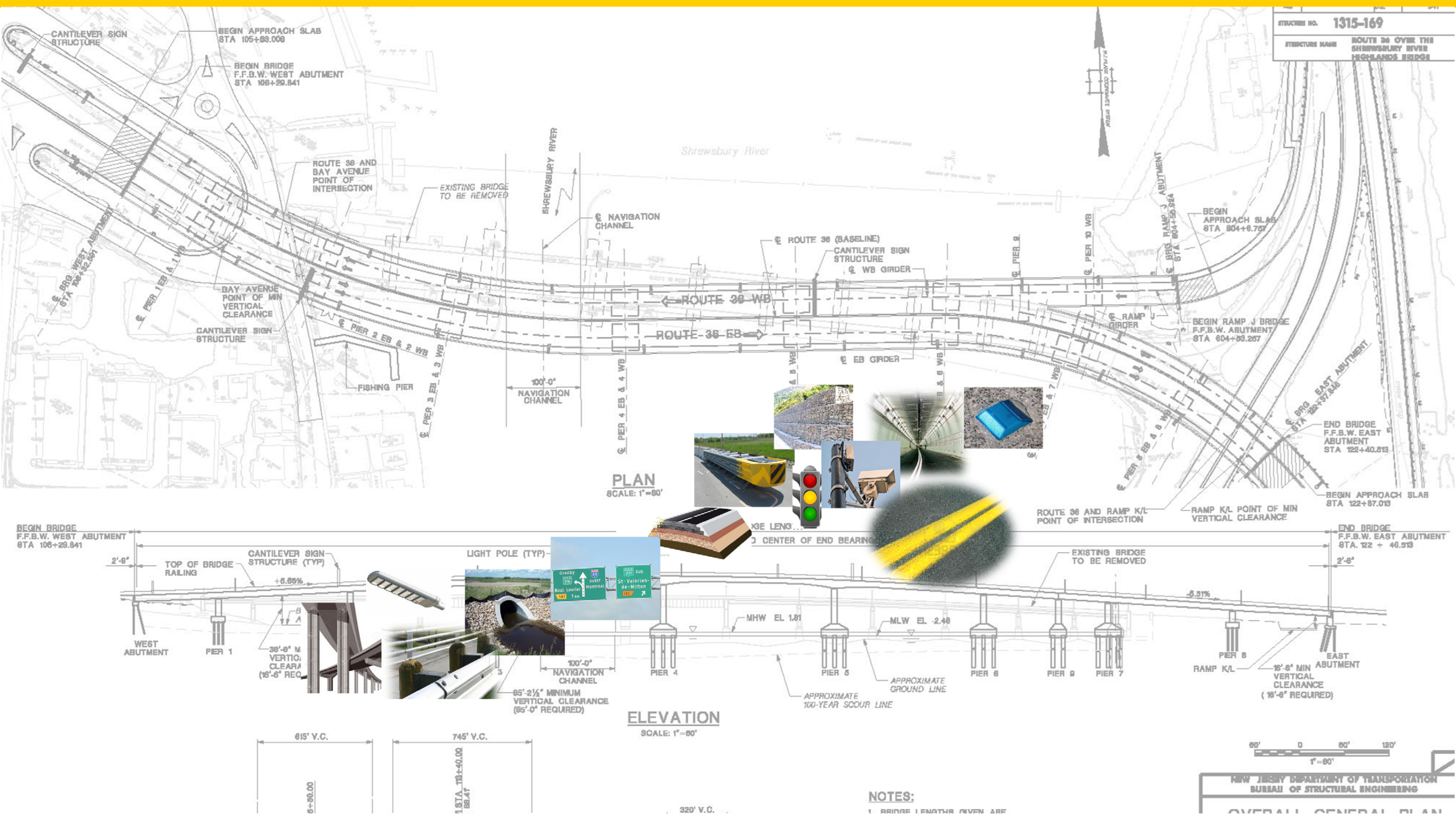
CCAT

CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

Final Report #29
September 2023



Design and Management of Highway Infrastructure to Accommodate CAVs

Samuel Labi
Tariq U. Saeed
Mohammadhosein Pourgholamali
Zainab A. Saka
Kumares C. Sinha

PURDUE UNIVERSITY®

CENTER FOR CONNECTED AND AUTOMATED TRANSPORTATION

Report No. 29
Project Start Date: January 2018
Project End Date: December 2022

September 2023

Design and Management of Highway Infrastructure to Accommodate CAVs

by

Samuel Labi
Professor

Tariq U. Saeed
Graduate Researcher

Mohammadhosein Pourgholamali
Graduate Researcher

Zainab A. Saka
Graduate Researcher

Kumares Sinha
Distinguished Professor

Purdue University

ACKNOWLEDGMENTS AND DISCLAIMER

Funding for this research was provided by the Center for Connected and Automated Transportation under Grant No. 69A3551747105 of the U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology (OST-R), University Transportation Centers Program. Also, general support was provided by Purdue's Next-generation Transportation Systems (NEXTRANS) Center, and the following initiatives at Purdue University's College of Engineering: the Institute for Control, Optimization, & Networks (ICON), the Autonomous & Connected Systems (ACS) initiative, and the Center for Intelligent Infrastructure (CII). We also thank the organizations, companies, and institutions that provided valuable in-kind cost share or other external support for this project, including Indiana DOT (Dr. Barry Partridge and Dr. Samy Noureldin), ETH Zurich (Dr. Bryan Adey), National University of Singapore (Dr. Ghim Ping Ong), Nanyang Technical University (Dr. Feng Zhu), and TU Delft (Dr. Goncalo Homem de Almeida Correia), Dr. Gummada Murthy (AASHTO), and other institutions and organizations. We also appreciate the input of Duke Dodoo, Mahmood Tabesh and Bortiorkor Alabi, graduate students at Purdue University, and Mostafa Saneii, and the general support provided by Ms. Debby Bezzina and Mr. Calvin Tuttle of CCAT Michigan.

