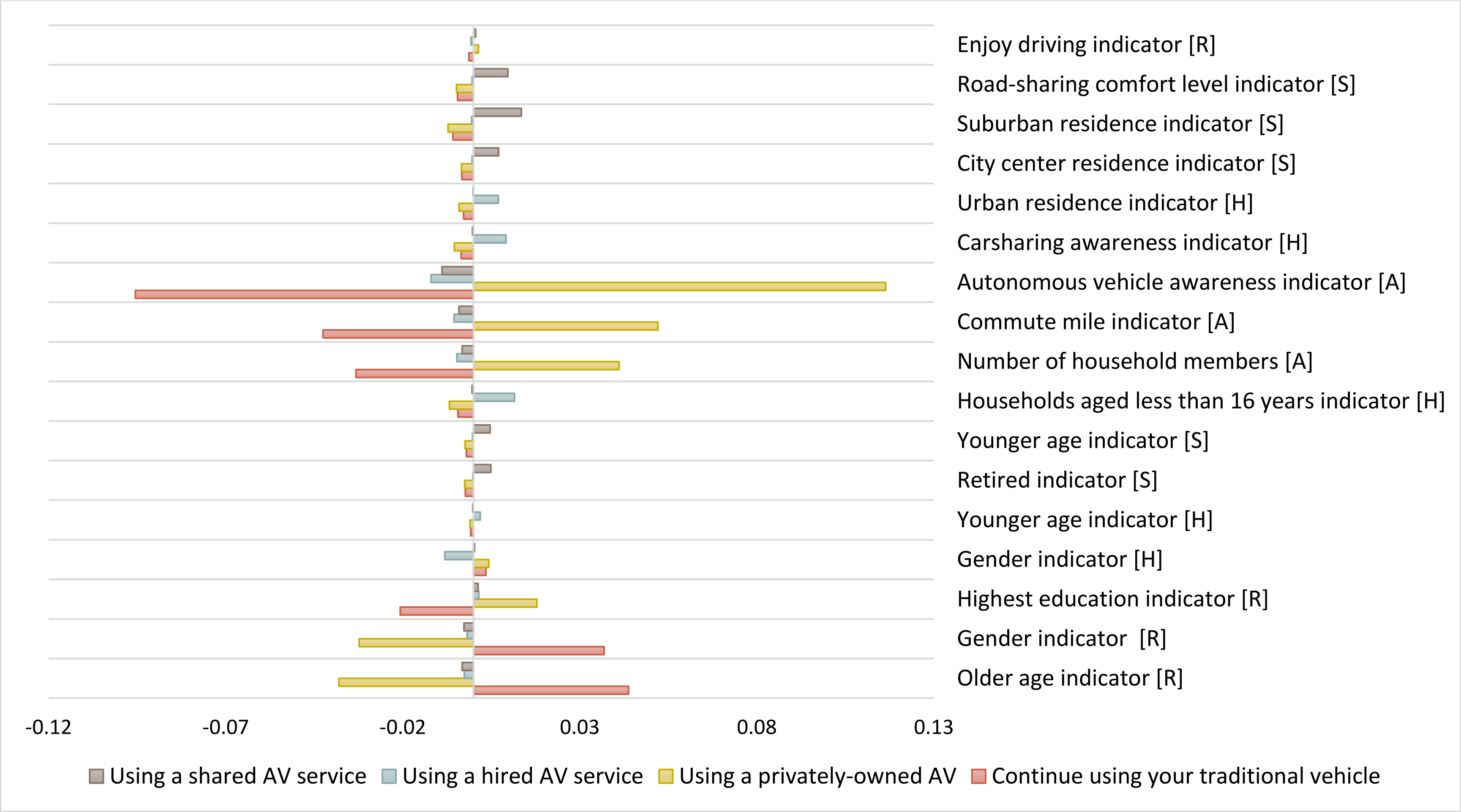


Fig. 5.4 Visual illustration of marginal effects for mobility preferences

*[R] continue using a privately-owned traditional vehicle; [A] using a privately-owned AV; [H] using a hired AV service; [S] using a shared AV service

5.4.3.4 Summary and Conclusions

While ride-hailing is believed to be a primary business model for AVs (a widely-held perception), this hypothesis does not seem to hold true in small- and medium-sized metropolitan areas of the U.S. at this time (at least during the early transition phase of AV operations) based on the findings of this dissertation. While evaluating the consumers’ interest across three AV-related modalities, the potential consumers in SMMAs were found to be more interested in private AV ownership rather than car-sharing or ride-hailing AV services. This result could be attributed to the independence, convenience of access, availability at all times whenever needed, and the freedom to do things associated with a self-owned vehicle. In addition, some consumers might think that an SAV service is a costly option where ride-sharing firms would charge the price plus a profit. These preferences regarding AV modes might change over time when a substantial majority of vehicles on the road network are SAVs. Initially, consumers might opt for a few SAV rides just to see how they like it and to develop trust in the technology at an early stage. However, the findings of this dissertation show that consumers continued to prefer using their traditional vehicle over all the AV-related modes during the early transition phase of AV operations, which could be due to the control that users enjoy having a traditional vehicle.

A commonly-held speculation regarding AV technology is that it is a mobility enabler for elderly travelers and could attract aging seniors. However, respondents from SMMAs more than 55 years old preferred using their traditional vehicle compared to the AV options. Travelers of this age group tend to resist changes that could cause a revolutionary transformation in their familiar lifestyles. Nevertheless, this trend could change with increased AV reliability and awareness. Another important item noted by this dissertation is that individuals with longer commutes (greater than 2.5 miles in this case) tended to prefer self-owned AVs, which could be an indirect indication of realization of the in-vehicle travel time benefits of AVs on the part of respondents wherein they could spend their time in a more productive way by doing other things (working on a laptop, eating, sleeping, etc.). This result also could be suggestive of the possibility of distant housing locations adding to the urban sprawl and the vehicle-miles-traveled due to consumers’ propensity to commute longer distances with AVs. Given these symptoms, there is a need for proactive measures and resilience planning to ameliorate the likely adverse impacts of this technology on travel patterns and land use through careful land-use policies.

This dissertation identified the direction and quantified the relative influence of various characteristics related to travel behavior, socio-demographics, built environment, technology awareness, and household structure (attributes of interest found statistically significant) on the mobility preferences of potential consumers from SMMAs. In addition, this dissertation provides a better understanding of the early adopters of various AV modes in terms of who will use AVs and under what implementation scenarios (self-owned, car-sharing, or ride-sharing). Policy-makers, transport planners, highway agencies, and regulators are interested in knowing the public's opinions about AVs, which can serve as a critical input to the overall process of policy development, land use planning, infrastructure preparedness, and regulations for facilitating the successful introduction of this emerging technology into the market. The findings from this dissertation offer useful preliminary insights for this process at the current point in time. Since AVs are not on the roadways yet, it is difficult for the public to comprehend the challenges and opportunities of this technology with much reliability and accuracy. While potential future consumers are generally aware of but not sufficiently knowledgeable about AVs, the results of this dissertation are reflective of the early stage of the transition phase and the possible changes that can be expected.

One of the more important findings of this dissertation was less propensity for AV use in rural areas, which could be helpful information for AV technology developers to better target their technology awareness campaigns to account for the rural applications of this technology at the development stage, which could help fuel the market penetration in these areas. Lastly, roadways cross all forms of the built environment and together constitute an interconnected network; and AVs will be expected to traverse different highway classes (freeways, arterials, collectors/distributors, and local roads). Therefore, for a successful integration of these vehicles into the transport system, policy-makers, transport planners, service providers, highway agencies, vehicle manufacturers, and all other stakeholders will need to design similar levels of preparedness and technology integration efforts across all these forms of the built environment with varying densities of dwellings including suburban and rural. Although the consumer preference scores in this dissertation do not reflect exactly the actual modal split due to the fact that AVs have yet to be introduced into the market, the consumer preferences expressed here could be an indicator for future travel mode choices and hence the potential travel behavior impacts of AVs. It is important to note that this dissertation was conducted in the U.S. and hence the results are not necessarily transferable to other countries due to differences in the transport system and consumer habits and attitudes.

Future research on this topic could utilize a rigorous inventory of alternatives including conventional and automated public transport modes (e.g., autonomous buses for the last mile) in the list of mobility choices and investigate how consumer preferences might change.

5.4.4 Road-sharing Comfort Level

5.4.4.1 Introduction

Several studies have highlighted the impacts of AV technology on transportation systems, roadway environment, and consumer life and living and its adoption and deployment under various implementation scenarios (Anderson et al., 2014; Labi et al., 2015; Le Vine et al., 2015; Saeed et al., 2015; Saeed et al., 2018; Menon et al., 2019). However, despite the merits of AV technology extensively highlighted in the past literature and media, there are always concerns and hesitation on the part of users to be the early adopters due to lingering uncertainties. While AV technology is undergoing a development and experimentation phase, any crash incident involving a test AV contributes to damaging the public's perceptions of AVs (The Guardian, 2018; The New York Times, 2018). These events have implications not only for the perceptions of potential future users of this technology but also for the trust of those who will continue to drive their own traditional vehicles and share the road with AVs. Two recent surveys by Advocates for Highway and Auto Safety (2017) and the American Automobile Association (2018) asked questions about public concerns regarding sharing the road with AVs. These studies only provided descriptive statistics and did not conduct an in-depth econometric analysis and explore the influence of the respondents' demographics (age, income, gender, education, etc.) and other factors on their road-sharing comfort level, as done in this dissertation. Advocates for Highway and Auto Safety (2017), which is a consumer lobbyist organization, surveyed 1,005 adults (18 years or older), and found that 64% (two-thirds) of Americans were concerned about sharing the road with driverless vehicles while 34% were unconcerned and 2% chose the option of "don't know." A survey by the American Automobile Association (2018) found that nearly half (46%) of the U.S. drivers would feel less safe sharing the road with a self-driving vehicle while only 13% would feel safe; others were indifferent (37%), choosing the option "it makes no difference," or were unsure (4%).

5.4.4.2 Model Specification

To study the likelihood of respondents' comfort level in a transition phase, an ordered probit modeling framework is used due to the ordinal nature of the response variable (Saeed et al., 2017; Qiao et al., 2018). A latent variable concept is used for deriving ordered probit models and provides a basis for modeling ordinal ranked data. For detailed derivation, please refer to the pioneering work of McKelvey and Zovoina (1975) (also see: Greene, 1997; Washington et al., 2011).

Consider the following model developed around latent regression,

$$y' = \beta X + \varepsilon \tag{5.3}$$

and

$$\left.\begin{array}{ll} y = 1 & if\ y' \le \mu_0 \\ y = 2 & if\ \mu_0 < y' \le \mu_1 \\ y = 3 & if\ \mu_1 < y' \le \mu_2 \\ y = 4 & if\ \mu_2 < y' \le \mu_3 \\ y = 5 & if\ if\ y' \ge \mu_3 \end{array}\right\} \tag{5.4}$$

where y' is an unobserved latent variable; β is a vector of the estimable coefficients; X is a vector of exogenous variables determining the discrete ordering for observation; ε is a disturbance term assumed to be normally distributed with zero mean and unit variance; and μ's are estimable parameters used as thresholds to be estimated with β and can be interpreted as intercepts. μ_0 is set equal to zero, which means only three thresholds are to be estimated. This leads to the formulation of choice probabilities for each of the five discrete choices used in this dissertation, as follows:

$$\left.\begin{array}{l} P[y = 1] = \Phi[-\beta X] \\ P[y = 2] = \Phi[\mu_1 - \beta X] - \Phi[-\beta X] \\ P[y = 3] = \Phi[\mu_2 - \beta X] - \Phi[\mu_1 - \beta X] \\ P[y = 4] = \Phi[\mu_3 - \beta X] - \Phi[\mu_2 - \beta X] \\ P[y = 5] = 1 - \Phi[\mu_3 - \beta X] \end{array}\right\} \tag{5.5}$$

where $\Phi(.)$ is the cumulative normal distribution. For all probabilities to be positive, $\mu_0 < \mu_1 < \mu_2 < \mu_3$.

Marginal effects were computed to quantify the effects of explanatory factors and find a correct interpretation of the direction (+ive, -ive) of that effect on interior categories (in this case y = 2, 3, 4) (Washington et al., 2011). The computed marginal effects quantify the effect that a unit change of an explanatory variable will have on outcome category's probability. The marginal effects of indicator variables were calculated as the difference in the estimated probabilities, with their value changing from 0 to 1 while all other variables were assumed to be at their arithmetic means. For continuous variables, the effects were calculated from the partial derivatives as follows:

$$\frac{\partial P(y=m)}{\partial X} = [\phi(\mu_{n-1} - \beta X) - \phi(\mu_n - \beta X)]\beta' \tag{5.6}$$

where *P (y = m)* is the probability of response category *m*; $\phi(.)$ is the probability mass function of the standard normal distribution; and all other terms are as defined earlier. The marginal effects for each response category refer to a change in the outcome probability of each threshold category *P (y = m)* given a unit change in an explanatory variable, *x*. A positive marginal effect for a specific discrete choice indicates an increase in the probability of that choice, while a negative value corresponds to a decrease in the probability of that choice in response to an increase in the explanatory variable.

One important shortcoming of using fixed-parameter models is the inherent assumption of a fixed and unique coefficient for all observations in the sample, which might not be realistic, given that individuals are intrinsically heterogeneous (Sarrias, 2016). To overcome the potential problem of unobserved heterogeneity in the data across individual observations, the model in this dissertation is estimated with random parameters (as done in other studies: Ahmed et al., 2017; Chen et al., 2017; Chen et al., 2019a; Chen et al., 2019b; Saeed et al., 2019; Waseem et al., 2019). Failing to account for unobserved heterogeneity when it exists and using the fixed-parameters model instead when the parameters vary across observations could potentially produce inefficient, biased, and inconsistent estimates (Washington et al., 2011). The random parameter formulation used in this dissertation is given as:

$$\beta = \beta_n + \varphi_n \tag{5.7}$$

where β_n is a vector of parameters associated with observations and φ_n is a normally-distributed term with mean 0 and variance σ^2. A simulated maximum likelihood approach was used to estimate random parameters using a 1000-Halton-draw sequencing approach for the simulation. To determine the adequate distribution of random parameters, multiple distributions were examined (including Weibull, lognormal, normal) but only normal distribution was found to be statistically significant. To choose the final model, the statistical superiority of the alternative model specifications (random vs. fixed parameters) was investigated through a likelihood ratio test. The random parameters model is found to be superior and is discussed in this dissertation.

5.4.4.3 Discussion of Model Estimation Results

This section discusses the results of the econometric model presented in Table 5.8, which analyzed the influence of the key explanatory factors on the response variable: the comfort level of road users driving their traditional vehicle and sharing the road with AVs. To further assess the individual parameter estimates and quantify the influence of the explanatory variables on the discrete choice probabilities, the marginal effects were computed and presented in Table 5.8 and visually illustrated in Figure 5.5.

The variables that were found to significantly influence the road users' comfort level included the trip characteristics, the awareness factors, and the socioeconomic and demographic features. The respondents that were aware of car-sharing services (Zipcar, Car2Go) were more likely to feel very comfortable or moderately comfortable. The awareness of respondents regarding car-sharing services was found to be negatively associated with the likelihood of their feeling neutral, moderately uncomfortable, and very uncomfortable, which could be due to the respondents expecting the emergence of AVs to function like a car-sharing service, and in that case, they would expect less road traffic and therefore less congestion due to less crowded roads, potentially contributing to a higher comfort level for them while driving their traditional vehicle and sharing the road with AVs. This perception by the respondents could be attributed to the media's tendency to excessively paint a picture of shared mobility in the era of AVs.

Respondents who were users of smartphones were likely to feel very comfortable or moderately comfortable driving a traditional vehicle on a mixed-stream road during the transition phase. This attribute could be interpreted as a proxy for the respondents' awareness about the safety and efficiency benefits of AVs, which is repeatedly and excessively highlighted in media and elsewhere. These anticipated benefits of AVs would add to their comfort level while driving their own traditional (driver-operated) vehicle in a mixed stream. These technology-savvy people also are more likely to stay updated on technological advancements, and they also may see the benefits of being able to play on their phones while the vehicle drives.

The results in Table 5.8 suggest that the respondents who enjoyed driving were more likely to feel very comfortable or moderately comfortable driving their own traditional vehicles. The marginal effects show a higher value of the influence of driving joy associated with the comfort level "very comfortable" than with "moderately comfortable." The positive association of this attribute with higher comfort levels is highly intuitive. This variable could be a cumulative indicator of the privacy and the full control associated with a traditional vehicle. To many people, AVs could be a device of social control and surveillance (The Economist, 2018).