Labi, S., Saeed, T.U., Pourgholamali, M., Saka, Z.A., Sinha, K.C. (2023). Design and Management of Highway Infrastructure to Accommodate CAVs, CCAT Report #29, The Center for Connected and Automated Transportation, Purdue University, West Lafayette, IN.

Contacts

For more information

Samuel Labi, Ph.D.
Purdue University
550 Stadium Mall Drive
HAMP G175B
Phone: (765) 494-5926
Email: labi@purdue.edu

CCAT
University of Michigan Transportation
Research Institute
2901 Baxter Road
Ann Arbor, MI 48152

uumtri-ccat@umich.edu
(734) 763-2498
www.ccat.umtri.umich.edu

Technical Report Documentation Page

1. Report No. 29

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle:
Design and management of highway infrastructure to accommodate CAVs

5. Report Date: September 2023

6. Performing Organization Code
N/A

7. Author(s)
Samuel Labi, Tariq U. Saeed, Mohammadhosein Pourgholamali, Zainab A. Saka, Kumares C. Sinha

8. Performing Organization Report No. N/A

9. Performing Organization Name and Address:
Center for Connected and Automated Transportation, Purdue University, 550 Stadium Mall Drive, W. Lafayette, IN 47907; and University of Michigan Ann Arbor, 2901 Baxter Rd., Ann Arbor, MI 48109

10. Work Unit No.

11. Contract or Grant No.
Contract No. 69A3551747105

12. Sponsoring Agency Name and Address
U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology, 1200 New Jersey Avenue, SE
Washington, DC 20590

13. Type of Report, Period Covered
Final report, Jan 2018 – December 2022

14. Sponsoring Agency Code
OST-R

15. Supplementary Notes
Conducted under the U.S. DOT Office of the Assistant Secretary for Research and Technology's (OST-R) University Transportation Centers (UTC) program.

16. Abstract
Over the past century, landmark advancements in vehicle technology have motivated road agencies to carry out changes in their road infrastructure design and management processes to accommodate these advancements. The advent of Autonomous Vehicles (AVs), however, poses infrastructure challenges that could be more profound compared to those faced in the past. This study first discusses AV issues and concepts that could influence the scope and types of roadway infrastructure design and management in the AV era. These issues include AV technology readiness, the levels of vehicle autonomy, the stages of AV operations, and stakeholder roles. The study discusses AV demand forecasts and related factors and identifies the stakeholder perspectives regarding infrastructure readiness. The study indicates that the transition period (characterized by a mixed traffic environment of AVs and HDVs) will last for several decades, and that any infrastructure design changes should be based only on the party (AVs vs. HDVs) whose physical or operational features require designs that are more conservative compared to the other party. Further, in cognizance of the phased nature of road infrastructure development, the report discusses how AVs are expected to influence the way infrastructure owners and operators (IOOs) will plan, design, and operate their infrastructure in the AV era: changes in highway planning processes, introduce new classes of assets and cause obsolescence of certain existing asset types, changes in dimensions of certain elements of highway design, lead to reduced inspection expenditures but higher maintenance and operating expenditures. The study also presents AV-related legislation, policy, and regulations that are relevant to road infrastructure planning and revenues needed for infrastructure upkeep. Infrastructure is generally managed at project or network levels. In a context of project-level management, the study presented a flexibility-based framework for evaluating AV-related infrastructure investments, considering the uncertainty associated with AV market penetration as the main source of volatility. The framework considers that the IOO may choose to expand, defer, or scale back the investments at a future time as needed. Then, in a context of network-level management, the study presents and demonstrates how AV infrastructure investments could be influenced by holistic network effects regarding traffic flows on a capacitated network. The methodology can be used by IOOs to optimally select AV-related infrastructure implementation years, locations, their respective capacities, and user fee levels within a given horizon period.

17. Key Words
Infrastructure readiness, Autonomous vehicles, Bi-level optimization, Investment analysis, Parking infrastructure.

18. Distribution Statement
No restrictions.

19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	222	

Form DOT F 1700.7 (8-72)	Reproduction of completed page authorized

TABLE OF CONTENTS

LIST OF TABLES 9

LIST OF FIGURES 10

LIST OF ACRONYMS 12

LIST OF TERMS 14

CHAPTER 1: INTRODUCTION 15
1.1 Study Background 15
1.2 Problem Statement 17
1.3 Study Objectives 18
1.4 Key Contributions of the Study Framework 19
1.5 Organization of this Report 20

CHAPTER 2 AV ISSUES AND CONCEPTS THAT INFLUENCE ROADWAY INFRASTRUCTURE READINESS 21
2.1 Introduction 21
2.2 Readiness of AV Technology 21
2.3 Levels of Vehicle Automation 22
2.4 Features of Automation and Connectivity 24
2.5 The AV Transition Period and its Phases 25
2.6 Discussion on the Influence of Road User Attitudes on the Transition Period Duration 29
2.7 Technology Development and Adoption Scenarios 29
2.8 Key Stakeholders and their Roles 30
2.9 The Stakeholder Participation Model (SPM) 32
2.10 ODD and its Relationship with Infrastructure 34
2.11 Some Initiatives at Various States in the US 36

CHAPTER 3 AV DEMAND FORECASTS 37
3.1 Introduction 37
3.2 Market Penetration (MP) 37
3.3 Statistical Modeling of AV Adoption Potential 40
3.3.1 Prelude 40
3.3.2 Data Collection and Description 41
3.3.3 Descriptive Statistics – Assessing AV Demand Potential using User Survey 44

3.3.4 Model Specification 47
3.3.5 Model Estimation Results—Interpretation of the Variable Signs 47
3.3.6 Further Discussion of the Results 52
3.4 Predicted market penetration – for all levels and each level of automation 53

CHAPTER 4. STAKEHOLDER PERSPECTIVES 55
4.1 Introduction 55
4.2 OEMs (AV Technology Developers) 55
4.2.1 Prelude 55
4.2.2 Survey Questionnaire, Findings and Discussion 55
4.2.3 Market Penetration Trends 58
4.3 Public-sector IOOs 59
4.3.1 Prelude 59
4.3.2 Survey Questionnaire, Findings and Discussion 59
4.4 Road Users 73
4.4.1 Prelude 73
4.4.2 Background information on AV safety perceptions 74
4.4.3 Model Specification 74
4.4.4 Discussion of Model Estimation Results 76
4.4.5 Implications of the Road-users' Road-sharing Comfort 79
4.5 Summary and Discussion 80
4.6 Limitations 82

CHAPTER 5. AV CONSIDERATIONS AT THE PLANNING PHASE OF INFRASTRUCTURE DEVELOPMENT CYCLE 83
5.1 Introduction 83
5.2 PSCCAR Guidance on Infrastructure Planning in the AV Era 85
5.3 AV-related Legislation, Policy, and Regulations related to Road Infrastructure Planning 86
5.4 Revenue Challenges facing Infrastructure Planning in AV Era 88
5.5 Cost Allocation and User Equity in the AV Era 88
5.6 Inconsistency of Road Design and Operations Standards 89
5.7 Planning for the Integration of AV-related Infrastructure with Extant Infrastructure 89
5.8 Planning for AV Supporting Infrastructure 90
5.9 Planning that Considers Potential Inequities 90

CHAPTER 6. AV CONSIDERATIONS AT THE DESIGN PHASE OF INFRASTRUCTURE DEVELOPMENT 91
6.1 Introduction 91
6.2 Establishment of a New Hierarchy of Infrastructure Classes in the AV Era 92
6.2.1 Introduction of new infrastructure elements 95

6.2.2 Modification of existing infrastructure elements through changes in standards................. 98
6.2.3 Removal of some of the existing infrastructure elements.. 100
6.2.4 Redistribution of some elements.. 100
6.2.5 Redesign of geometric and other design elements.. 101
6.2.6 Strategic directions for road design in the AV era.. 106
6.3 The Concept of Design for Changeability (DfC).. 107
6.4 Challenges and Opportunities in Design... 108

CHAPTER 7. CONSIDERING AV FEATURES/CAPABILITIES AT THE OPERATIONS-MONITORING-MAINTENANCE PHASE OF THE INFRASTRUCTURE DEVELOPMENT CYCLE 110
7.1 Introduction.. 110
7.2 Road infrastructure monitoring.. 110
7.3 Road Maintenance and Operations 111

CHAPTER 8. A GENERAL FRAMEWORK FOR EVALUATING PROJECT-LEVEL AV-RELATED STIMULI CONSIDERING UNCERTAINTY... 113
8.1 Introduction 113
8.1.1 Step 0 – Pre-evaluation Activities.. 113
8.1.2 Step 1. Establish the AV- related infrastructure investment alternatives 115
8.1.3 Steps 3-5. Establish list of the investment evaluation criteria 115
8.1.4 Steps 6-9.. 116
8.2 Traditional Analysis Methods (used in Step 6).. 117
8.3 Newer Approaches that account for Uncertainty and Flexibility 118
8.3.1 Real Options Analysis (ROA) 118
8.3.2 Types of Options used in ROA... 121
8.3.3 Option Valuation Methods.. 123
8.3.4 Limitations of ROA and Potential Remedies.. 125
8.3.5 ROA Parameters 125
8.3.6 ROA-Discussion 126
8.4 Overcoming the Barriers to Effective Evaluation of AV Infrastructure Investments 126
8.4.1 Political Influences.. 126
8.4.2 Unstable Goals and Objectives of the IOO... 126
8.4.3 Difficulty of Achieving Holistic Solutions... 127
8.4.4 Multiplicity of Stakeholders and their concerns 127
8.4.5 Severity of Budgetary Constraints.. 127

CHAPTER 9. PROJECT-LEVEL AV-RELATED INVESTMENT EVALUATION CONSIDERING UNCERTAINTY: A CASE STUDY 128
9.1 Introduction 128
9.2 The Binomial Lattice Method for the ROA Analysis 128
9.3 Investment scenario I 130
9.3.1 Introduction 130
9.3.2 Quantification of Cost Components 130
9.3.3 Results and Discussion 131
9.4 Investment scenario II 132
9.4.1 Introduction 132
9.4.2 Results and Discussions 132
9.4.2.1 NPV Method 132
9.4.2.2 The ROA Method 133
9.4.3 Limitations 136
9.5 Discussion 137

CHAPTER 10. A FRAMEWORK FOR NETWORK-LEVEL AV-RELATED INVESTMENT PLANNING CONSIDERING HOLISTIC EFFECTS 138
10.1 Introduction 138
10.2 Methodology 140
10.3 Preliminaries 141
10.3.1 The Upper-Level Model 142
10.3.2 The Lower-Level Model 144
10.4 Solution Algorithm 150
10.5 Numerical Experiment 153
10.5.1 Problem Setting 153
10.6 Assumptions, Analysis, and Discussion 154
10.7 Final Remarks 158
10.8 Appending Information Part 1 159
10.9 Appending Information Part 2 163

CHAPTER 11. SUMMARY AND CONCLUSIONS 166
11.1 Prelude 166
11.2 A Synopsis of the Research 166
11.3 Discussion and policy recommendations 167
11.3.1 Considerations for infrastructure evolution 167
11.3.2 Infrastructure design and policy standardization 168
11.3.3 Coordination among road infrastructure agencies 169
11.3.4 Formal and regular coordination between stakeholders 169