The respondents' likelihood of feeling very comfortable or moderately comfortable driving their traditional vehicles in a mixed-stream road was negatively associated with employment outside the home, meaning that respondents whose workplace was not their home were more likely to feel very uncomfortable or moderately uncomfortable. This could be due to these respondents having to drive to the workplace. This effect also could be attributed to the concerns associated with the likelihood of encounters or contact with AVs in the traffic stream during this time when the state of this technology is uncertain.

The respondent's age was another important variable that was found to significantly affect the respondent's comfort level associated with driving a traditional vehicle in a mixed traffic stream. The respondents between 18 and 24 years old were more likely to feel very comfortable or moderately comfortable driving their traditional vehicles while those more than 55 years old were more likely to feel very uncomfortable or moderately uncomfortable driving their traditional vehicles in a mixed-traffic environment. This relationship of the respondent's comfort level with their age is very intuitive and is consistent with the outcomes of a previous study where millennial drivers (18-36 years old) were found more likely to feel safer sharing the road with AVs while driving a traditional vehicle than Generation X (37-52 years old) and baby boomers (53-71 years old) (AAA, 2018). The respondents with an annual income between \$25,000 and \$49,000 were found more likely to feel very comfortable or moderately comfortable driving their vehicle, which could be attributed to the fact that respondents in this income group cannot afford other options (that could possibly be a bit more expensive). Rather than being picky about the comfort level, they prefer to accept what is offered to them. Another attribute that was found statistically significant for affecting the respondents' likelihood of feeling comfortable is a commute mile indicator, which is defined as "1" if a respondent must drive to a workplace located more than a mile away. The effect of this variable is somewhat intuitive in that driving more than a mile to work daily decreases the respondents' likelihood of feeling comfortable (very comfortable or moderately comfortable) in a mixed-stream roadway environment.

Other variables that were found statistically significant were indicators for gender (female), the highest level of education (bachelor's degree and above), and familiarity with the connected vehicles. These variables were found to have normally-distributed random parameters. Based on the probability for normal distribution, for 84.8% of the observations, it was more likely that female drivers felt uncomfortable sharing the road with AVs. Female drivers are relatively more risk-averse with higher levels of concern (Kyriakidis et al. 2015; AAA, 2018) and prefer a more certain and safer roadway environment; and their perceptions largely indicate the lack of trust about the mixed-stream driving environment. For an indicator of the respondents with the highest level of education as a bachelor's degree and above, for 97.77% of the observations, there was a likelihood that respondents would feel uncomfortable, which could be attributed to the current state of AV technology and all the discussion surrounding the uncertainty associated with this technology, mainly in terms of its safety. One such example is the several events of collisions and fatal crashes involving AVs during testing on the actual roadway in a mixed stream, which were widely reported in the media. There is a possibility that respondents with a comparatively higher level of education follow the news about the development and testing of AVs more closely and have a better understanding of how this technology works and what its current state is. The amount of risk involved in the current state of the technology contributed to the lower comfort levels of the highly educated respondents in the transition phase. For 83.96% of the observations, the respondents who had heard about connected vehicles were less likely to feel uncomfortable driving a vehicle in a mixed traffic stream. This could be a proxy for the awareness of respondents about the potential benefits of this emerging technology.

The respondents who did not drive to work or school themselves were more likely to feel comfortable in a mixed-stream road of both AVs and human-operated vehicles, which is somewhat intuitive because non-driving travelers have already given up control of the vehicle (to another human driver) and thus may be more comfortable with others (including machines) controlling the vehicle. From the marginal effects presented in Table 5.8 and Figure 5.5, a unit change in this attribute resulted in an average 0.097 increase in the respondents' likelihood of feeling very comfortable, an average 0.048 increase in the respondents' likelihood of feeling moderately comfortable, an average 0.010 decrease in the respondents' likelihood of feeling neutral, an average 0.071 decrease in the respondents' likelihood of feeling moderately uncomfortable, and an average 0.063 decrease in the respondents' likelihood of feeling very uncomfortable.

Table 5.8 Model estimation results for comfort level in sharing the road with AVs

Explanatory Variables	**Parameter Estimates**	**Marginal Effects**				
		Very comfortable	**Moderately comfortable**	**Neutral**	**Moderately uncomfortable**	**Very uncomfortable**
Non-random parameters						
Constant	1.110[a]					
Going to work/school (1 if do not drive to work or school yourself, 0 otherwise)	-0.366[b]	0.097	0.048	-0.010	-0.071	-0.063
Awareness about any car-sharing service like Zipcar or Car2Go (1 if heard about any car-sharing service, 0 otherwise)	-0.174[a]	0.053	0.016	-0.009	-0.035	-0.024
Smartphone use (1 if user of a smartphone, 0 otherwise)	-0.142[b]	0.041	0.015	-0.006	-0.029	-0.021
Enjoy driving (1 if enjoy driving, 0 otherwise)	-0.204[a]	0.059	0.022	-0.009	-0.042	-0.030
Employment status (1 if employed full-time, 0 otherwise)	-0.152[a]	0.046	0.015	-0.008	-0.031	-0.021
Workplace (1 if workplace is not home, 0 otherwise)	0.122[b]	-0.037	-0.011	0.007	0.025	0.016
Young age (1 if aged between 18 and 24 years, 0 otherwise)	-0.262[b]	0.086	0.017	-0.019	-0.053	-0.031
Older age (1 if aged more than 55 years, 0 otherwise)	0.136[b]	-0.040	-0.014	0.007	0.028	0.020
Income level (1 if income is between $25,000 and $49,000, 0 otherwise)	-0.103[c]	0.032	0.009	-0.006	-0.021	-0.014
Commute miles (1 if travel to workplace located more than 1 mile away, 0 otherwise)	0.196[b]	-0.062	-0.015	0.013	0.040	0.024
Random parameters						
Gender (1 if female, 0 otherwise)	0.176[a]	-0.054	-0.016	0.010	0.036	0.024
Standard deviation of the parameter density function	0.171[a]					
Positive sign density of the random parameter distribution	84.8%					
Bachelor's and higher degree (1 if the highest level of education is a bachelor and above, 0 otherwise)	0.168[a]	-0.052	-0.015	0.010	0.035	0.023
Standard deviation of parameter density function	0.084[a]					
Positive sign density of the random parameter distribution	97.77%					
Heard about connected vehicles (1 if yes, 0 otherwise)	-0.135[a]	0.041	0.012	-0.008	-0.028	-0.018
Standard deviation of parameter density function	0.136[a]					
Positive sign density of the random parameter distribution	16.04%					
Threshold 1	0.818[a]					
Threshold 2	1.292[a]					
Threshold 3	2.201[a]					
AIC	6050.8					
Log-likelihood function at the convergence	-3005.404					

a, b, c manifest significance at 1%, 5%, 10% level.

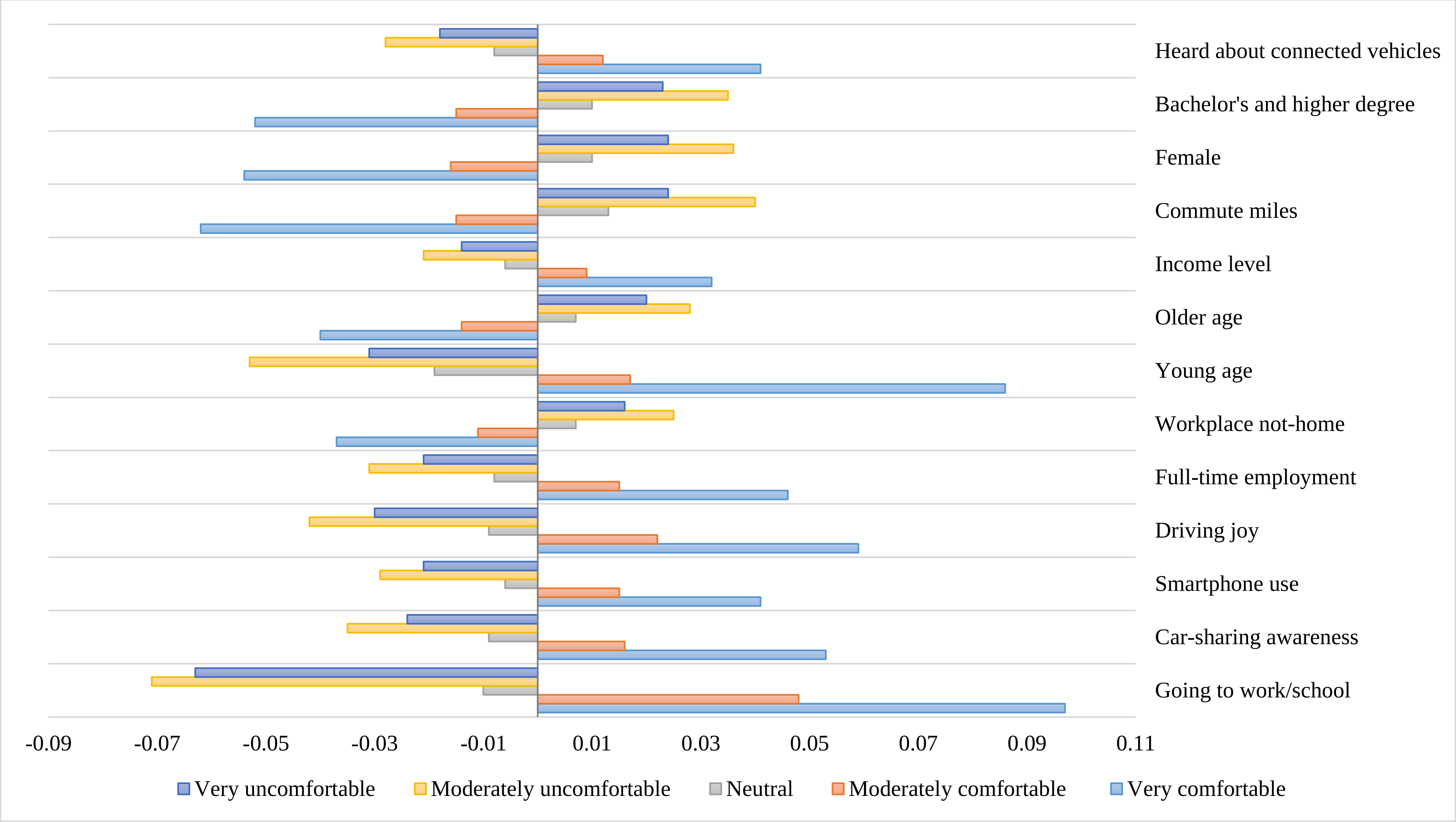


Fig. 5.5 Visual illustration of marginal effects for road user comfort level

5.4.4.4 Implications of the Road User Surveys for AV-related Road Readiness

This section explores the factors that influence the respondents’ comfort level in driving a regular vehicle while sharing the road with AVs. Those who did not drive to school or work, were aware of car-sharing-services, used smartphones, enjoyed driving, were employed full-time, were between 18 and 24 years old, and had an annual income between $25,000 and $49,000 were more likely to feel comfortable while those who did not work at home and drove more than a mile to work/school daily, and were more than 55 years old were less likely to feel comfortable in a mixed-stream road of HDVs and AVs. Moreover, respondents who were female, held a bachelor’s degree or greater education, or were familiar with connected vehicles generated normally-distributed random coefficients.

To facilitate the effective deployment of smart-vehicle technology, it is important to understand the road user trust in these systems to support their assimilation into the mainstream marketplace and also their deployment on the public roadways. One of the key questions investigated in this dissertation was about the traditional-vehicle users’ comfort level in sharing a road with AVs in a transition phase. The findings provide insights that will assist automotive manufacturers, technology developers, and ride-hailing firms in designing a supply plan for the transition phase and the associated investment decisions. The findings also could be used by highway agencies for policy formulation, transportation systems planning for AV technology, and preparing road infrastructure to accommodate both traditional and AVs in the transition phase, while duly accounting for their concerns and preferences.

As found in this chapter, 68% of the respondents from SMMAs preferred to continue owning their regular vehicles compared to the AV options offered to them in different forms (self-owned, hired, and shared). As such, it is important to capture the input and preferences of these traditional vehicle owners/or users related to AV-related redesigning and retrofitting strategies under consideration for highway infrastructure and design. To do so, the information about road-sharing comfort level in this dissertation could be leveraged to investigate the public acceptability of proposed redesign and retrofitting options. For example, future studies could investigate how the levels of respondents’ road-sharing comfort would change across various retrofitting options, such provision for an exclusive lane for AVs, an exclusive lane for heavy vehicles, etc.

5.5 Discussion and Conclusions

The three key stakeholders, technology developers, highway agencies and road users, were surveyed with the intent to capture their opinions and preferences with respect to the items that are specifically relevant to them. The questions in these different surveys were crafted in a way to ask the right questions from the right audience. The technology developers were asked about (a) the expected timing of the very first commercial availability of AVs for public use, (b) favorable timing, in relevance to market penetration rates, of road infrastructure readiness to support AV operations, (c) freeway infrastructure readiness for AV operations, (d) likely locations for the initial AV deployment, and finally (e) the likely emergence of market penetration trends. Due to their leadership of AV technology developing and testing, technology developers represent the most appropriate source to comment on the potential timing of the deployment and commercial availability of AVs for the public use. Also, they are fully aware of the current state of technology, its potential evolution, and the ongoing testing of this technology (and its performance and reliability during the testing phase). The state and capabilities of the AV technology and the timing of commercial deployment will have implications for market penetration. As such, technology developers were asked what they think about how the market penetration rates are expected to grow or change. Two scenarios of market penetration trends, pessimistic and optimistic, were developed based on the responses from industry.

Moreover, since highway agencies hold the stewardship of road infrastructure, they deal with the development of new road facilities, and expansion, retrofitting, rightsizing, modernizing, maintenance, rehabilitation, and reconstruction of the existing infrastructure facilities. Highway agencies including state highway agencies and a few local agencies were surveyed, through AASHTO, to capture their perspectives and opinions regarding the emergence of AV operations and its implications for the road infrastructure and design features. The question asked from agency respondents were related to (a) the favorable timing of road infrastructure readiness to accommodate AV operations, (b) the likely locations for the initial AV deployment, (c) freeway infrastructure readiness for AV operations, (d) minimum market penetration rates plausible for making major roadway design changes, (e) likely change in amount of vehicle travel, (f) likely change in amount of passenger travel, (g) anticipated change in infrastructure funding needs with AV operations, and (h) overall parking needs. They are also about the expected changes in the geometric design features, i.e., (a) shoulder width of arterials and freeways, (b) superelevation of new roads containing only AVs, (c) radius of horizontal curves for new roadways with AV operations only, (d) gradient of vertical curves for new roadways with AV operations only, (e) need for real-time monitoring of traffic and cyber-physical infrastructure, (f) speed limits in a transition phase, and (g) speed limits in a fully autonomous era. The respondents emphasized an immediate need for: (a) equal implementation of infrastructure and information technology nationwide, for instance, WiFi and internet, across all forms of built environment and all types of roadways; (b) greater uniformity of traffic control devices and consistency in infrastructure across regions and states; (c) more roadside infrastructure; (d) real-time work zone traffic control updates for AVs; (e) new improved pavement markings and on all road types, that traditionally have been omitted from local roadways; and (f) an equal modernization and retrofitting of local roadway networks.

Table 5.9 comprises the viewpoints of industry and agencies regarding the questions they were asked. An important finding to note here is that when both agencies and industry were asked about the likely change on freeways that they think would be good to support AV operations at the initial deployment phase, 41% of the industry respondents and 44% of the agency respondents suggested to allocate a dedicated lane in this regard. This shows a very close agreement in the responses regarding freeway readiness. A second noteworthy item is related to the likely locations for the initial deployment of AVs. The highest number of responses from both sides were in favor of high-speed roadways (freeways and expressways). Some of the agency responses noted that the business models of the industry will define the likely locations of AV deployment. These two aforementioned findings render additional evidence in support of one of the scenarios that are being analyzed later in this dissertation for economic feasibility.

Furthermore, two types of road users were also surveyed with the intent (a) to explore the likely adoption and use of AVs in future and hence, demand especially in the context of use-case scenario (self-owned, hired, shared), and (b) the comfort level of traditional vehicle users, while sharing roads with AVs. In the absence of historical data, these surveys could be used as an effective tool to generate consumer data. The road user survey is a demonstration of how highway agencies can use this tool when carefully designed, to collect feedback of road users about candidate infrastructure modifications in their respective jurisdictions. Such information can be leveraged to investigate the user acceptance of AV technology, hence, defining the demand; this demand information can be used by agencies to adjust the supply side i.e., redesigning and retrofitting of highway infrastructure needed for AV operations. Carefully designed, tested and calibrated survey tools could be useful to agencies in decision-making particularly during the early stage of the transition phase.