11.3.5 Develop mechanisms for information sharing between IOOs and other stakeholders.... 170
11.3.6 Recognition of the role of infrastructure as a holistic issue not standalone..................... 170
11.4 Contributions of the Report 171
11.5 Recommendations for Future Work.. 171

CHAPTER 12 SYNOPSIS OF PERFORMANCE INDICATORS 173
12.1 USDOT Performance Indicators Part I 173
12.2 USDOT Performance Indicators Part II.. 173

CHAPTER 13 STUDY OUTCOMES AND OUTPUTS 175
13.1 Outputs.. 175
13.1.1 Publications, conference papers, and presentations.. 175
13.1.2 Other Products 177
13.2 Outcomes 178
13.3 Impacts.. 178

REFERENCES 179

APPENDIX... 215

LIST OF TABLES

Table 2.1 AV-related initiatives at a sample of US states 36
Table 3.1 AV market penetration forecasts 39
Table 3.2 Summary of road user responses 43
Table 3.3 Descriptive statistics of key variables... 45
Table 3.4 Prospective consumer mobility preferences across the built environment 46
Table 3.5 Model estimation results for mode preferences 50
Table 3.6 Average marginal effects for mobility preferences 51
Table 4.1 Questions to OEMs and their responses 57
Table 4.2 IOO respondents – Questions and summary responses 71
Table 4.3 Model estimation results for User comfort level in sharing the road with AVs........... 78
Table 4.4 Responses of the OEMs and IOOs – A Comparison 82
Table 6.1 Infrastructure readiness for AV-related technologies 93
Table 6.2 Stopping sight distance: HDV vs. AV 103
Table 6.3 SSD on level roads for human-driven vehicles and AVs (Othman, 2021)................. 104
Table 6.4 Proposed lane width for AVs: A synthesis of recommendations 105
Table 8.1 Terms used across financial and real options 120
Table 9.1 Analogies in real and financial options for dedicated AV lane investment…………..129
Table 9.2 Underlying values of the asset at each node 134
Table 9.3 Value of the defer option using backward induction method.................................... 134
Table 9.4 Valuation of the option "defer", using the MCS approach... 136
Table 10.1 Summary of notations 163
Table 10.2 Parking fee levels under the base planning scenario 164
Table 10.3 Performance of different prospective parking facility decommissioning benefit levels (in $M) 165

LIST OF FIGURES

Figure 2.1 SAE and NHTSA classifications of automated driving systems................................ 22
Figure 2.2 Descriptions of SAE J3016 Levels of Driving Automation....................................... 23
Figure 2.3 Other descriptions of the levels of automation... 24
Figure 2.4 Basic hardware of a typical autonomous vehicle 25
Figure 2.5 Timeline of HDV-only traffic, mixed traffic, and AV-only traffic............................ 26
Figure 2.6 Hypothetical AV Safety Bump... 27
Figure 2.7 As travelers continue to have positive personal experiences in autonomous vehicles, user trust in AVs is expected to increase 28
Figure 2.8 The stakeholder quad.. 32
Figure 2.9 Conceptual ODD elements... 35
Figure 3.1Consumers' prospective mobility preferences 46
Figure 3.2 Marginal effect of factors that influence mobility preferences 52
Figure 3.3 Predictions of AV trends – Percentages of market penetration, sales, and travel....... 54
Figure 3.4 Market penetration and level of autonomy (MPLA) diagram.................................... 54
Figure 4.1 Years at which AVs are expected to constitute specific fractions of the traffic stream 58
Figure 4.2 AV market penetration trends (optimistic and pessimistic) 59
Figure 4.3 HDV drivers' comfort levels regarding road sharing with AVs 74
Figure 4.4 Illustration of marginal effects for road user comfort level 79
Figure 5.1 Phases of road development and typical tasks at each phase 83
Figure 5.2 Suggested criteria at various planning levels of AV related Investment 84
Figure 5.3 AV implementation levels in the various states 87
Figure 6.1 Infrastructure Options that could Facilitate Shared Ridership (Duval et al, 2019)..... 92
Figure 6.2 Classes of CAV-related infrastructure.. 94
Figure 6.3Phasing plan example for roadway lane-assignment transition to accommodate AVs 96
Figure 6.4 Sample communication setup.. 97
Figure 6.5 High-contrast markings 98
Figure 6.6 Example of road sign with barcode 99
Figure 6.7 Stopping sight distance: HDV vs. AV.. 102
Figure 6.8 SSD for different upward grades for HDVs and AVs.. 104
Figure 6.9 Aspects of changeability... 108
Figure 8.1 Multi-criteria framework for evaluating CAV-related road investments................. 114
Figure 8.2 Binomial lattice with three time-step 124
Figure 9.1 Binomial lattice structure for five time-step... 129
Figure 9.2 NPV outcomes at different levels of AV market penetration................................... 131
Figure 9.3 NPV outcomes for Scenario II (providing a dedicated lane) 134
Figure 9.4 Sensitivity analysis of NPV w.r.t agency and user dollar weights........................... 134

Figure 9.5 Illustration of decision-making points in NPV and ROA methods 136
Figure 9.6 Sensitivity of the option value to the risk-free rate Monte Carlo simulation 136
Figure 10.1 The structure of the bi-level optimization framework 141
Figure 10.2 Travel and parking behavior modeling of sub-group 1 of AVs and HDV travelers……………………………………………………………………………144
Figure 10.3 Network transformation 146
Figure 10.4 Solution algorithm 152
Figure 10.5 Locations of available and potential parking facilities on Sioux-Falls network 153
Figure 10.6 Best objective values over iterations 155
Figure 10.7 Optimal parking configuration under the base planning scenario 156
Figure 10.8 Configuration of parking facility planning under different budgets 157

LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
AAA	American Automobile Association
ADS	Automated Driving System
AM	Asset Management
AV	Autonomous/ Automated Vehicle
AVSI	AV-supporting Infrastructure (pronounced “av-see)
AWF	Auxiliary Work and Funding
BL	Binomial Lattice
CBD	Central Business District
CAV	Connected Autonomous Vehicle
CAVI	CAV Investment
CBD	Central Business District
CV	Connected Vehicle
DCF	Discounted Cash Flow
DfC	Design for Changeability
DOT	Department of Transportation
DSRC	Dedicated Short Range Communications
EV	Electric Vehicle
FAP	Fully Autonomous Phase
FHWA	Federal Highway Administration
FMVSS	Federal Motor Vehicle Safety Standards
GHSA	Governors Highway Safety Association
HDV	Human-Driven Vehicle
IAM	Infrastructure Asset Management
IOO	Infrastructure Owner and Operator
IOT	Internet of Things
ITS	Intelligent Transportation Systems
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
MaaS	Mobility-as-a-Service
MCS	Monte Carlo Simulation
MP	Market Penetration
MPLA	Market Penetration and Level of Autonomy
MUTCD	Manual on Uniform Traffic Control Devices
NHTSA	National Highway Traffic Safety Administration
NPV	Net Present Value
ORS	Operational Road Section
PFLP	Parking Facility Location Problem

PMU	Personal Mobility Units (also, PMV, PTU)
PMU	Personal Mobility Vehicles
PTU	Personal Transport Units
PUDO	Pick-up drop-off (zones)
ROA	Real Options Analysis
RSU	Road-Side Units
SAE	Society of Automotive Engineers
SAV	Shared Autonomous Vehicle
SPM	Stakeholder Participation Model
SMMA	Small- and Medium-sized Metropolitan Areas
SPM	Stakeholder Participation Model
SSD	Stopping Sight Distance
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VMT	Vehicle Miles Traveled
USDOT	United States Department of Transportation

LIST OF TERMS

Automated Driving System (ADS)	Hardware and software collectively capable of performing the entire dynamic driving tasks on a sustained basis.
Auxiliary Work and Funding	Additional infrastructure repair, retrofit, and expansion (and associated funding) beyond current infrastructure owner and operator responsibilities. This additional need is to support AV operations at a certain minimum threshold level of service.
Dynamic driving task (DDT)	All the real-time operational and tactile functions required to operate a vehicle on an in-service road.
Infrastructure Readiness Level (IRL)	A quantitative statement of highway infrastructure system maturity in terms of its capability to support a certain specified level of AV operations. This includes the physical infrastructure, safety, governmental and institutional processes, data management (acquisition, sharing and privacy), systems interoperability and communications.
Infrastructure Owner and Operator (IOO)	In the context of highway transportation, IOOs are organizations that own and/or operate the physical (and in some cases, cyber) infrastructure that supports travel. IOOs include public and private agencies, such as State and local DOTs, transit agencies, and operators of toll roads and bridges.
Original Equipment Manufacturer (OEM)	OEMs are the companies that manufacture, sell, or maintain AVs and their supporting components. OEMs define vehicle ODDs and are responsible for safe operations of the vehicle within the ODD irrespective of the IOO's actions.
Operational Design Domain (ODD)	Specific conditions under which a given driving automation system or feature thereof is designed to function.
Fully Autonomous Phase (FAP)	A prospective future period where 100% of vehicles in the traffic stream have full or near full autonomy (Levels 4 or 5).
Stakeholder	In the context of AVs, a stakeholder refers to a group of individuals or entities that are expected to (a) gain some utility (mobility, safety, etc.) or suffer some adversity (inequity, etc.) due to AV operations, (b) be involved in the manufacture, sale, or maintenance of AVs and/or their supporting components, or (c) responsible for the planning, design, operations, and maintenance of infrastructure intended to support AVs.
Transition Period	The period between 100% market penetration (MP) of non-AVs and 100% MP of AVs that are characterized by mixed traffic (AV and HDV) on the road space

(Sources: ANSI Blog: SAE Levels of Driving Automation, https://blog.ansi.org/?p=158517; Gopalkrishnan et al., 2015)

CHAPTER 1: INTRODUCTION

1.1 Study background

Since the advent of the motor vehicle at the turn of the last century, advancements in automobile technology and road design, and the evolving safety and mobility needs of the traveling public have continually led to highway infrastructure modifications. For example, in the current era, the key elements of smart mobility – autonomy, connectivity, shared rides, and airborne vehicles – continue to attract the attention of transportation agencies that provide the supporting infrastructure. For these innovations, the continued advancement of these technologies, their deployment and their user adoption will not only influence but also be influenced by availability of supporting road infrastructure.

As such, autonomous vehicle (AV) technology is expected to profoundly influence the way engineers plan, design, and operate highway infrastructure (TRB, 2014; AASHTO, 2017, 2018; FHWA, 2018; Reid, 2021). Gopalakrishna et al. (2015) noted that even though highway agencies function at a pace that is much slower compared to technology companies and automobile manufacturers, both parties will need to co-evolve. A recent report by the USDOT Center for Connected and Automated Transportation (CCAT) estimated that the expenditures needed to support AVs can be substantial (Mwamba et al., 2023). Given that infrastructure agencies already face maintenance backlogs and strained budgets for their traditional infrastructure, it is not certain whether they can comfortably bear these additional responsibilities. Therefore, they will need to identify optimal or innovative CAV-related infrastructure timing and spending solutions. **In this report, we use the acronyms AV and CAV synonymously.**

From the consumer (traveler/road user) perspective, the advent of AVs is generally being viewed with cautious optimism. It is anticipated that AVs will ultimately gain wide acceptance among travelers (TRB, 2014), thereby, changing the nature of road transportation (Johnson, 2017) and leading to safety and mobility benefits (FHWA, 2018). However, these prognostications will not be realized without a sustained increase in travelers' proclivity to patronize AVs and until the road infrastructure is ready to support AV operations (Johnson, 2017). As AV market penetration increases and travelers begin to observe (or at least, perceive) the benefits of AVs, infrastructure owners and operators (IOOs) will be pressured to provide the infrastructure to support expanded operations of AVs.