Nevertheless, these studies highlight the need for closer interaction among the key stakeholders for implementing AV operations. This interaction will be mutually beneficial and help discern three things: technological developments at the industry level, the need for types and levels of efforts required at the agencies, and the likely adoption of AVs at the consumer level. By keeping stakeholders aware of each other's ventures and limitations, the current knowledge gaps could be filled considerably. In addition, this will help overcome the intensity of uncertainty and make more informed decisions at all levels.

Table 5.9 Comparison of industry and agency responses

Questions	**Possible Responses**	**Industry**	**Agencies**
At the INITIAL deployment of driverless vehicles on a FREEWAY, which of the following design changes would you suggest?	A dedicated/ separate/ exclusive lane for driverless vehicles	41%	44%
	A dedicated lane for trucks and other lane(s) for driverless and traditional automobiles.	6%	24%
	No change is necessary (option for industry) | specify otherwise (option given to agencies instead)	53%	32%
In your opinion, which of the following locations should be the first for deploying driverless vehicles?	High-speed roadways (freeways, expressways)	53%	32%
	Urban highways	0%	8%
	Central business districts	18%	8%
	Restricted residential neighborhoods	12%	24%
	Rural roadways	6%	0%
	Other (please specify)	11%	28%

5.6 Limitations

While referring to the survey of road users, the results presented in this chapter explain current preferences; however, today's attitudes are not of immense help in discerning how preferences may change in the future. Without the actual introduction of AVs in the market, public perceptions and perspectives cannot be measured with much certainty. As such, the actual level of AV demand in a given market may deviate from what is predicted initially. Since AVs are a newer technological concept, public perceptions about these emerging vehicle technologies are likely to be unstable. Consequently, similar surveys should be carried out periodically to feel the fluctuating pulse of the market and unveil consumers' preferences instantaneously. In other words, today's demand forecasts are time-specific, as their relevance may change over time. In addition, it is important to note here that these forecasts are area-specific, as such they cannot be generalized for all geographical locations across the country or across the globe.

Another limitation of the road user survey is that it uses cross-sectional data; however, a more plausible approach would be to gather longitudinal data (opinions and perspectives of respondents over a period of time) and track changing perspectives. To this end, future research would benefit from exploring the changing opinions with a comprehensive longitudinal survey.

Moreover, the industry forecasts and responses will also need a periodic update due to the time rate of change of technology evolution and maturation. The market penetration trends presented in this dissertation may change as the state of technology and the deployment timing and models become clearer and more certain with time.

Finally, the road user survey presented in this chapter was conducted in the U.S. and hence the results are not necessarily transferable to other countries because of possible differences in the transport system characteristics and socio-economic conditions. The temporal and spatial variability and relevance of the findings must be given due consideration.

5.7 Chapter Summary

This chapter presented the perspectives and opinions of three key stakeholders about the major elements and tasks of implementing AV operations. The responses of questions, asked from technology developers, highway agencies, and road users through questionnaire surveys, were presented and discussed. The limitations of these surveys were also noted. In the next chapter, the types of highway infrastructure readiness and roadway design changes that may be required to support the road operations of AVs are identified and discussed.

6. ROAD INFRASTRUCTURE AND DESIGN READINESS

6.1 Introduction

The previous chapter addressed the perspectives and opinions of three key stakeholders about the major elements and tasks of AV operations. Some of the AV-related infrastructure needs were captured through the agency responses. This chapter identifies and discusses the types of highway infrastructure readiness and roadway design changes that may be required to support the road operations of AVs. The required levels of infrastructure readiness for AVs are expected to vary across the various stages of AV operations, primarily the transition phase and the fully autonomous era. This chapter discusses this issue using road geometric design features as an example. Finally, Design for Changeability (DfC), a concept adopted from systems engineering, is proposed as a strategy to promote infrastructure readiness for AVs.

6.2 Types of Infrastructure Readiness

6.2.1 Introduction

The current highway infrastructure is designed for human drivers who are subject to a variety of errors due to distraction, impairment, fatigue, inexperience, and other factors. For example, roadways and the shoulder widths are far greater than the vehicle widths to serve as buffer zones that reduce opposing sideswipes or run off the road crashes. Additionally, safety features such as rumble strips, median cables, guardrails, transverse strips, signs for stopping or slow-down, and other warning devices are provided cognizant of the imprecise and often errant nature of human driving. AVs are expected to offer more precise and minimal-error operations compared to human driving and therefore may lead to the reduction or elimination of certain infrastructure elements such as the above and also could require new infrastructure elements.

For these reasons, it is imperative that highway agencies are able to clearly measure the extent of their existing infrastructure needs and their preparedness at each stage of AV operations, as discussed in Chapter 2 of this dissertation. During the transition phase, roadways will be expected to host both HDVs as well as AVs, and highway infrastructure must be compatible to host both types of vehicles. In the ensuing sections, five main types of infrastructure readiness are identified and discussed at the stages of transition and fully autonomous operations. Some of these changes may occur during the fully autonomous era, but not necessarily during the transition phase. Moreover, some changes are expected to be incremental and will occur as AV operations increase on the roadways (i.e., higher levels of market penetration). The changes that will likely be needed can be categorized as follows:

a) Enhanced maintenance
b) Introduction of new infrastructure elements
c) Removal of some of the existing elements
d) Redistribution of some elements
e) Redesign of some elements

Table 6.1 presents the types of roadway infrastructure needs that are associated with the existing and anticipated AV technologies, are discussed in some detail in the following sections.

Table 6.1 Infrastructure readiness for AV-related technologies

SAE Levels of Automation	**Role of Human Drivers**	**Example Technology and/ or Capabilities/Competencies**[1,2,3,4,5]	**Infrastructure Readiness**[6,7]
Level 0 (No Automation)	All driving tasks monitored and executed by human drivers	Forward collision warning	None
		Lane departure warning	Well-maintained pavement markings
		Blind-spot monitoring	None
		Automated wipers	None
		Headlights	None
		Lane-keeping assistance	Well-maintained pavement markings
		Turn signals	None
		Hazard lights	None
Level 1 (Driver Assistance)	Human drivers must monitor the driving environment and drive all other functions.	Adaptive cruise control	None
		Automatic braking	None
		Lane-keeping assistance	Well-maintained pavement markings
		Adaptive headlights	None
		Electric stability control	None
		Parental control	None
Level 2 (Partial Automation)	The human driver must monitor the driving environment (system pokes driver or deactivates itself with the intent to seek the attention of driver).	Adaptive cruise control mixed with lane centering	Well-maintained pavement markings
		Traffic jam assist on limited-access highways at slow speeds (Mercedes, Tesla, Infiniti, Volvo, etc.)	Well-maintained pavement markings
		Automated assistance in roadwork and congestion	Well-maintained pavement markings and road signs
		High-speed Automation (Supercruise)	Well-maintained pavement markings and road signs
Level 3 (Conditional Automation)	Human drivers may read a book, text, or surf internet, but must be ready to intervene when required by the system	Traffic sign recognition	Well-maintained signs
		Traffic jam pilot	Well-maintained pavement markings and road signs
		On-highway platooning	Well-maintained roadways
		Left turn assist	Well-maintained pavement markings
Level 4 (High Automation)	Human drivers may sleep, and the system can go to minimum risk condition in case required so.	Automated valet parking (locate a parking spot, park, and return to the driver when summoned without any human interaction)	Well-maintained pavement markings
		Emergency Stopping Assistant	None

Table 6.1 continued

Level 5 (Autonomous/ Full Automation)	Operation without any human driver. Riders will be able to provide destination or intended navigation input.	Lane-keeping	Well-maintained pavement markings
		Platooning	Well-maintained roadways with no potholes and other similar distresses.
		Auto-valet parking	Parking infrastructure
		High-speed automation	Pavement markings; Traffic signs and signals
		Emergency stopping assistance	None
		Automated assistance during congestion and work zones	Pavement markings, Beacons, Traffic lights

1 Shladover (2018)
2 Kockleman et al. (2017)
3 NHTSA (2013)
4 NHTSA (2016)
5 Parent control: for instance, (a) Ford's speed control allowing to set a limit to 80 mph; volume control allowing to adjust the volume of the radio remotely; a belt reminder system muting vehicle’s radio and chime for few seconds; an earlier fuel reminder; and a speed reminder at 45, 55 or 65 mph. (b) Chevrolet’s “Teen Driver” system comprising 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, front pedestrian braking.
Automated braking: dynamic brake support in emergencies and crash imminent braking), also called forward collision avoidance technology or automatic emergency braking.
6 Platooning is expected to subject roadways to repeated higher loads instantaneously especially in case of trucks. Therefore, road pavements will be required to be designed to a much higher standard to enable them to withstand these traffic loadings.
7 None means “there is no need for readiness”

6.2.2 Enhanced Maintenance

As shown in Table 6.1, the infrastructure readiness required by most AV technologies is related to the enhanced maintenance of pavement markings, pavement surfaces, and road signs. It is anticipated that to support AV operations at their initial deployment, agencies will need to provide enhanced all-weather high-reflectivity pavement markings and road surfaces in excellent condition, which is consistent with the survey results presented in Chapter 5.

Pavement markings with higher contrast and enhanced reflectivity improve lane detection by human drivers and AVs with machine vision systems (Pike et al., 2019). Another infrastructure type that may require immediate retrofitting to support AV operations are road signs with improved visibility and legibility to facilitate interpretation via machine vision.

To support AV operations, agencies may need to be vigilant about their roadway surfaces and make them easily read by AV sensors. Technology developers can help overcome the problem of the poor state of pavements and road markings by equipping AVs with more robust and reliable sensors, but such sophistication likely may have significant cost implications for potential AV buyers that may impede AV adoption.

The deployment of AVs on public roads also will require more frequent and intensive maintenance so that the lane markings, road pavements, signs, and AV-critical infrastructure can be continuously maintained in a state of good repair. As noted in one of the agency responses in Chapter 5, pavement striping will need to be carried out regularly because the current need and levels of road maintenance also are based on human vision. Frequent maintenance will also be needed for new types of infrastructure assets such as hi-tech elements (cyber-physical infrastructure supporting communication) that have relatively shorter life spans. It may be necessary to develop pavement and road materials specifically targeted towards AV operations and to investigate the effect of various meteorological conditions on pavement marking visibility to AV machine vision.

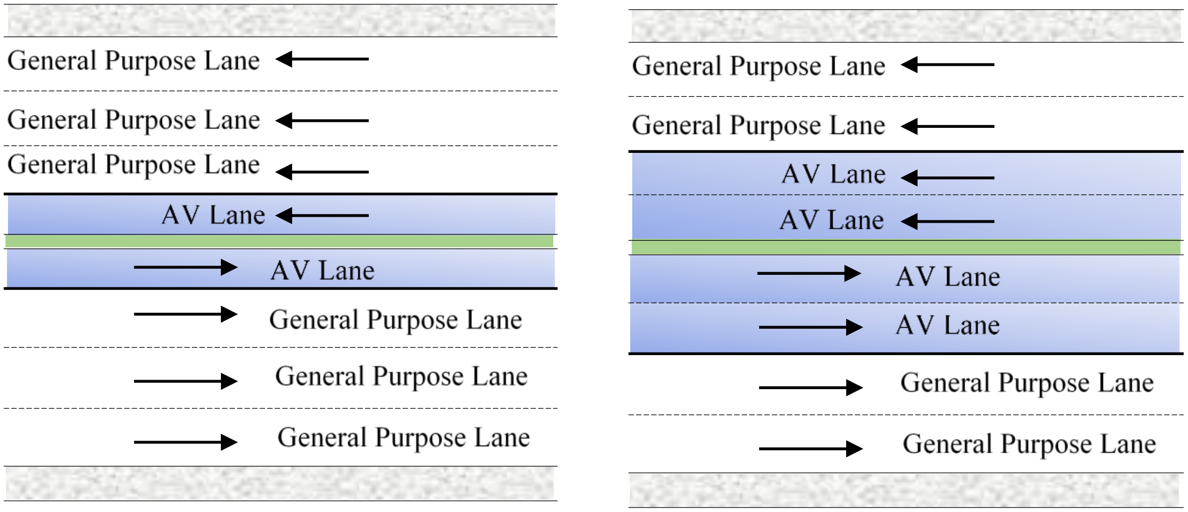
6.2.3 Introduction of New Infrastructure Elements

New infrastructure elements that may be needed to support AV operations include (a) addition of new road lanes to be dedicated to specific speeds or purposes during the initial deployment of AVs; (b) a dedicated lane for AVs during the transition phase particularly during the period of initial

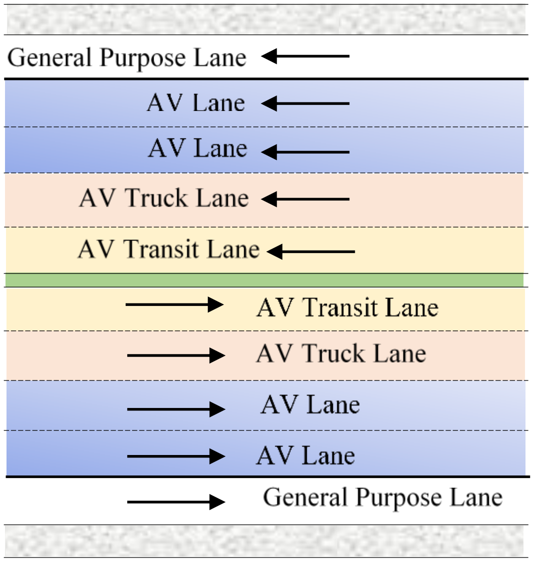
AV deployment when it is expected that both traditional and AVs will use the roads; (c) a restricted lane for freight transport to allow truck platooning; and (d) exclusive transit lanes for autonomous buses. Provision of exclusive lanes may facilitate AVs to platoon. Simko (2016), through a simulation framework, predicted an increase in the carriageway capacity by up to 500 percent through AV platooning. This much increase in capacity seems too high and may not be attainable; however, a positive impact on capacity is definitely expected. As such, during the transition phase, AVs with the ability to platoon in exclusive express lanes could offer a more efficient alternative compared to general-purpose lanes carrying traditional vehicles. Separating AVs from traditional traffic by providing exclusive AV lanes may generate more benefits in terms of fuel consumption and travel time efficiency. With an increase in the AV market penetration, the number of special-purpose lanes can be incrementally increased, as shown for freeways in Figure 6.1.

The phases in Figure 6.1 correspond to AV market penetration. As AV market penetration grows, the number of AV exclusive lanes is increased until Phase III is reached. In Phase III, traditional vehicles are constrained to exclusive lanes and the remaining roadway contains AVs. With an increased AV operation on roads at higher levels of market penetration, improvement in traffic efficiency is anticipated and a resultant increase in capacity. Consequently, it may not be necessary to acquire additional right-of-way to construct additional lanes in the future, which is contrary to what happens in the case of traditional vehicles, when more land is acquired to construct new lanes to handle growth in traffic (when demand becomes higher than supply).

New infrastructure elements also may include hi-tech infrastructure at intersections that will allow vehicles to communicate and pass without traditional stoplight timing. This element is expected to happen only in the fully autonomous era because the traditional traffic signal system will be maintained as long as roadways contain some traditional vehicles. Other new elements will include an integrated network of cyber-physical infrastructure to support various types of connectivity including infrastructure to vehicle (I2V), vehicle to infrastructure (V2I), vehicle to pedestrian (V2P), and vehicle to everything (V2X). For example, regarding V2I communication, there will be a need for infrastructure associated with dedicated short-range communications (DSRC). For longer-range communications, cellular technology and its associated infrastructure may be needed. AVs are expected to be electric eventually, which may generate a need for electric vehicle charging infrastructure. All of this may occur slowly over time and may not be needed in the early transition phase.



(a) Phase I (b) Phase II



(c) Phase III

Fig. 6.1 Phased transition of roadways to accommodate AVs

6.2.4 Removal of Some of the Existing Infrastructure Elements

The AV era may cause the obsolescence of certain existing infrastructure elements and their subsequent retirement from the asset inventory, which is likely to occur when all the vehicles on the roads are autonomous. Examples include traffic signals and park-and-rides. In the era when AVs will be able to communicate with each other and negotiate their right-of-way, some infrastructure elements, such as traffic lights, may not be even required as noted by Duarte and

Ratti (2018). Traffic lights were developed, some 150 years ago, to help negotiate conflicting traffic at roadway intersections. As noted by Tachet et al. (2016), traffic lights, a more than century-old communication gadget, could potentially be removed by implementing the distributed networks of traffic data exchange, specifically, the authors proposed a slot-based solution at intersections where the vehicles could work out their right-of-way themselves through the exchange of data about their speeds, directions, and locations. These slot-based intersections could produce twice as much throughput in a given time at intersections equipped with traffic lights. Olmos et al. (2016) predicted even higher throughput with the use of their proposed AV-synchronized traffic optimization schemes that combine the data from travelers' cellphones. As noted in the Highway Capacity Manual, the capacity of at-grade intersections is only about half that of the intersecting routes. While AVs may know how to avoid conflicts with other vehicles using artificial intelligence, traffic control signals and signs no longer will be needed to direct human operators and help negotiate the right-of-way. However, this is mainly true for the fully autonomous era; and in the transition phase, the existing traffic control systems will be necessary. Furthermore, on low-volume and rural roads where traffic control systems do not exist, extensive signage, striping, and traffic control devices may be required during the transition phase.

6.2.5 Redistribution of Some Elements

Some infrastructure elements may require locational redistribution. For example, current city parking schemes may undergo redistribution due to the anticipated reduction in city-center parking facilities and increased need for passenger pick-up and drop-off zones. As noted by Duarte and Ratti (2018), cities will likely be able to recover much of the land occupied by large parking garages, particularly in downtown areas. Reduced private ownership of vehicles is expected due to the more frequent and dominant use of AVs as a shared service. If that prediction becomes a reality, AVs are expected to have a utilization rate of 75 percent compared to the 4 percent utilization rate of self-owned traditional vehicles on an average day, which are estimated to be idle 96 percent of their life (The Economist, 2015). As such, the need for massive parking infrastructure, including valet services, parking meters, and handicap parking to meet long-term storage of unused vehicles, will reduce over time due to the increased use of shared AV ride services. There may be less demand for parking garages and on-street parking spots as well, at least in central business districts or prime city areas, which consume space that could otherwise be used for an additional traffic lane or sidewalk space. This impact may have profound consequences on the future urban landscape including the city centers.

6.2.6 Redesign of Some Elements

Certain infrastructure elements will likely undergo design revisions which may include changes in dimensions or frequency. Such design changes may be expected mainly when the fully autonomous era is reached. AVs are believed to be inherently safe with no traffic collisions; therefore, the need for certain safety assets such as shoulders, guardrails and rumble strips, will be reduced. The physical dimensions of some infrastructure elements may change, and the design dimensional features of certain assets will likely decrease (e.g., narrower lanes and smaller lateral clearance). The potential geometric design impacts of AVs are discussed in the next section.

6.3 Changes in Roadway Geometric Design

6.3.1 Introduction

The criteria governing the geometric design of roadways generally involve configuring lane width, design speed, stopping sight distance (sight distance for safe stopping based on human drivers), shoulder width, horizontal curve radius, superelevation rate, maximum grade, cross slope, vertical clearance, and design loading structural capacity (AASHTO, 2018; Mannering and Washburn, 2016). For example, defining the sharpness of a curve known as a horizontal curve, identifying the banking required on a horizontal curve, or determining the rate of change in the vertical slope on a road segment that joins segments with different grades (termed as a vertical curve). Moreover, the roadside safety aspect of the design includes features, such as shy distances and clear zones. The concept of roadway geometric design evolved from the physics-based railroad design; however, the former is based on human needs with a primary objective of providing consistent features and predictable experiences to meet user expectations.

Roadway geometry involves design controls and features that (a) ensure the comfort and security of drivers by maintaining lateral acceleration below levels that may cause discomfort; (b) help avoid encounters and conflicts through adequate stopping sight distance and sight lines at intersections; and (c) define vehicle trackways through lane width configurations and float and drift between lane markings. To these ends, horizontal alignment addresses curve dynamics and forces and horizontal offset sight distance; vertical alignment provides adequate sight distance and driver comfort at crest curves or headlight demands at sag curves; and cross-sectional features address lane and shoulder width and provide offsets to physical elements or adjacent users (bicyclists or parked cars) (AASHTO, 2018).

The underlying major factors that inform the geometric design of roadways are the design driver and the design vehicle (vehicle dimensions and vehicle performance are defined in terms of physics). From the vehicle performance perspective, AVs are not expected to have any considerable impact on the geometric design standards as the main laws of physics that govern vehicle performance may remain the same. However, two key phenomena, i.e. acceleration and deceleration of AVs, could have implications for roadway geometric design in certain areas (Washburn and Washburn, 2018). The AV deceleration rates may affect the design of (a) deceleration lanes for turning lanes or off-ramps, (b) horizontal and vertical curves for stopping, and (c) maximum steepness of downgrades. On the other hand, the AV acceleration rates may impact the design of acceleration lanes for on-ramps and the steepness of upgrades. However, AVs will continue to be used by humans so the acceleration and deceleration rates may not undergo any drastic revisions that could make the ride uncomfortable for the AV occupants. In other words, human needs and tolerance levels are expected to continue to govern this aspect of geometric design consideration and therefore is not expected to cause any design changes.

6.3.2 Stopping Sight Distance

Stopping sight distance (SSD) (Figure 6.2) refers to the distance that is needed to comprehend an object in a roadway and bring the vehicle to a stop. It indicates how far (distance) a driver can perceive an obstacle in the roadway. The sight distance at every point along a roadway should be at least that needed for a below-average driver or vehicle to stop (AASHTO, 2018). The design of horizontal and vertical curves is predicated on the sight distance together with the design speed and reaction time of the human drivers, as shown in Equation (6.1).

$$SSD = 1.47\ Vt + 1.075\ (V^2/a) \qquad (6.1)$$

where, SSD = stopping sight distance in feet; V=design speed in mph; t = brake reaction time (2.5 seconds); and a = deceleration rate in ft/s^2. SSD can also be represented as:

$$SSD = \text{Reaction Distance} + \text{Braking Distance} \qquad (6.2)$$

where reaction distance refers to the distance a driver covers from the point of detecting a hazard until applying brakes or swerving. The braking distance, also called the stopping distance, is the distance a vehicle covers from the time of the full application of its brakes until the complete stopping of the vehicle.

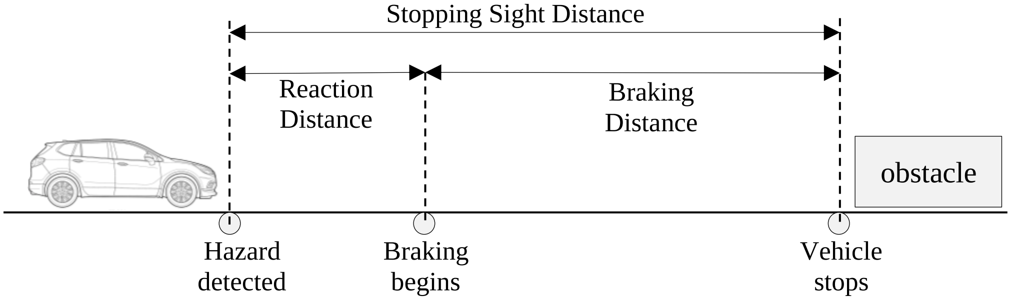


Fig. 6.2 Visual illustration of stopping sight distance

The reaction distance is influenced by two factors, i.e. the vehicle's speed and driver's reaction time.

<u>Vehicle speed</u> (proportional increase): 3 x higher speed = 3 x longer reaction distance.

<u>Reaction time</u>: Generally, AASHTO (2018) recommends 2.5 seconds for brake reaction time, but this time increases with age, fatigue, complexity of the task, physical impairments, and, use of alcohol and drugs, which are specific to human drivers. Additionally, an unexpected event may add 0.5 to 2.5 seconds to the reaction time. Drivers 45–54 years old are considered to have the best reaction time in traffic, whereas drivers 18–24 years old and those over 60 demonstrate the same reaction time in traffic. Although younger people have sharper senses, older drivers are more experienced. This reaction time can be reduced in two ways: (1) preparedness and (2) quicker anticipation of hazards. The factors that contribute to increased reaction times include alcohol, drugs, medication, and fatigue, which are specific to human drivers. AVs are independent of these human-specific traits. Some of the simulation studies show that with AVs the perception/reaction time could be reduced to 0.83-0.84 seconds (Dixit et al., 2016) or 0.5 seconds from 2.5 seconds (perception/reaction time of human drivers). If the perception/reaction time for AVs in Equation (6.1) falls to 0.5 seconds, the stopping sight distance values at different design speeds can be calculated as shown in Table 6.2. The computations show a higher percentage reduction in the sight stopping distance at lower design speeds.

Table 6.2 Stopping sight distance for human and autonomous driving

Design speed, mph	Reaction time, seconds	Stopping sight distance, ft	Percent reduction
40	2.5 0.5	300.6 182.97	39
45	2.5 0.5	359.74 227.44	37
50	2.5 0.5	423.71 276.71	35
55	2.5 0.5	492.47 330.77	33
60	2.5 0.5	566.04 389.64	31
65	2.5 0.5	644.40 453.30	30
70	2.5 0.5	727.6 521.76	28
75	2.5 0.5	815.5 595.02	27
80	2.5 0.5	908.3 673.09	26

The computations in this table are predicated on a deceleration rate of 11.2 ft/sec^2 recommended by AASHTO (2018) for level roadways.

According to AASHTO (2018), the perception/reaction time of 2.5 seconds at a design speed of 75 mph is translated into a reaction distance of 275.6 ft and a braking distance of 539.9 ft. When this perception/reaction time falls to 0.5 sec with AVs at the same design speed (Table 6.2), this can be translated to reaction distance as:

Reaction Distance = (0.5sec/2.5sec) x 275.6 ft = 55.12 ft

According to Equation (6.2), the stopping sight distance can be computed as:

Reaction Distance + *Braking Distance* = 55.12 ft + 539.9 ft = 595.02 ft. This value also can be compared to that computed in Table 6.2 using Equation (6.1). The braking distance can be expected to fall somewhere between the comfortable and the emergency braking distance due to the presence of human occupants in the AVs. However, in this case, the braking distance is assumed to be at a comfortable level. The braking distance is generally affected by the vehicle's speed by an exponent of 2, road (gradient and conditions), the load, and the brakes (condition, braking technology, and how many wheels are braking). It is quite difficult to achieve reliable estimates of the braking distance as the road conditions and the tire grip can vary greatly. For example, the braking distance may be ten times longer when there is ice on the road.

Currently, different human drivers have different perception/reaction times, but once AVs are operating on the roadways (particularly when all vehicles on the roads are fully autonomous), these perception/reaction times are expected to be uniform across all vehicles, unlike human driving. This uniformity is expected to have a profound impact on traffic safety and efficiency due to the ability of AVs to achieve a uniform reaction distance, which may enable them to platoon.

One of the major limitations associated with human driving is the line of sight of drivers, as shown in Figure 6.3. Due to this line of sight, some road obstacles are not detectable in situations such as around the bend of a curve. With AVs, the human drivers will be replaced by machine vision sensors, LiDAR, cameras, and artificial intelligence-based communication systems, which will make things detectable irrespective of the line-of-sight, meaning that the line-of-sight vision capability may be no longer relevant for AVs that use certain detection/vision technologies. Sight distance is a crucial variable used in the design of the rate of change of slope for a vertical curve. In case the obstacle detection technology contained in AVs is capable of sensing through the crest of the vertical curve, the rate of change of slope along the curve may be made greater for the same design speed. The same observation was made by Washburn and Washburn (2018). However, it is important to note that this design modification could only be allowed for roadways containing only AVs.

Washburn and Washburn (2018) also noted that AVs may react to a roadway obstacle by applying the brakes much faster, which could lead to an increase in design speed if all other factors remain the same. Moreover, the renewed concept of stopping sight distance with the emergence of AVs also may necessitate the re-evaluation of some features, especially objects offset along the road (e.g., bridge abutments, median barriers, crash walls, parapets), crest curves, sag curves together with overhead structures, distance/headway between the vehicles, intersection storage and turn bay lengths, and the intersection sight distance.

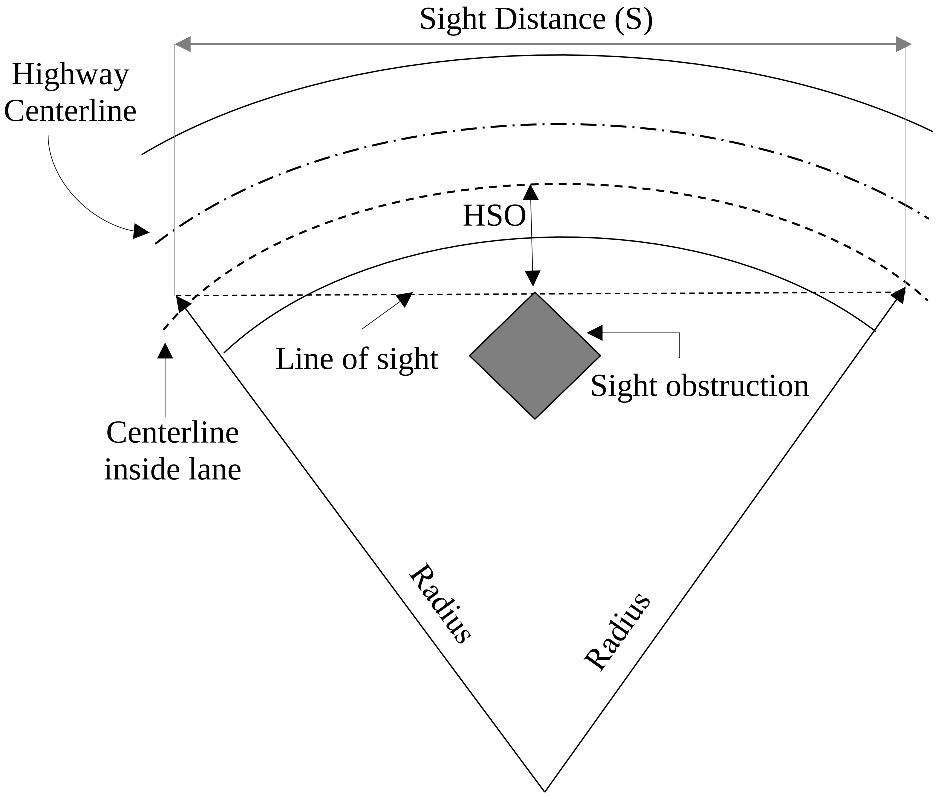


Fig. 6.3 Line-of-sight on horizontal curve sight distance

6.3.3 Acceleration Lengths for Entrance Terminals with Flat Grades

In the case of 100% market penetration of AVs on freeways, merging maneuver lengths for entrance lengths with flat grades (2 percent or less) potentially could remain the same both in the case of the taper and parallel design type. Based on the real-time communication among the AVs, the vehicles in the right lane could adjust their speed to allow the entering vehicles. However, from the highway capacity/throughput standpoint, the entering vehicles would need to drive approximately at the same speed as that of vehicles in the right lane. If it is assumed that in the future, all the vehicles on freeways will be driving at a speed of 70-75mph even at very high volumes, most likely it will not be possible to shorten merging maneuver lengths because vehicles would still need to accelerate. This is true for AVs with gas combustion engines. However, AVs in the future are expected to be electric and electric vehicles can accelerate five times as fast as a gas combustion engine vehicle (Leisch, 2018), which therefore offers an opportunity for reducing the merging maneuver length.

6.4 Impact on Throughput/Capacity

Throughput or capacity (vehicles per hour per lane) refers to the maximum number of vehicles that can be accommodated on a roadway. It serves as a measure of the relative productivity of the system compared to an alternative. With AV operations, there is an opportunity to increase the capacity on the roadways, and this potential increase in capacity can be demonstrated for basic freeway segments using speed/flow curves from the Highway Capacity Manual. At a free-flow speed of 70-75 mph, the capacity is 2,400 passenger cars per hour per lane and an average passenger-car speed of 53.1 mph. This refers to a density of 45 mph (=2400/53.1), which can be used to compute headway as follows.

The spacing of passenger cars (pc) at 70-75 mph free-flow speed = 5,280 ft/45 pc/mi/ln = 117.33 ft (headway approximately 5-6 car lengths at 53.1 mph). Distance-based headway refers to the distance between two successive vehicles on a roadway at any given time. The reciprocal of the density otherwise gives the distance headway.

The increase in freeway capacity can be achieved with AVs in two ways: 1) increasing the speed while keeping the same spacing of 117.33 ft and 2) reducing the headway, say to the 0.5-sec perception/reaction time that fully autonomous operations are anticipated to achieve. The implications of these modifications on the highway capacity are demonstrated as follows.