The relationship between connected and automated vehicle technologies and highway infrastructure development continues to be of great interest among government agencies and organizations (Booz Allen Hamilton and WSP, 2020; Chan and Wang, 2021; Tengilimoglu et al., 2023; Amelink et al., 2020). From a broad perspective, Duval et al. (2019) argued that full deployment of AVs will depend on whether private and public stakeholders invest in the infrastructure needed to support this technology. There are complexities associated with various operational conditions including driving in different operational design domains (ODDs) such as in snow or at night, correctly interpreting traffic signs and control devices of non-uniform design across states, and sensing faded pavement markings for lane keeping. These challenges can be overcome through carefully planned and adequate infrastructure readiness. Any inadequacy in road infrastructure quality which poses an impediment to AV operations, could be exacerbated by road repair funding inadequacies or uncertainties. It has been argued that existing infrastructure faces serious challenges in terms of its readiness to accommodate AVs (Johnson, 2017; Young, 2017). In their report titled "Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations," Fagnant and Kockelman (2015) identified infrastructure readiness as a key area that must be addressed prior to deployment of AVs on public roads. McFarland (2015), Sage (2016), Tracy (2017) and KPMG (2018) considered infrastructure as one of the major hurdles to AV deployment on existing roads. The current poor state of the infrastructure could be attributed mostly to aging – most of the infrastructure was built several decades ago; they have exceeded their design lives and are due for replacement.

In the context of the current state of the infrastructure, the U.S. Department of Transportation (2016) reported that about 65 percent of U.S. roads are in poor condition. The U.S. transportation infrastructure was rated 12th in the World Economic Forum's 2014–2015 global competitiveness report (Schwab and Sala-i-Martin, 2014). Inadequate preparedness of road infrastructure could be consequential. Not long ago, a driverless car failed a test drive in Los Angeles due to poor lane markings (Sage, 2016). A similar vehicle on autopilot operating 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 cross-state inconsistencies in design are considered major hindrances to the AV deployment.

The 2020 Autonomous Vehicles Readiness Index compiled by KPMG (2020) rated the United States fourth (of all the developed countries) in terms of its infrastructure readiness to host AVs. Automakers and technology developers have echoed these concerns as they have found the existing infrastructure to be unsuitable for AV navigation (Sage, 2016). The effect of poor infrastructure is cyclical. Poor conditions and low quality of road infrastructure 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 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, and consequently, reduce impetus for AV infrastructure readiness.

Notwithstanding the concerns about the state of good repair the infrastructure, the reality is that, even if they were in good condition, these infrastructure assets currently have designs that may become increasingly obsolete in the emerging AV era. Bamonte (2013) recognized that the existing highway infrastructure is designed and built to meet the driving capabilities and information needs of human drivers, and that highway agencies must start preparing for the emerging era of autonomous vehicles. However, a framework for doing this, and the impacts of prospective emergence of AVs on highway infrastructure needs, have not been studied adequately (TRB, 2014; Saeed et al., 2015; Johnson, 2017). As such, IOOs (transportation agencies at different levels – federal, state, city, and other local jurisdictions – and private-sector infrastructure developers) may not be sufficiently informed or prepared to make the needed investments in their physical infrastructure to accommodate AVs. As they seek to better prepare their infrastructure for AVs, IOOs grapple with questions including:

- **Market penetration**. To what extent will AV market penetration drive AV infrastructure needs? What are the expected future trends in AV market penetration and levels of autonomy? What minimum level of market penetration should trigger each level of infrastructure provision? How does one define these levels of preparation?

- **Infrastructure design and management**. How should highway infrastructure design and management change to support AV operations? What should be the relationship between the investment timings and the changes in AV MP and LOA?
- **Uncertainty**. What are the major sources of uncertainty associated with the four key stakeholders – AV consumer demand, road infrastructure, AV technology, and government policy – and how do these uncertainties influence AV-related road infrastructure planning?

Silberg et al. (2013) expect AVs to transform the existing highway infrastructure development that could reduce the $7.5 billion that the US currently spends annually on roads, highways, bridges, and other related roads infrastructure. The authors argued that such savings will be due to 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 traffic throughput.

Infrastructure preparedness for AVs can be considered not only a challenge but also an opportunity to address longstanding infrastructure issues in the US. A 2018 paper in the NAE journal "The Bridge" stated that the need to prepare current infrastructure to support AVs offers parallel and synergistic opportunity to improve roadway infrastructure that is already in need of such retrofits (Harrington et al., 2018). As AV technology advances and demand grows, the need to replace, repair, and retrofit the aging US infrastructure will become more visible, and there will be greater urgency to address these needs. According to the Harrington et al., (2018) article, this will "revitalize the conversation around infrastructure and its role in the transportation ecosystem". As such, as IOOs continue their routine functions of repairing and replacing existing traditional infrastructure, their awareness and appreciation of an AV future will motivate them to ensure that such improvements address challenging operational design domains (ODDs). These include driving at night, in snow, in poor visibility environments, or difficulty in correctly interpreting the different road markings and signages that exist across the various states. As the emergence and widespread deployment of AVs draws closer, they can be used to justify requests for increased funding for the road infrastructure maintenance.

Finally, it is worth iterating that investments in infrastructure to support AVs will depend on stakeholders' realization of the wider impacts (both beneficial and adverse) of AVs. These impacts can be estimated through a careful *ex ante* investigation of the impacts of AVs. The current literature is replete with research related to the various impacts of AVs including travel behavior, operations, city planning, emissions, energy use, safety, and land use (Duarte and Ratti, 2018; Soteropoulos et al., 2019; Gandia et al., 2019; Gkartzonikas and Gkritza, 2019). Further research on the wider societal, economic, and environmental benefits of AVs must be carried out to build a stronger and informed case for AV-related infrastructure investments.