(1) Suppose the capacity speed is increased from 53.1 mph to 70 mph (assumed to be the uniform speed with AVs), the new capacity can be computed as:

32% increase x 2400 pc = 765 pc

Capacity = 2400 + 765 = 3165 pc/hr/lane

(2) At 70 mph, a vehicle travels 51ft in 0.5 seconds. While assuming 0.5 seconds perception/reaction time by an autonomous vehicle and 0.5-second headway between vehicles at 70 mph, the vehicle spacing is decreased from 117.33 ft to 51 ft, implying a decrease of 56%. This implies:

Capacity = (0.56 x 3165 pc) + 3165 pc = 4937pc/hr/ln (105% total increase)

As shown, a 105% increase in the freeway capacity can be achieved with AV operations. A similar increase in capacity can also be expected with the provision of an exclusive lane, where AVs will have the opportunity to platoon.

6.5 Other Considerations

6.5.1 Need for Shoulders

Other important considerations include the configurations of the shoulder width and the lane width for roadways that will host AVs only. The question is whether shoulders will be needed in the AV era, to which the answer is perhaps yes, but only at some intervals to accommodate vehicle breakdowns, flat tires, and system failure, as well as emergency vehicles. Although vehicle breakdowns are random events, it can be argued that shoulders will continue to exist even in the AV era.

6.5.2 Lane-width Configuration and Tighter Street Design

The AASHTO Green Book defines lane width configurations on various road facility types for vehicle widths of 7 ft (of passenger cars) and 8.0 to 8.5 ft (of buses and trucks). With AV operations, there may be an opportunity for narrower lanes by eliminating the extra width currently provided as a buffer to minimize the possibility of interaction with vehicles in adjacent lanes due to the errors associated with human driving (loss of control, distraction, etc.). As such, there will be a transition towards a more compact road design. The right-of-way on current roadways can be easily retrofitted to achieve this by reconfiguring the lane markings. Doing so on the current roadways could lead to having more lanes in the same amount of space; however, the design of new roadways with narrower lanes could require the acquisition of less land for right-of-way and thereby save agency funds. Moreover, through a compact roadway design and narrower right-of-way, a substantial amount of pavement construction and maintenance costs could be saved. It is important to note here that the configuration of lane widths in curves will require a more cautious evaluation due to vehicle turning paths and vehicle overhangs.

6.5.3 Barrier-protected Exclusive Lanes

For mixed-use facilities that will have dedicated lanes for AVs in a transition phase, barrier-protected operations are considered favorable; however, it is not certain how much buffer would be adequate for separating AVs from HDVs.

6.5.4 Roadway Safety Devices

Another question that needs to be investigated is whether the roadways hosting only AVs will require roadside safety devices and elements such as guardrails, attenuators, cable median barrier, and concrete barrier. This can be determined with certainty once the safety performance of AVs and the related technologies is known with certainty. It would be crucial to know whether AVs will leave the traveled way and what events could make them do so. Furthermore, related to this, the need for shy line offsets to abutments and other fixed objects will require re-evaluation. Shy line offset is the distance beyond which a roadway object/obstacle is not perceived as a hazard by a driver (AASHTO, 2018). In other words, a driver will not react to an object beyond the shy line offset. As a common practice, the roadside barrier is placed beyond the shy line offset. Moreover, if roadside safety devices are not needed in an era of 100% MP of AVs, there may be a possibility to build steeper unprotected side slopes.

6.5.5 Efficient Acceleration and Deceleration

AVs are expected to accelerate and decelerate more efficiently by sensing all other vehicles in the vicinity, which could create opportunities to allow steeper grades, shorter ramp terminals, shorter merge areas, smaller gap acceptance for turning and crossing vehicles, and shorter queues and shorter turn bays.

6.5.6 Nationwide Standardization, Uniformity, and Consistency of Road Infrastructure

During the current test deployment of AVs on existing roadways, technology developers are facing the challenge of inconsistency in the road infrastructure. For example, in the U.S., speed limit signs come in a variety of different dimensions; exit lanes sometimes are separated from the rest of the highway using dashed lines; and most traffic signals are installed vertically with green on the bottom, red on top, and yellow/or orange in the middle, but some of the signals are installed horizontally. The machine vision of AVs may conveniently read these signal colors when oriented in a certain position that is consistent across the country roadway network. Reading all signs and traffic signals and detecting lane-marking configurations is critical to the successful deployment and operations of AVs. From the software and algorithm development perspective, AVs can be easily programmed to sense consistent road infrastructure elements without any difficulty for trans-national travel. In other words, one of the critical factors to the successful deployment of

AVs on roadways is the consistency and standardization of road infrastructure across the country or across countries in some cases where most of the trade and travel occur through roadways.

The interaction between AVs and human drivers at turn signals during the transition phase also needs to be addressed. A delay of a fraction of a second in a driver's judgment or discernment can be the lead to a collision instead of a safe turn. For AVs whose behavior may be completely new to human drivers in mixed traffic, a mechanism will be needed to make the intent of AVs very clear to HDVs at turn signals.

6.5.7 Readiness of Infrastructure across all Roadway Classes

For the successful deployment and operations of AVs on a road network during the transition phase, a similar level of retrofitting, modernization, and readiness will be required across all highway classes, especially low-volume local roads. An extensive network of roadside infrastructure, lane markings, signage, stripes, and signalized intersection communication devices will be required. These items are currently missing or traditionally have been omitted on a majority of access roads, as noted in the agency responses in Chapter 5.

6.5.8 Adaptive Roadway Design Approaches

It can be safely presumed that roadway geometric design will continue to be based on human-oriented design criteria during the transition era of AV operations and even afterward mainly because the vehicles will continue to contain human occupants. Therefore, the roadway design modifications will be made in light of the comfort level of humans. Nevertheless, as technology advances, roadway design approaches can be adapted to benefit from more cost-effective and efficient designs. This may lead to capital cost savings complementing the enhancements in safety and operational performance. Moreover, until the state of AV technology is completely certain and higher levels of AV market penetration are attained, we must continue to account for and design for HDVs during the transition era. However, the new roadways can be designed and constructed based on "Design for Changeability", allowing for possibilities of adaptation for the emerging vehicle technology.

6.5.9 Significant Investment in terms of Time, Funds, and Other Resources

A significant amount of investment in terms of time, funds, and other resources would be needed to support the successful deployment and operations of AVs under all operational design domains.

For example, road pavement markings on highways are inconsistent and often faded. AV technology is unable to operate due to damaged signs, faded lane markings, or damaged lights, and the many inconsistencies found on most of the roadways. Moreover, the quality of roads in the U.S. has been ranked 10th out of 137 countries across the globe by the World Economic Forum's 2017-18 global competitiveness report, whereas U.S. was rated 7th in terms of infrastructure readiness to host AV operations (KPMG, 2018). An estimated 65 percent of U.S. roads being in poor condition (resulting from cracks and potholes on roadways including Interstates, freeways, intersections, main roads in urban and city settings), and poor state of road markings and uneven signage on the three million miles of paved roads across the country are the primary source of an inadequate supply of infrastructure for AVs (Young, 2017). The projects addressing the AV-related road infrastructure readiness will require substantial political will power and support to pass necessary legislation and regulations pushing these extensive projects forward. Shabby road infrastructure, with higher levels of deteriorated conditions, turns out to be even a bigger obstacle to the deployment of AVs outside of the U.S. (Johnson, 2017).

6.6 Design for Changeability (DfC)

Considering a gamut of uncertainties encompassing AV operations, the system engineering concept of "Design for Changeability (DfC)" (Fricke, 1999) was proposed as a solution approach for infrastructure development and preparedness for AVs. Changeability is defined as the possibility to alter, modify, or change the system configuration in the presence or absence of external impact after the system has been in operation (Ferguson et al., 2007; Ross et al., 2008; Mekdeci et al., 2015; Sánchez-Silva, 2019). Other terms used in a similar context are futureproofing (Masood et al., 2014) and reconfigurability (Ferguson et al., 2007; Siddiqi and de Weck, 2008; Singh et al., 2009). To incorporate changeability in the civil engineering design, futureproofing has been defined by Masood et al. (2014) as "the process of making provision for future developments, needs, or events that impact particular infrastructure through its current planning, design, construction, or asset management processes."

Changeability has four major aspects (Figure 6.6) (Saleh et al., 2001; Crawley and de Weck, 2003; Crawley et al., 2004; Hastings and McManus, 2004; Fricke and Schulz, 2005). 1) Robustness refers to a system's ability to be inconsiderate to the changing environments and combat events without being mangled to the extent that is not commensurate with the original purpose (CEN, 1994; Canisius et al., 2011). Such systems continue to serve their intended function under varying operating conditions without being influenced and changed (Taguchi, 1993; Clausing; 1994). In other words, no changes from the operating environment are to be incorporated into robust systems for coping with changing environments. 2) Adaptability refers to the ability of a system after it has been in operation, to adapt, reconfigure, realign, or retrofit itself to the changing operating environment in the absence of an external intervention (Fricke and Schulz, 2005 and Ross et al., 2008). Such systems continue to serve the intended purpose under varying conditions through changing or reconfiguring themselves. In other words, no changes from the operating environment are to be incorporated into adaptable systems for coping with changing environments. 3) Agility signifies the ability of a system to be altered rapidly. In this case, changes from outside need to be implemented to withstand changing environments. 4) Flexibility refers to a system's ability to be reconfigured or altered easily (Saleh et al., 1991; Sethi and Sethi, 1991; de Neufville and Scholtes, 2011; Deshmukh, 2012; Spačková and Straub, 2017). This trait signifies the system's ability (managerially or physically) to cope with change and uncertainty after it is in operation. In this case, changes from outside need to be implemented to withstand changing environments.

While these four capabilities are not necessarily required by a system always or at least at the same time; however, the systems that are designed and planned to operate for a longer time will attain its service life and work efficiently only if they are flexible and adaptable (Sánchez-Silva, 2019). This is exactly what is expected in the case of highway infrastructure systems. Roadways are designed and built to operate in a changing environment, which cannot be predicted with absolute accuracy at the design phase. However, there is always a scheme of uncertain but predictable or expected futures.

With regard to AV technology, it can be predicted that it is inevitable, but when and how it will happen is uncertain. As such, developing flexible and adaptable design strategies for roadway infrastructure will enable them to withstand new and unplanned events, especially with the emergence of new vehicle and information technologies. While information technology has a service life in months and vehicles in years, infrastructure is designed to operate and last for decades. Technological advancements are occurring at breakneck speeds, posing a deep uncertainty for highway infrastructure design and related capital-intensive investments. One of the main reasons for the passive and precipitous role of highway agencies in the context of infrastructure readiness for AVs is the rapidly evolving and uncertain nature of technology. Road infrastructure cannot be expected to change as fast as cell phones and information technology. However, this deliberate passiveness of highway agencies could hinder the deployment of AVs. The question persists how to go about this. To this end, this dissertation suggests that agencies adopt the “Design for Changeability” approach for highway infrastructure design.

Highways are developed to ensure that they will continue to maintain or increase their value, over their lifetime, for all the stakeholders. This requires that the ability of road network to create value for stakeholders is continuously monitored and evaluated and may necessitate the reconfiguration of infrastructure systems, elements, design, and operations with the intent to respond to changes in the operating environment and as new opportunities emerge. This is particularly required given the evolving nature of vehicle technology and the resulting changes/opportunities expected. As such, highway agencies should be open to design provisions in infrastructure design and development that facilitate change and feedback from both the users and the technology developers. Most importantly, besides financial considerations, the stakeholders’ perspectives should be accounted for in the decision-making process related to AV-oriented infrastructure investments.

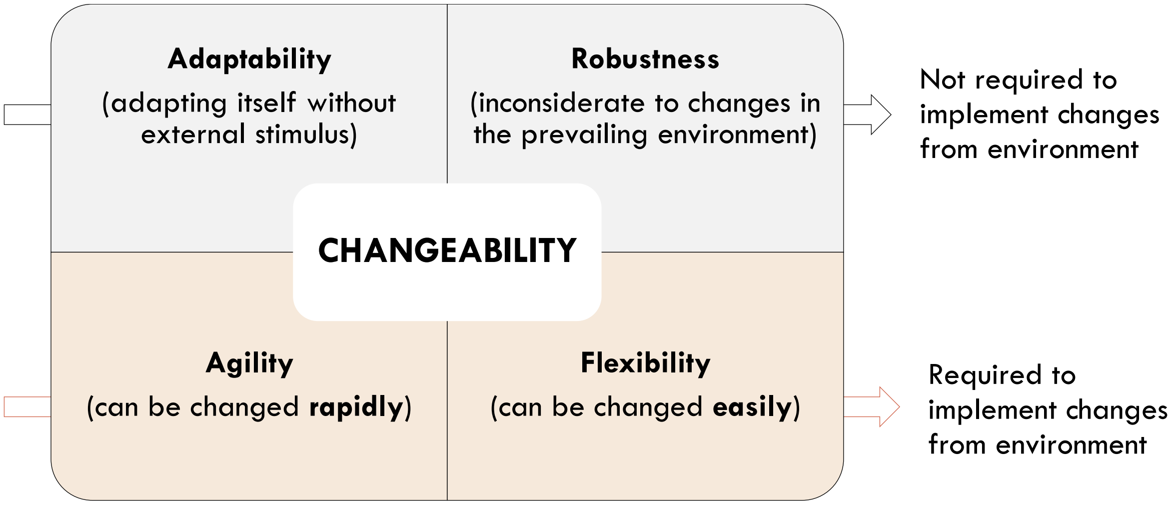


Fig. 6.4 Facets of changeability

6.7 Chapter Summary

This chapter identified and discussed the potential modifications in highway infrastructure and roadway design features required to support the deployment and operations of AVs. These reconfigurations and retrofitting actions were explicitly examined across the transition phase and the fully autonomous era. Moreover, the expected changes in geometric design and the related features and practices were also explored and studied. A strategy for the design and construction of new roadways was proposed with the intent to enable them to respond to the uncertain future associated with AV operations and be adaptable at higher levels of convenience and lower levels of efforts in terms of cost and time. The next chapter presents an economic evaluation of a freeway section with an exclusive AV lane.

7. ECONOMIC EVALUATION: CASE STUDY

7.1 Introduction

The previous chapter identified and discussed the types of highway infrastructure readiness and roadway design changes that may be required to support the road operations of AVs. Based on the perspectives of the stakeholders captured directly through survey instruments (Chapter 5) and the changes identified in the previous chapter, road infrastructure readiness was economically evaluated for two scenarios: first, deploying the AVs in the existing lanes in a mixed traffic stream while they share lanes with traditional vehicles; and, second, providing an exclusive lane for AV operations on freeways. These two scenarios are demonstrated through a case study of a highway corridor that runs from West Lafayette to an international airport in Indianapolis (IND) in the state of Indiana. The length of this Interstate highway stretch is approximately 66 miles (a 6-lane facility), which is comprised of about 52 miles of I-65, 11 miles of I-465, and the remaining miles on I-70. This highway corridor was particularly selected as a case study because West Lafayette is the home of Indiana’s flagship university, Purdue University, and Indianapolis is the home to the international airport to Purdue. Therefore, there is a considerable two-way daily vehicular traffic between these two destinations, which is served by this corridor. In addition, freeways were identified as the most likely locations for the initial deployment of AVs, both by the agency and industry respondents.

7.2 Scenario I

7.2.1 Introduction

This first scenario assumed that the AVs were deployed in the existing lanes in a mixed traffic stream, while they share lanes with traditional vehicles. This scenario particularly corresponds to the lower market penetration of AVs (≤15%), which assumes that pavement markings are the single most important piece of infrastructure, at least right now, to allow for the functioning of autonomous driving. Some studies do not recommend the addition of exclusive lanes for AV operations at less than 20% market penetration due to multiple reasons including the issues of equity and possibility of traffic congestion in the general-purpose lanes in the case of insufficient usage of the exclusive lanes (National Academies of Sciences, Engineering, and Medicine, 2018).

To this end, the only infrastructure readiness that was suggested to facilitate AV operations was the deployment of pavement markings made of wet reflective all-weather tape. The unit (install) cost of this marking material is \$2.5 per linear foot (\$13,200 per linear mile) (Meeks, 2019) and its service life ranges between 2 and 8 years. This pavement marking material has been tested for AV operations on actual roadways under different weather conditions, particularly during heavy rains at different times of the day, on concrete pavements during a sunny day when it becomes difficult for human drivers to see the markings, and at different times of the day, including night conditions. This marking material has been found to provide profound visibility and navigation to the lane detection and lane guidance systems of AVs, under a variety of adverse meteorological conditions (Meeks, 2019; Pike et al., 2019). By using this marking material, situations arising from the sealed cracks on the roads, where AV camera systems either do not detect pavement markings or misidentify objects on the pavement as lane markings, have been profoundly resolved.

Currently, for pavement markings, the Indiana Department of Transportation (INDOT) is exclusively using waterborne paint with a unit cost of \$210 per linear mile and a service life of 1 year. In other words, all pavement markings on this Interstate corridor are repainted each year using waterborne paint. These waterborne paint-based markings offer several challenges to the AV operations, for example, poor or worn markings, markings disappearing at night in the rain, markings disappearing in dry glare conditions, yellow lines disappearing on concrete or light-colored roads, and false identification of crack seals, seams, and scars as lane markings.

For the economic analysis of this scenario, the NPV method was used to analyze the problem, which assumed an improvement in road safety (a decrease in road crashes) and congestion (a decrease in travel time delay), with the deployment of wet reflective pavement markings for AV operations on the Interstate highway corridor (with an AV market penetration of ≤15%). The analysis period used was 10 years, which suggests that once AVs are initially deployed, the market penetration (the percentage of AV users in a traffic stream at a given location, in this case, the Interstate corridor) is not expected to exceed 15% for this period.

7.2.2 Quantification of Cost Components

This step involves the quantification of key cost components, which are comprised of agency costs and user costs. The agency cost is comprised of the total installed cost of wet-reflective pavement markings and the annual maintenance cost. The travel time cost and the crash cost are considered to be the user cost for the analysis of this scenario.

For the users to gain the benefits of decreased crashes and travel time through the use of AVs on the Interstate corridor, it was assumed that the agency uses wet-reflective tape for pavement markings. The initial capital and annual maintenance costs were computed based on the cost values and service life estimates noted in the previous section. A user and agency weight cost ratio of 1:1 was used. Using a conservative approach, a service life of 3 years was used for the pavement markings.

For the computation of crash cost savings, crash data were acquired from the Center for Road Safety at Purdue University. On average, the corridor was found to have annually 43 fatal/incapacitating injury crashes, 95 non-incapacitating/possible injury crashes, and 789 property-damage-only crashes. Crash cost savings were estimated based on their economic implications using the guidelines of the National Safety Council (NSC, 2015). The data on two-way traffic volume (annual average daily traffic) was acquired from INDOT (2019), which was approximated to be 50,000 vehicles per day (vpd) (two-way combined).

For the computation of travel time savings, an average of $17 per hour per vehicle was used to monetize the travel time cost (Schrank et al., 2012).

7.2.3 Results and Discussion

Figure 7.1 shows the results of analyzing the first scenario of AV-oriented infrastructure changes under different settings/assumptions. For the analysis, four different discount rates were assumed: 3%, 5%, 7%, and 10%. The U.S. Office of Management and Budget (OMB) requires using a discount rate of 7% for federal projects and TIGER grant applications (LaHood, 2011). This analysis used a discount rate of 7% and also a higher rate of 10%. The higher discount rate was employed to account for the extreme uncertainty associated with the market penetration of AV technology. Moreover, at the 5% market penetration level, AV mobility was assumed to produce total benefits of 10% (crash cost and travel time cost savings). For 10% and 15% AV operations on the Interstate corridor, the cost savings were assumed to be 10% and 20% respectively. Past studies developed a wide variety of such estimates either based on assumptions or using simulation frameworks. For example, Fagnant and Kockelman (2015) assumed a crash reduction of 50% and a travel time delay reduction of 15% at 10% AV market penetration on freeways. They assumed a crash reduction of 75% and 90%, and a travel time delay reduction of 35% and 60% at AV market penetration levels of 50% and 90% on freeways, respectively. Several studies found that with an increase in AV market penetration, the benefits to both users and agencies increased (Tientrakool, 2011; Atiyeh, 2012; Shladover et al., 2012; NAE, 2018).

Figure 7.1 clearly indicates that the user benefits outweigh the agency costs at all points. Even at a higher discount rate, the infrastructure change remained economically feasible. The analysis was repeated using a discount rate of 10% and a service life of 1 year for pavement markings, suggesting more frequent maintenance (on an annual basis). Even with more frequent maintenance of pavement markings, the NPV values were found to be $32.03M, $62.16M, and $92.30M at market penetration levels of 5%, 10%, and 15%, respectively.

At the initial stages when AV market penetration is in its infancy, highway agencies can initiate AV-oriented freeway retrofitting with this very basic step of deploying wet reflective tape markings across freeways, arterials, and other major streets. Such an investment could be easily made system-wide (across the whole state), which may encourage a more widespread public use of AVs.

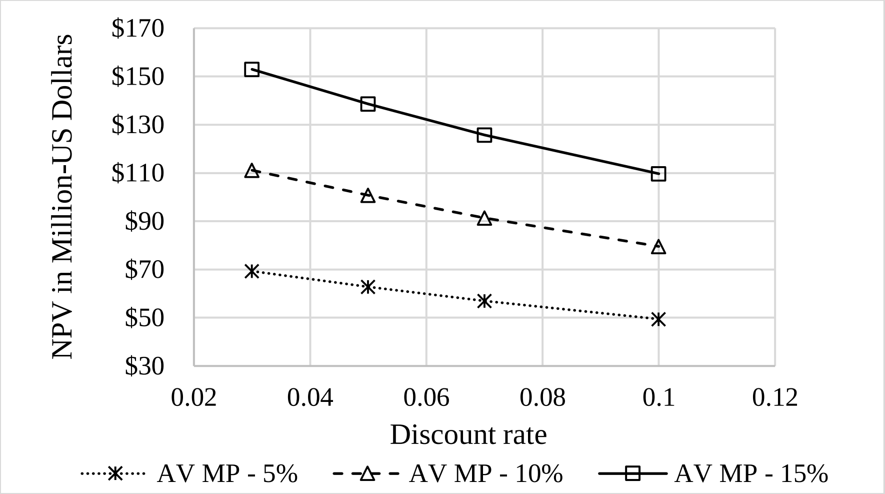


Fig. 7.1 NPV outcomes at different AV market penetration levels

7.3 Scenario II

7.3.1 Introduction

In the stakeholder responses to the survey questions presented in Chapter 5, high-speed freeways are largely noted as the first likely roadway types to host AV operations. Better road pavement condition and fewer chances of interactions/encounters on freeways compared to other roadways made them more favorable candidates during the transition phase. Moreover, 41% of the industry respondents and 44% of the agency respondents suggested allocating a dedicated lane for AV freeway operations at the early stages of deployment.

The costs of construction, maintenance, and improvements are an example of the agency's costs. On the other hand, the changes in crash occurrences and travel time refer to the costs and benefits incurred by the users. Also, an opportunity for AVs to platoon on dedicated freeway lanes offers an additional benefit of fuel cost savings for the users. All these cost and benefit components incurred by the agency and the road users were quantified in terms of monetary values with the intent to find the net economic impacts of this scenario. After all the cost elements were established, the economic evaluation was carried out, using the NPV and ROA approaches.

The BL and Monte Carlo simulation methods were implemented for analyzing this scenario; however, the BL method is recommended to determine the option value mainly because it allows tracking the project value throughout the period of analysis and with less computational effort. This attribute makes the BL method more applicable in the context of real-world practice at the agency level.

7.3.2 Quantification of Cost Components

The second scenario was comprised of adding one lane in each direction, to the 6-lane Interstate corridor by converting the left shoulder into a travel lane. A wider shoulder travel lane is recommended to be deployed by remarking the current freeway pavement for creating narrower regular lanes and narrower right shoulders. The same number of general-purpose (non-AV) lanes would be available as were before the deployment of this new dedicated AV lane. Therefore, no substantial new construction or right-of-way is required. This is expected to ensure more efficient use of the existing freeway space and reduce investment needs.

There could be a challenge for AVs when they ingress/access or egress the dedicated lane, particularly during heavy traffic. This problem can be overcome by deploying the meter at the main freeway ahead of on- and off-ramps, along with speed controls using variable speed limits (VSL) as vehicles reach these meters. The same solution, shown in Figure 7.2, was proposed by Saeed et al. (2018a; 2018b) and DeCorla-Souza and Verdouw (2019).

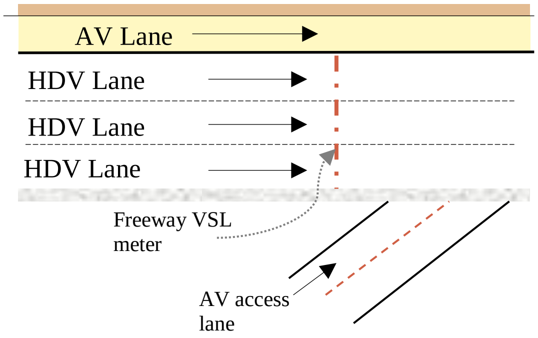


Fig. 7.2 Control of AV ingress and egress movements at Interstate corridor

For this scenario, the construction costs comprised of the cost components associated with remarking the pavement of the Interstate corridor (studied in this dissertation) using wet reflective tape and installation of metering and VSL system covering a 66-mile stretch (cost estimates acquired from USDOT, 2019 and Meeks, 2019). This initial cost was approximated to be $9.5M, with an annual maintenance cost of $14.5M. The maintenance cost was set to account for the maintenance of pavement markings, road surfaces, signs, metering, VSL system, etc. A user and agency cost weight ratio of 1:1 and an analysis period of 5 years were used for analyzing the second scenario. The market penetration of AVs (the percentage of AVs on this corridor) was assumed to be greater than 15%. At this level of market penetration, the user cost savings were assumed to be comprised of 35% reduction in crashes, a 25% reduction in fuel consumption, and travel time savings of 25%. Some studies suggest the addition of exclusive AV lanes at market penetration rates greater than or equal to 20% (National Academies of Sciences, Engineering, and Medicine, 2018). However, this dissertation has used a threshold of 15%, as the addition of a dedicated lane may encourage wider adoption of AVs by the road users.

7.3.3 Results and Discussion

This section presents the results and discussion of three methods implemented to analyze scenario II.

<u>NPV Method</u>

Figure 7.3 shows the NPV outcomes for four discount rates of 3%, 5%, 7%, and 10%. With an increase in the discount rate to account for uncertainty, the value of NPV decreases. However, the

proposed infrastructure change, i.e. the addition of a dedicated travel lane for AV operations in both directions, remains feasible, given the assumed proportions of benefits. Moreover, the analysis was repeated to account for the trade-off between the agency cost (AC) dollar and the user cost (UC) dollar, by employing different weight ratios, which could influence both the feasibility of the proposed investment and the optimal decision. Figure 7.4 shows that the proposed addition of a dedicated AV lane is no longer viable when AC/UC weight ratio is 3.1.

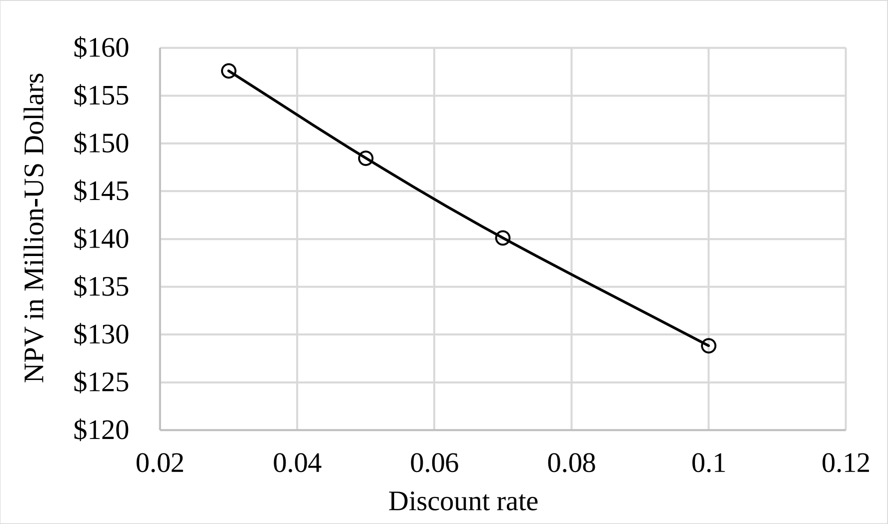


Fig. 7.3 NPV outcomes for the provision of a dedicated lane

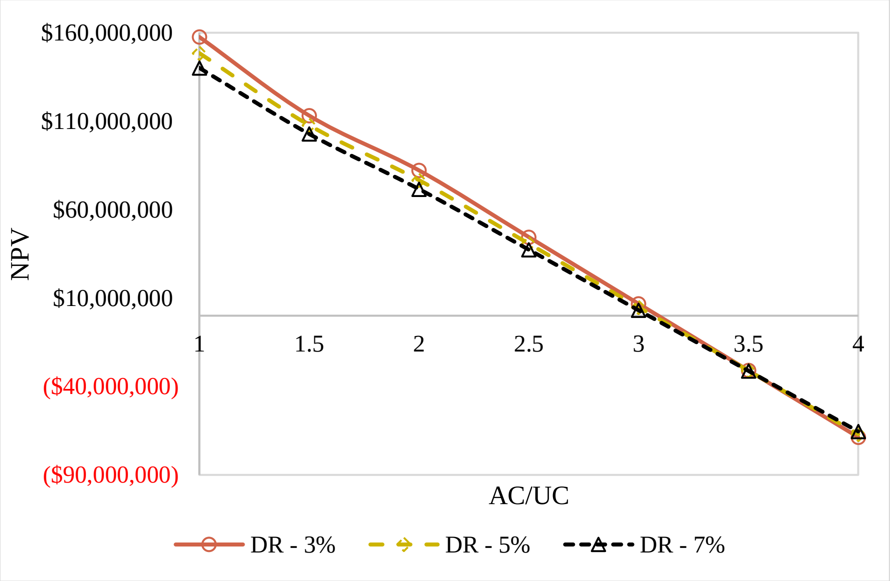


Fig. 7.4 Sensitivity analysis of NPV w.r.t agency and user dollar weights

Binomial Lattice Method

For ROA analysis using the binomial lattice method, Table 7.1 presents the key items used in the computation. The lattice structure for this case study is presented in Figure 7.5. As discussed earlier in Chapter 3 of this dissertation, over a time step Δt, the value of the asset under consideration (a dedicated AV lane) has a probability *p* of ascending by a factor *u*, and a probability *1-p* of descending by a factor *d*. The up *u* and down *d* factors are computed using the Cox, Ross, and Rubenstein (CRR) model as $u = e^{(\sigma\sqrt{T})}$; $d = 1/u$.

At each node (that determines the value of an asset) in the lattice, the underlying value of the asset moves up by a factor *u* (to account for the upside opportunity) or down by a factor *d* (to account for the downside risk). The CRR model ascertains that the lattice structure is recombinant; this means that when the underlying asset moves up and then down (*u*, *d*), the value will remain the same if it had moved down and then up (*d*, *u*). This is termed as *merging* or *recombining* of the two paths. This attribute of the CRR model expedites the computation of the option value by reducing the number of nodes. Moreover, it also facilitates the direct computation of the value of the underlying asset at each node without first building the tree.

Table 7.1 Analogous real and financial options for dedicated AV lane addition

	Financial Options	**Real Options**
Underlying asset	Stock price	Asset (a dedicated AV lane) value
Exercise price	Strike price	Cost of adding a dedicated lane
Source of uncertainty	Stock price	Market penetration of AVs
Option type	Call (option to defer)	Defer the addition of a dedicated lane
Time step	Day	Year

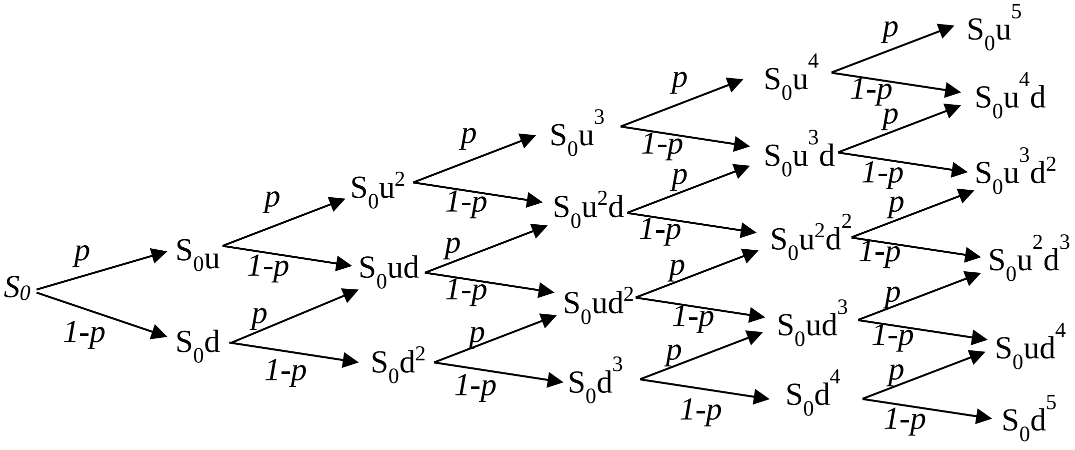


Fig. 7.5 Binomial lattice structure for five time-step

Starting with the nodes at the extreme right, the instant cost savings associated with the execution of the proposed project (the addition of a dedicated lane for AV operations), were computed and compared with the expected cost savings when the project is deferred. To do so, Equations (7.1) and (7.2) were employed.

$$\overline{\Omega}_{\mathrm{k,l}} = \left[p * Value_{uppernode} + (1-p) * Value_{lowernode}\right] * \exp(-r_f \Delta t) \tag{7.1}$$

$$Option\ Value_{k,l} = \max(\Omega_{\mathrm{k,l}}, 0) \qquad \text{if } l = \text{analysis period and}$$

$$Option\ Value_{k,l} = \max(\Omega_{\mathrm{k,l}}, \overline{\Omega}_{\mathrm{k,l}}) \qquad \text{if } l \neq \text{analysis period} \tag{7.2}$$

Where $p = \left(\frac{e^{(r_f * \Delta t)} - d}{u-d}\right)$ is the risk-neutral probability; $\Omega_{\mathrm{k,l}}$ refers to instant cost savings at node (*k,l*); $\overline{\Omega}_{\mathrm{k,l}}$ is the expected cost savings at node (*k,l*); and r_f is the risk-free rate. Other symbols are the same as defined earlier in Chapter 3. Moreover, the analysis is based on the American option valuation, which allows exercising the option at any point in time before its date of expiration.