1.2 Problem Statement

As far back as the 2014 Automated Vehicles Symposium in San Francisco (TRB, 2014)., the need for adequate road infrastructure to support connected and autonomous vehicle (CAV) operations has continued to resonate widely. 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." The authors identified critical issues related to road infrastructure readiness and discussed the implications of AV implementation scenarios on roadway infrastructure condition and maintenance requirements. The authors also discussed the reciprocal relationship between road infrastructure adequacy and the initiation of AV operations. They indicated that infrastructure inadequacy can stymie full deployment of AVs, adding that the use of more sophisticated technology-based infrastructure may increase road maintenance costs significantly, and advocated for further research on AV-related highway infrastructure investment evaluation. Also in 2017, AASHTO (2017) published a document that identified the infrastructure challenges associated with mixed traffic streams (both AVs and HDVs sharing the roadway) and argued for research on infrastructure requirements for AVs and the requisite physical modifications to the existing infrastructure. In Europe, the European Road Transport released a connected automated driving roadmap that highlighted the need for infrastructure development ti support AVs (ERTRAC, 2019). Farah et al. (2018) discussed the state of the art and future research directions regarding infrastructure for automated and connected driving.

IOOs at all levels of government (federal, state, and local) and in the private sector seek guidance on the scope, types, and scale of infrastructure associated with the different levels of AV automation and market penetration (TRB, 2014; AASHTO, 2017; Johnson, 2017; AVS, 2018; FHWA, 2018). Unfortunately, this issue is further exacerbated by uncertainty associated with the various stakeholders (uncertainty of the OEM's AV technology development pace; uncertainty of travelers' adoption of AVs; and uncertainty of the willingness and capability of governments to pass legislation and establish the requisite supporting policy). These multiple sources of uncertainty seem to make road agencies hesitate in investing in AV-related infrastructure (FHWA, 2018). Their hesitation seems understandable, for the reasons stated above. Typically, road infrastructure investments are justified based on user demand. As such, increased AV market penetration can motivate agencies to renew, right size, upgrade, expand, or modernize their road infrastructure. The agencies can proactively provide infrastructure that will fuel AV market penetration, encourage supporting policy and legislation, and encourage development of AV technologies by assuring the OEMs of adequate ODDs for AVs.

In sum, there exists a need to discuss AV issues and concepts in the context of roadway infrastructure and identify the infrastructure-related roles of the key stakeholders, to establish AV demand forecasts made in the literature, and to acquire insights into AV stakeholder perspectives on infrastructure readiness. Next, it is needed to identify AV considerations at the various phases of road infrastructure development – road planning, roadway design, and operations-maintenance-monitoring. Further, it is needed to develop, for the benefit of highway agencies, methods and frameworks for (a) evaluating their prospective AV-related infrastructure investments particularly in an environment of uncertainty, and (b) planning AV-related infrastructure investments considering holistic and interdependent effects in a road network. Finally, there is a need to establish policy guidelines for road agencies to enhance their infrastructure preparations for the emerging era of autonomous vehicle operations.

1.3 Study Objectives

Based on the problem statement presented above, the objectives of this study are:

- Discuss AV issues and concepts in the context of roadway infrastructure and identify the infrastructure-related roles of the key stakeholders.
- Identify the factors that affect AV demand, as a potential input to: demand trend forecasts and the timing of AV-related infrastructure provision.
- Acquire insights into AV stakeholder perspectives on infrastructure readiness (through a questionnaire survey).
- Discuss AV considerations at the various phases of road infrastructure development – road planning, roadway design, and operations-maintenance-monitoring.

- Present and demonstrate a project-level framework for AV-related infrastructure investment evaluation considering uncertainty.
- Present and demonstrate a network-level framework for AV-related infrastructure investment evaluation considering holistic network (traffic) effects.
- Propose policy guidelines for road agencies to enhance infrastructure preparation for AVs.

The various evaluation frameworks and policy guidelines presented in this report could serve as planning roadmaps that transportation agencies can use as points of reference in the initiation or continence of their AV-related infrastructure investments.

1.4 Key Contributions of this Study

There has been some background work in the literature. The Finnish Transport Infrastructure Agency (2021) studied infrastructure support and classification for automated driving on Finnish motorways. Gyergyay et al. (2019) developed an automation-ready framework for urban transport and road infrastructure planning, and Gouda et al. (2021) carried out an automated assessment of infrastructure preparedness for autonomous vehicles. Liu et al. (2019) caried out an insightful systematic review of literature on road infrastructure requirements for CAVs. Lu et al. (2019) developed and analyzed multiple scenarios regarding infrastructure requirements for automated driving. Milakis et al. (2017) analyzed the implications of automated vehicles on the infrastructure development and transportation in the Netherlands. Osichenko and Spielhofer (2018) identified the need for infrastructure to accommodate AVs as one of the future challenges for the road asset management. Rana and Hossain (2021) reviewed existing research on the relationship between road infrastructure and CAVs. Tengilimoglu et al. (2023) presented infrastructure requirements for the safe operation of automated vehicles: Opinions from experts and stakeholders.