Using Equations (7.1) and (7.2), Table 7.2 and 7.3 present the underlying values of the dedicated AV lane (computed forward in time) and the value of the defer option respectively, using a time step of 1 year and a risk-free rate of 0.03. The volatility of the market penetration was assumed to be 25%. At the top node at year 5, the underlying value is $813.34M, which exceeds the strike price. The option can be rationally exercised (meaning that the proposed addition of a dedicated AV lane may be delayed). However, towards the end of year 5, the underlying value does not exceed the strike price; hence, the option is allowed to expire, and the option value is zero.

Table 7.3 presents the computed values of the *defer option* at each node, based on backward induction method, which calculates the option value at the final node first (starting from the right side, in this case, year 5) and then moves to the left side to find the option value at each node. The value of the proposed project if it is implemented now would be the underlying value less the project costs, whereas the value of the call option is the average of the succeeding option value discounted back using risk-free rate, that is:

At year 4, the value of the proposed addition of a dedicated AV lane, if it is implemented, will be equal to ($633.43M - $75M = $558M). The value when the project is deferred will be computed as max($558M, $560M) = $560M. These computations were done based on Equations (7.1) and (7.2). All the computations in Tables 7.2 and 7.3 are in the units of million US dollars.

Table 7.2 Underlying values of the asset at each node

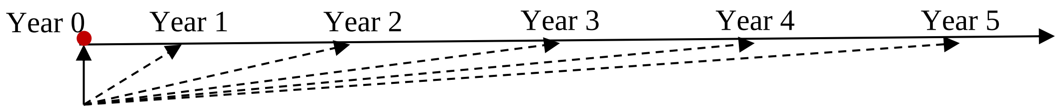
Nodes of the BL	Years (analysis period)					
	0	1	2	3	4	5
0	233.0271704	299.2128	384.1969	493.3185	633.4335	813.3447
1		181.4817	233.0272	299.2128	384.1969	493.3185
2			141.3381	181.4817	233.0272	299.2128
3				110.0742	141.3381	181.4817
4					85.72591	110.0742
5						66.7634

Table 7.3 Value of the defer option using backward induction method

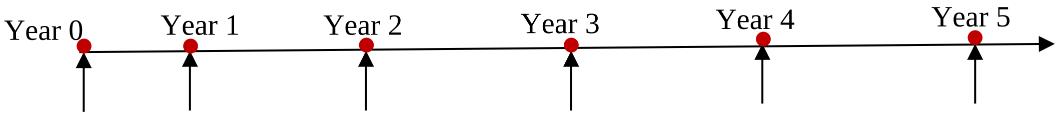
Nodes of the BL	Years (analysis period)					
	0	1	2	3	4	5
0	168.453117	232.0401	314.4651	421.1989	560.2364	737.9184
1		115.5684	164.3181	227.6197	308.7705	417.8922
2			74.19985	111.4658	160.8942	223.7865
3				41.71802	69.17472	106.0554
4					17.0003	34.6479
5						0

As shown in Table 7.3, at year 5 and node $S_0u^2d^3$ (the cells filled in grey in Tables 7.2 and 7.3), the option may be allowed to expire and the project may be executed (the dedicated lane for AVs may be added). As evident in this case, the ROA approach considers and monetizes the flexibility inherent in a project, which in this case is the possibility to wait and observe what the level of uncertainty (AV market penetration) is. It is evident from Table 7.3 that there is a monetary value associated with the flexibility to delay decisions until market penetration forecast uncertainty decreases with time and the collection of additional actual real-world data.

In contrast, the conventional NPV forces the decision-makers to make a decision at the start of a project while keeping all the factors constant. In other words, the NPV method assumes that future decisions are to be made at the time of the analysis. Figure 7.6 illustrates the difference between the NPV and the ROA approaches. The value obtained from ROA is also called NPV+ or “Expanded NPV,” mainly because it complements the conventional NPV with an operational/managerial option value.



(a) A single decision-making point for the proposed investment, in case of NPV



(b) Flexibility to make decisions each year based on prevailing conditions, in case of ROA

Dots indicate the decision-making points.

Fig. 7.6 Illustration of decision-making points in NPV and ROA methods

The analysis was repeated several times to investigate the sensitivity of the option value to the main factors, the volatility, and the risk-free rate. Figure 7.7 indicates an increase in the option value with an increase in the risk-free rate while the other factors were kept constant. Furthermore, increasing the volatility of AV market penetration beyond 45% was found to have a very small effect (slight increase) on the option value when all other factors were kept constant.

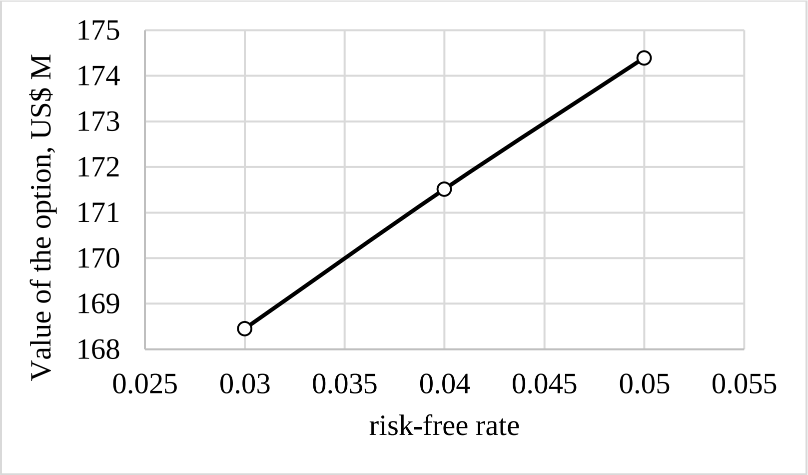


Fig. 7.7 Sensitivity of the option value to the risk-free rate

Monte Carlo Simulation Method

Table 7.4 presents the computations carried out to determine the value of the call option “defer the addition of a dedicated lane”. The option value was calculated using 5,000 simulation trials;

however, a small subset of these trials is presented in the table. The time increment, Δt, used in the simulation is 0.5 year. At the end of the option's life of 5 years, the option will be exercised if the value of the proposed addition of an AV lane exceeds the strike price ($75M). In that case, the value of the option (reported in the second last column in Table 7.4) would be equal to the value of the proposed addition of lane at the end of the 5th year minus the strike price. However, the option (the deferral of AV lane provision) will not be exercised but is allowed to expire, when the value of the project in a given simulation trial is not greater than the strike price. This implies that in these cases, the option does not carry any value. The values in the second last column of Table 7.4 are discounted to determine the present values for all the simulation trials. These present values are presented in the last column of Table 7.4; the value of the option is equal to the average of these present values.

In the case being studied in this dissertation using the MCS method, it is found that the option can be exercised 96.78% of the times over the lifetime of the option, which is equal to 5 years. The value of the option is found to be $167.49M, which is approximately the same as that found by the BL method ($168.45M). The MCS method was repeated multiple times using a different number of simulation trials; at 5,000 simulation trials, the value of the option was found to be the same as that obtained in the case of BL method. However, unlike the BL method, a substantial amount of computational efforts was employed in the process.

Table 7.4 Valuation of the option “defer”, using the MCS approach

	Time step increment												
Trials	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Value of the proposed investment**	**Expanded NPV**
1	233	303.31	249.77	242.34	313.49	345.66	277.16	299.70	371.00	203.17	173.14	98.14	84.66
2	233	179.99	176.24	187.24	224.73	230.88	179.10	165.09	189.50	117.43	108.16	33.16	28.60
3	233	253.20	264.24	225.22	213.43	229.34	265.04	252.76	274.20	340.60	358.09	283.09	244.20
4	233	278.69	289.89	297.73	352.98	324.65	401.21	311.91	311.62	434.49	533.44	458.44	395.46
5	233	272.25	303.28	289.60	220.12	292.12	350.35	223.46	218.51	172.78	192.25	117.25	101.15
6	233	249.43	165.59	121.00	102.05	96.49	75.11	76.88	90.32	93.02	82.33	7.33	6.33
7	233	189.48	252.49	203.38	197.96	170.60	128.40	154.73	139.91	118.73	50.51	0.00	0.00
8	233	150.44	133.92	125.41	120.06	111.96	89.45	72.96	72.83	66.50	73.30	0.00	0.00
9	233	154.51	175.96	126.62	121.42	124.32	87.88	83.57	62.06	62.19	62.76	0.00	0.00
10	233	208.17	208.72	175.48	188.25	191.88	176.58	153.79	131.69	147.18	105.41	30.41	26.23
11	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.	.
4999	233	164.71	141.18	134.63	99.40	68.32	64.82	65.29	61.62	67.43	80.71	5.71	4.93
5000	233	274.88	318.95	270.29	322.05	296.14	229.27	247.31	236.94	239.24	205.31	130.31	112.41

All the numerical non-bold values in the table have the units of million U.S. dollars.

7.3.4 Limitations

Currently, there is no evidence of the potential benefits of AVs from the real-world operations of these vehicles on existing roadways. However, past researchers have carried out simulation studies with an effort to replicate the real-world roadway environment to investigate the potential impacts of AVs on safety, congestion, and other important aspects of human travel. This dissertation used either forecast from past simulation studies or made assumptions to quantify the benefits associated with AV operations. As compared to the forecasts from past simulation studies, the assumptions regarding the benefit estimates used in this dissertation were kept less glowing. There is an opportunity to revisit the problem using the actual proportions of benefits (savings in crash cost, travel time, and fuel consumption) once the impacts of AV operations are known with absolute certainty. Nevertheless, this dissertation presents a framework that can help highway agencies account for the uncertainty associated with the market penetration of AVs into their decision-making related to AV-oriented infrastructure retrofitting. Using this framework, agencies can analyze a wide range of possible scenarios of AV-oriented infrastructure readiness.

Moreover, an implicit assumption of path independence is associated with the BL method, which means that the value at any state is not dependent on which path is taken to reach that state or how the state is reached. In practice, this means that nothing fundamental happens to the system over the period of the proposed project.

7.4 Conclusions

This chapter conducted an economic evaluation of two scenarios of transitioning to AV operations: the first scenario was based on lower AV market penetration ≤ 15%, which considered marking the road pavement with AV-friendly material to assist the lane keeping and lane guidance systems of AVs. These road markings were considered the only AV-related infrastructure change to be made at MP ≤ 15%. Moreover, the first scenario assumed that AVs will share the roads with HDVs in the existing lanes. The agency and user cost components were identified and quantified. Using the NPV method, it was found that the user benefits outweighed the agency costs.

The second scenario was based on adding a dedicated lane for AVs on freeway corridors by converting the inside/left shoulder into a travel lane. This conversion of the shoulder into an AV travel lane was considered to be done by remarking the Interstate pavement and narrowing the other travel lanes. The merging movements (ingress and egress in the case of the dedicated lane) of AVs were suggested to be facilitated through the deployment of metering and VSL systems on the main corridor ahead of the on- and off-ramps. These infrastructure readiness initiatives associated with this second scenario were evaluated economically utilizing the NPV and ROA methods. In both cases, the addition of a dedicated lane was found to be beneficial. However, the ROA method additionally could determine the time (years) by which the agency could delay the implementation of this infrastructure change, given the nature of uncertainty associated with AV market penetration. The conventional NPV approach helped with the decision-making at the start of the proposed project, but it could not account for the uncertainty associated with the AV market penetration. In contrast, the ROA method was able to account for the monetary value of the flexibility associated with the addition of a dedicated AV lane. ROA was implemented using a BL approach and the Monte Carlo simulation; however, by using the BL method, the value of the option could be tracked throughout the analysis period with less computational efforts. By determining the value of the call option at each node, the BL method helped compare the proposed investment's values before and after the option was exercised. The two scenarios were demonstrated using a 66 mile (a four-six lane facility) stretch of Indiana's highway corridor that runs from West Lafayette to Indianapolis International Airport.

Finally, for the user benefits, the first scenario considered the crash and travel time cost savings, whereas the second scenario considered the crash, travel, and fuel cost savings. In this vein, future research could consider a broad range of agency, user, and non-user impacts and revisit the problem using multi-criteria analysis. For the agency cost/benefit component, one such impact could be revenue generation from tolling the dedicated lane (perhaps only during certain times of the day and for certain types of AVs, for example, self-owned AVs and not shared AV services to incentivize and encourage the shared use of AVs). To determine the user and non-user impacts, future research could potentially consider emissions, cybersecurity, and other social and environmental impacts.

7.5 Chapter Summary

This chapter conducted an economic evaluation of two scenarios of infrastructure readiness required for transitioning to AV operations. The user and agency cost components associated with these scenarios were independently identified and quantified. The first scenario was analyzed using the conventional NPV approach, whereas the second scenario of adding a dedicated AV lane to the Interstate corridor was analyzed using both the NPV and ROA methods. ROA was found to compute the monetary value associated with flexibility and uncertainty attached to scenario II. Accounting for flexibility caused an increase in the value of the proposed AV-lane addition. ROA also determined the time by which highway agencies could delay the proposed investment. The limitations of the analyses were also acknowledged. The next chapter concludes this dissertation.

8. SUMMARY AND CONCLUSIONS

8.1 Introduction

This chapter presents a summary of the conclusions, policy recommendations regarding AV-oriented infrastructure readiness and investments that may be useful for government agencies, the main contributions of the dissertation, and recommendations for future work.

8.2 Summary

As noted in Chapter 1, not much research has been done with regard to preparing existing road infrastructure to accommodate AV operations. This dissertation studied the types of infrastructure readiness that may be required for transitioning to autonomous vehicle operations on highways. The need for collaboration among the key stakeholders of AV operations was highlighted in this dissertation using a Stakeholder Participation Model. In addition, this dissertation proposed a framework to account for uncertainty surrounding autonomous vehicle operations, particularly in terms of market penetration. The framework includes a flexibility-based decision-making process. Specifically, a real options approach was proposed in the framework. The framework was implemented for a case study involving an Indiana Interstate corridor. Using the case study, it was found that ROA is able to capture the latent value of proposed AV-oriented infrastructure investment and is more realistic compared to the traditional NPV approach. Moreover, the design-for-changeability approach was proposed for developing new roadways or for changes to the existing roadways to accommodate AVs, in the view of the inherent uncertainties associated with this emerging AV technology. This design approach will enable the infrastructure design to be flexible enough to respond to an unknown future.

The key concepts related to AV operations were presented in Chapter 2 of the dissertation. Details of the Stakeholder Participation Model (SPM) were presented to illustrate how feedback from different stakeholders will inform AV-related infrastructure planning and retrofitting at the agency level. The SPM requires input from key stakeholders (i.e., road users, infrastructure owners and operators, and technology developers) and sustained information sharing among them to help measure the adequacy of infrastructure needs. In addition, conceptual mathematical relationships were suggested to demonstrate the endogenous and interdependent roles of the stakeholders. The transition phase of autonomous vehicle operations was found to be particularly critical due to the complex nature of the roadway environment. This phase is expected to be characterized by a constantly changing mix of AVs and HDVs as they operate jointly and possibly interact.

Chapter 3 identified various sources of uncertainty surrounding the era of autonomous vehicle operations. These uncertainties were discussed in relation to their potential implications for the timing and types of AV-oriented infrastructure changes. The market penetration of AV technology was noted as the main parameter of volatility that could influence AV-oriented infrastructure retrofitting and investment decisions by roadway agencies. The merits, demerits, and applicability of traditional value engineering and real options analysis approaches were discussed in the context of the AV-related infrastructure investment decisions that agencies are expected to make. Moreover, different options and methods for valuing those options were reviewed in detail.

The main framework for the dissertation was presented and discussed in Chapter 4. The quantification and/or monetization of the flexibility associated with AV-oriented infrastructure changes is a key aspect of the framework. Another vital aspect of the framework involved how to gather the input of the key stakeholders and incorporate that feedback to define, more reliably, the AV user demand and the level of roadway infrastructure preparedness for AVs.

In Chapter 5, the first step of the framework was implemented by soliciting the perspectives of road users, highway agencies, and AV technology developers, using well-designed survey questionnaires. The spatial and temporal limitations of the survey findings were also noted. The responses from highway agencies helped identify the types of infrastructure readiness that may be needed to support AV operations. The responses from road users provided a measure of the level of potential future adoption of AV technology as self-owned vehicles, shared vehicles, or a hired service and hence, helped assess the potential AV adoption. The concerns and perspectives of non-AV road users, who are expected to continue to drive their traditional vehicles and share the road with AVs, were also captured. Finally, AV technology developers were surveyed about the timing of the availability of AVs for public use, in addition to other key items related to AV technology.

In Chapter 6, the types of highway infrastructure readiness and roadway design changes that may be required to support the operations of AVs on roadways were identified and discussed. These changes are expected to vary across the various stages of autonomous vehicle operations due to the expected variations in market penetration levels and the nature and capabilities of emerging AV technologies. The Design for Changeability approach was proposed as a solution for highway agencies as they move forward with AV-related infrastructure changes.

Chapter 7 presented an economic evaluation of two scenarios of road infrastructure readiness for supporting the transition to autonomous vehicle operations. The first scenario was based on a maximum AV market penetration of 15% and involved marking the road pavement with AV-friendly material to assist the lane keeping and lane guidance systems of AVs. These road markings were the only AV-related infrastructure change to be made in this scenario. The first scenario assumed that AVs will share the roads with HDVs in the existing lanes. Using the NPV method, the user benefits were found to outweigh the agency costs. The second scenario involved the provision of an AV-dedicated lane on Interstate freeway corridors by converting (via pavement remarking) the existing inside (left) shoulder into a travel lane and narrowing the other travel lanes. The scenario included the facilitation of AV merging movements (ingress and egress in the case of the dedicated lane) by deploying metering and variable speed limit (VSL) systems on the main corridor upstream of the on- and off-ramps. Scenario II was analyzed using both the NPV and ROA approaches. ROA was found to capture the monetary value of the flexibility associated with Scenario II. That flexibility yielded an increase in the value of the proposed addition of the dedicated AV lane. Moreover, ROA also determined the time by which highway agencies could delay the proposed investment.

8.3 Policy Recommendations

In the United States, federal, state, and local agencies are responsible for the oversight of the construction and maintenance of the road infrastructure that is within their jurisdiction. In the context of AV-related infrastructure preparedness, the role of federal agencies is expected to become particularly critical to ensure the consistency and uniformity of roadway infrastructure across all jurisdictions. To help achieve this, this dissertation recommends that efforts should be made to promote (a) nationwide standardization, (b) consistency and uniformity in infrastructure, and (c) development of related policies and regulations. These are explained below.

First, at the current time, the main obstacle to the successful deployment of AVs is the fragmentation of highway agencies based on their jurisdictional boundaries and the resulting inconsistency in AV-oriented infrastructure readiness. Roadways within different jurisdictional boundaries and built environments (city centers and urban, suburban, and rural areas) together constitute an interconnected network. Vehicles drive on these shared roadways that traverse administrative boundaries. Similarly, AVs are expected to drive across all regions of the built environment and over different classes of highways (freeways, arterials, collectors/distributors, and local roads). If some jurisdictions have infrastructure and roadways ready to support AV operations while other jurisdictions do not, this inconsistency would bring only partial benefits to AV adopters and only for a portion of their travel, which could ultimately impede the widespread public adoption of AVs. Therefore, to successfully integrate these vehicles into the transportation system, policymakers, transportation planners, service providers, transportation agencies, vehicle manufacturers, and all other stakeholders should make similar levels of preparation and technology integration efforts across all forms of the built environment including city centers and rural areas. This could be accomplished in part by updating the FHWA’s Manual on Uniform Traffic Control Devices.

Second, there is a definite need for coordination among transportation departments and agencies at the federal, state, and local levels to ensure that the new priorities and policies related to AVs are cohesive in nature. To offer the most uniform and consistent driving environment for AVs in terms of roadway infrastructure, there is a need to depart from the silo of statewide regulations and move toward uniform nationwide regulations. However, this shift will involve major challenges due to the differing perspectives, priorities, and financial standings among the states. Transportation agencies at the federal, state and local levels would be required to make the necessary enhancements and changes to the infrastructure and road networks within their jurisdictions. This, in turn, would require rigorous supervision and stronger leadership from national bodies, such as the FHWA (inside the U.S.), and close coordination among highway agencies to attain the required consistency and uniformity in infrastructure at all levels. A strong coherence in the infrastructure modifications across the states, across all road classes, and across various forms of the built environment will be key to the successful implementation of AV operations and the full realization of its associated safety and efficiency benefits.

Third, this dissertation recommends that to address the challenges posed by AVs, bodies such as the FHWA (in the U.S.) and similar bodies in other countries, should maintain or adopt a strong leadership role in convening various stakeholders to discuss the following:

- Infrastructure needs
- Potential impacts of AVs on safety, policy, operations, regulations, and planning

- Prioritization of actions and steps to incrementally integrate AV technology into existing policies and current agency programs
- Truck platooning applications and automated truck freight delivery
- Potential impacts of truck platooning and automated truck freight delivery on infrastructure needs
- Travel demand changes due to AVs
- Land use implications
- Infrastructure funding
- Right-of-way use
- Inter-agency collaboration

To this end, it is recommended that various groups be formed comprising representatives from federal, state, and local transportation agencies; the American Association of State Highway and Transportation Officials (AASHTO); infrastructure owners and operators; the American Planning Association (APA); the Association of Metropolitan Planning Organizations (AMPO); original equipment manufacturers; the National League of Cities (NLC); the Consumer Federation of America; the American Trucking Association (ATA); the Institute of Transportation Engineers (ITE); the Intelligent Transportation Society of America (ITS); the Society of Automotive Engineers (SAE); the National Highway Traffic Safety Administration (NHTSA); the American Association of Motor Vehicle Administrators (AAMVA); the American Automobile Association (AAA); the Transportation and Development Institute (T&DI) of the American Society of Civil Engineers (ASCE); the American Public Transportation Association (APTA); the Federal Transit Administration (FTA); legal institutions; service providers; vehicle manufacturers; technology developers; the freight community; and research organizations. Such a rigorous effort will help catalyze nationwide engagement and resolve many complex issues related to infrastructure requirements, standardization of infrastructure design, land use planning, economic impacts, equity issues, the current and evolving state of AV technology, legislation and regulations, and policy development and planning. This effort will also facilitate the mutual sharing of information to help stakeholders make necessary preparations in their respective domains. Furthermore, a clearly defined mechanism is needed for sustained information sharing and the formation of new strategic partnerships among stakeholders. For instance, technology developers and transportation agencies can collaborate to identify and plan for areas where the existing roadway environment, design features, roadway infrastructure, and other operational design features could create obstacles to the successful deployment of AVs. More importantly, the perspectives of and insights from highway users must be sought continuously, both indirectly through advocacy groups and directly through survey tools.

Fourth, the service life horizons for information technology devices and vehicle technologies (often measured in months and years, respectively) are different than those of infrastructure (often measured in decades). Therefore, the infrastructure will be faced with funding, design, and planning challenges. Infrastructure decisions made today will have implications for AV operations for decades to come, and, as such, close coordination and communication among stakeholders is essential. Transportation agencies must stay abreast of technology developments to thoroughly understand the current and future needs of AV technology and the ways infrastructure may accelerate or impede the AV deployment and market growth.

Furthermore, it is important to identify and distinguish between the short- and long-term impacts of AV technology on road infrastructure. In light of these impacts, transportation agencies should lay out a clear plan for infrastructure readiness in the short and long terms while maintaining a long-term vision. To keep pace with rapidly evolving AV technology, the first action required for the readiness of road infrastructure is to make the roadway environment easily recognizable by the machine vision systems of AVs. Moreover, during the transition phase, the road infrastructure is expected to support a mixed traffic stream, different transportation modes, and different driving behaviors (those of traditional, automated, and autonomous vehicles). As such, it is crucial to clearly discern the short- and long-term infrastructure needs. The short-term needs may include rigorous maintenance of lane markings, enhanced repairs of road pavements, and improvements to road signs to make them visible in all weather conditions. Moreover, increased vehicle electrification in the AV era may also necessitate the promotion of an extensive transnational network of electric vehicle charging infrastructure.

Transportation agencies at all levels should facilitate the national harmonization of infrastructure, policies, and regulations for realizing the full safety, mobility and efficiency benefits of AVs. In addition, technology developers should also develop and design technology in the context of infrastructure planning, funding, and maintenance horizons. It should be noted, however, that designing AV technology robust and advanced enough to accommodate infrastructure inconsistencies could make it cost-prohibitive for the users.

Another critical point that requires serious consideration by transportation agencies is data generation, housing, and sharing between high-tech infrastructure and vehicles. With the AV deployment, roadways with smart infrastructure installations are expected to generate more reliable and streamlined information exchanges between infrastructure and vehicles. As such, the roadway infrastructure needs to serve as a distributed sensor network using an Internet-of-Things approach for sharing data and information with vehicles. In this regard, transportation agencies need not only data housing infrastructure but also the capability to evaluate their capacity and readiness to provide the soft computing skills required for the oversight of high-tech cyber-physical infrastructure elements and to fulfill the data needs of AV technology (for example, digital work zone maps or road closure information). Agencies should start considering strategies for the wider integration of sensing, communications, analytics, and decision support technologies and systems into their operations.

Furthermore, the process of attaining full market penetration of AVs will be gradual and could take decades. Therefore, the limitations and needs of the current technology should be reflected in the agency planning process well into the future. Given the continuous evolution of AV technology, it is rather difficult to predict long-term infrastructure needs. This difficulty is further exacerbated by the uncertainty in infrastructure funding. To this end, designing and planning for changeability are proposed as the most feasible solution for infrastructure development and modifications in the era of autonomous vehicle operations. The infrastructure preparations in the short term must be compatible with vehicle technologies at all NHTSA levels and support both short- and long-term mobility options. Therefore, infrastructure agencies need to maintain constant communication with AV technology developers to ensure the agencies' cognizance of the emerging needs of AVs. Moreover, the process of infrastructure readiness could be highly expensive and hard to justify, particularly for low-volume roadways. The infrastructure value approach that accounts for uncertain futures can help justify these massive investments.

8.4 Contributions of the Dissertation

The main contributions of this dissertation are as follows:

1. As noted earlier, existing research related to AV-oriented infrastructure readiness and road design configurations is limited. This dissertation has identified and studied in detail the main

types of infrastructure changes and roadway design retrofitting that may need to occur to facilitate transitioning to autonomous vehicle operations.

2. This dissertation developed a framework that can help highway agencies account for uncertainty, particularly that associated with AV market penetration, into their decision-making related to AV-oriented infrastructure retrofitting. Using this framework, agencies can identify and analyze a wide range of possible scenarios of AV-oriented infrastructure readiness, at both the project and network levels.
3. This dissertation demonstrated that the infrastructure investment decision-making process associated with AV-related readiness can be enhanced substantially when the real options analysis approach is applied during the evaluation of the decisions. The case study results showed that ROA can enable highway agencies to capture the monetary value of investment flexibility. Such flexibility is needed to account for the uncertainty associated with AV market penetration and the consequent timing of infrastructure readiness/change. Such flexibility translates into the need for having options, such as the option to defer an infrastructure change until a more optimal future period or the option to proceed with the proposed infrastructure investment. ROA does not replace NPV but complements it by including the value of flexibility in the AV-related infrastructure decision-making process. The ROA approach is particularly vital and relevant for AV-oriented infrastructure readiness, which may require substantial investments, particularly at the network level. Traditional value engineering approaches are not able to capture the latent value of the proposed investment and, therefore, may not justify any proposed infrastructure readiness project. In contrast, ROA yields outcomes that provide a more realistic picture of the overall value of AV-oriented infrastructure readiness investments.

8.5 Recommendations for Future Work

1. The results of the survey of road users presented in this dissertation capture the current preferences of road users. However, today’s perspectives may not reflect how preferences may change in the future. Since AVs are a newer technological concept, public perceptions about them are likely to be unstable. Consequently, periodic surveys should be conducted to gauge the fluctuating pulse of the market and capture consumers’ preferences at different instants for use in decision-making at the agency level. Moreover, different agencies (state DOTs and other

local agencies) should conduct similar surveys (of a representative random sample) in their administrative jurisdictions to acquire more updated and relevant input of road users.

2. Industry forecasts of AV market penetration, presented in this dissertation, will need periodic updates due to the continuous evolution and maturation of AV technology. The market penetration trends presented in this dissertation may change as the state of the AV technology and the deployment schedules and models become clearer and more certain with time.
3. For quantifying user benefits in Chapter 7, Scenario I considered crash and travel time cost savings, whereas Scenario II considered crash, travel time, and fuel cost savings. Future research could consider a broader range of agency, user, and non-user impacts and extend the problem using multi-criteria analysis. For the agency cost/benefit component, one such impact could be the revenue generated from tolling the dedicated AV lanes (maybe only during certain times of the day and only for certain types of AVs, for example, self-owned AVs, to incentivize the use of shared AVs). For the user and non-user impacts of AV-related infrastructure change, future research could consider emissions and other social and environmental impacts.
4. This dissertation addressed the economic evaluation of AV-oriented infrastructure changes from a project-level perspective (specifically, for a freeway corridor). However, it might be useful to consider a network-level problem, which could include a statewide network of all types of roads (arterials, collectors, and access roads). Such a network-level problem could help highway agencies discern the systemwide economic tradeoffs (costs and benefits) of the infrastructure investments required for transitioning to AV operations.

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VITA

Tariq U. Saeed holds a B.Sc. in civil engineering from the University of Engineering and Technology Peshawar, Pakistan (2007-2011) and an M.S. in civil engineering (concentration in computational engineering; and transportation and infrastructure systems engineering) from Purdue University (2014-2015). Tariq joined Purdue University in August 2014 as a Fulbright scholar and completed his Ph.D. in civil engineering (same concentration as that in M.S.) in August 2019. Tariq's research interests are diverse and span multiple knowledge domains. He uses analytic methods from statistics, econometrics, machine learning, finance, economics, operations research, behavioral science, and systems engineering to study persistent and looming challenges on the landscape of transport and infrastructure engineering, planning, policy, and practice. Tariq has published numerous technical articles in well-reputed journals including the Analytic Methods in Accident Research, Accident Analysis and Prevention, Transportation Research Part A: Policy and Practice, Journal of Transportation Engineering Part A: Systems, and Journal of Infrastructure Systems.

During doctoral studies, Tariq has been the recipient of several competitive awards and fellowships including Purdue Engineering Outstanding Graduate Student Research Award; Purdue College of Engineering's Hugh W. and Edna M. Donnan doctoral dissertation fellowship based on outstanding academic and research accomplishments; Fulbright doctoral degree award (2014-18); Fulbright award to attend Massachusetts Institute of Technology (MIT); ThinkSwiss research fellowship by the Office of Science, Technology, and Higher Education of the Embassy of Switzerland in Washington D.C. to attend Swiss Federal Institute of Technology (ETH) in Zurich, Switzerland; Jack E. Leisch Fellowship from the American Society of Civil Engineers; and several other prestigious honors including those from the International Road Federation, Eno Center for Transportation, American Public Transportation Foundation (APTF Board scholarship and Jerome C. Promo scholarship), Purdue Climate Change Research Center, and Essam and Wendy Radwan fellowship (twice) from the Lyles School of Civil Engineering at Purdue University.

Tariq is currently a member of the TRB standing committee on statistical methods (ABJ80) and ASCE T&DI's economics and finance committee.

PUBLICATIONS

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Presentations, Proceedings, and Invited Talks

Tariq has presented his research in international conferences, symposia, and workshops worldwide including United States, United Kingdom, Switzerland, Brazil, Singapore, and Turkey.