The study described in this report makes a few contributions. First, the study considers stakeholders' perspectives on infrastructure preparations towards CAVs. From the perspective of technology companies, the level of AV technology is expected to influence the types and scope of AV-related infrastructure changes needed to accommodate AVs. AV users are expected to drive market penetration and, hence, will influence the need, type, and scope of infrastructure preparation by the highway agencies. This report uses survey questionnaires as a tool to capture these viewpoints for consideration by highway agencies in their investment decision-making processes. The second contribution is an identification of the types of road infrastructure modifications that will be needed. It is important to identify the needed changes to road infrastructure and roadway design features at different levels of AV market penetration and prevailing levels of autonomy. This study attempts to do this through a survey of IOOs, the expectations of OEMs regarding infrastructure readiness for AVs, an extensive literature review, and discussions with experts. The third contribution is the consideration of a life cycle perspective. The study discusses AV considerations at the various phases of road infrastructure development – road planning, roadway design, and operations-maintenance-monitoring. The fourth contribution is a project-level study that considers uncertainty: a framework is presented and demonstrated to show how agencies can evaluate their AV-related infrastructure investments in a robust manner. The fifth contribution is a network-level study that considers traffic interdependencies: a framework is presented and demonstrated to address AV-related infrastructure investment planning considering holistic network (traffic) effects. The sixth contribution is related to the provision of policy guidelines to support AV related infrastructure preparations.

1.5 Organization of this Report

The study report is organized as follows. Chapter 1 presents the study background, problem statement, study objectives, the key elements of the study framework, and the way the report is organized. Chapter 2 discusses important background information including AV issues and concepts in the context of roadway infrastructure and identifies the infrastructure-related roles of the key stakeholders. Infrastructure preparations hinge on demand forecasts, and therefore, Chapter 3 presents AV demand forecasts provided in the literature. Chapter 4 discusses insights into AV stakeholder perspectives on infrastructure readiness acquired from a questionnaire survey. Chapters 5-7 discuss AV considerations at the various phases of road infrastructure development – road planning, roadway design, and operations-maintenance-monitoring. Chapters 8 and 9 present and demonstrate a framework on how to address AV-related infrastructure investment evaluation considering uncertainty. Chapter 10 presents a framework on how agencies could carry out plan their AV-related infrastructure investment planning considering network traffic effects and demonstrates the framework using a case study involving electric vehicles. Chapter 11 concludes the report with a summary of the major findings, key policy recommendations, main contributions, and recommendations for future work. Also in this chapter, the report sets forth several policy guidelines that could guide road agencies that seek to further enhance their infrastructure preparation for AVs. Chapter 12 presents a synopsis of the USDOT performance indicators accomplished in this study, and Chapter 13 lists the outputs, outcomes, and impacts of the study.

CHAPTER 2 AV ISSUES AND CONCEPTS THAT INFLUENCE ROADWAY INFRASTRUCTURE READINESS

2.1 Introduction

This chapter explains the key issues and concepts related to AV capabilities and operations. Such a discussion is particularly relevant to AV infrastructure preparation because the elements of AV technology, technological readiness, and adoption scenarios are expected to influence the types and design of road infrastructure in the AV era. For example, car sizes might be smaller if they are fully capable of self-driving. Some features like mirrors may no longer be necessary, and bumpers would be less bulky (consistent with expectations of fewer collisions overall but higher proportion of accidents with minor damage) (Duvall et al., 2019). The chapter first presents the various levels of vehicle autonomy/automation as defined by the International Society of Automotive Engineers (SAE) (2014; revised in 2016) and the NHTSA (2016). This is followed by a discussion of the anticipated timeline of AV emergence on public roads and the various stages of AV deployment. Then the key stakeholders and their roles are discussed. A Stakeholder Participation Model (SPM) is presented to illustrate how inputs to and outputs from various stakeholders will influence IOO's planning of AV-related infrastructure investments.

2.2 Readiness of AV Technology

AV readiness has often been likened to that of consumer electronics, albeit with some differences. It is generally agreed that several years of testing and regulatory approval will be needed before AVs reach a point where they will attain a satisfactory level of Technology Readiness to operate safely and reliably in all conditions (McLeod, 2021). Unlike consumer electronics, motor vehicles have significantly longer service lives, are costly, and are highly regulated, and therefore, new vehicle technologies will likely require decades to gain sufficient market penetration (Litman, 2022). The author further asserts that any AV crash due to system failure (even though this is expected to be rare) will not only be potentially deadly if it occurs but also translate into longer times of development to ensure their reliability. This is precisely what has been observed after the several instances of AV crashes that have occurred in various parts of the country in the past few years. These events will influence the availability of higher-level AVs and are expected to affect their long-term affordability following prospective technological advancements in automation and sensing.

It seems clear that significant technological advance is necessary before AVs will be capable of operating not only at normal conditions but particularly at environments made complicated by the presence of other road users (particularly, the vulnerable kind), unexpected road surface conditions (including potholes and roadway debris), heavy fog, disabled vehicles, and work zones (Simonite 2016). As of 2021 AVs were considered to have reached a level of 6 on the 10-point Technology Readiness Level (TRL) scale (McLeod 2021). Technology readiness is a pertinent issue in AV demand estimation, for two reasons: (a) the TRL will be influenced by the demand for AVs, and (b) TRL will influence the demand for AVs.

2.3 Levels of Vehicle Automation

A complete statement of automated market penetration cannot be made without specifying the breakdown of such demand by the SAE level of automation (LOA). For example, a 90% market share of AV could consist of either: 80% of LOA levels 1-3 and 10% of levels 4-5; or, 10% of levels 1-3 and 80% of levels 4-5. The infrastructure preparations and policy will be different for these two situations even though they represent the same total level of automation. Therefore, this chapter begins with a review of the levels of automation, and a discussion of concepts that could influence customer demand for AVs at each level of automation.

A few years ago, SAE International (the erstwhile-named Society of Automotive Engineers), developed a set of guidelines to classify automated driving features, from Level 0 (no driving automation) to Level 5 (full automation). Figure 2.1 presents these levels vis-à-vis those established by the NHTSA. At Level 0, the human driver conducts all driving tasks, and the vehicle does not take over any aspect of driving. The vehicle may include driver assistance features such as blind-spot and lane-departure warnings. At Level 1, the vehicle can control one aspect of the driving task: either the steering or the speed, for example, cruise control and lane centering. At Level 2, the vehicle has both lateral and longitudinal control (the ADS controls both the steering and speed) but always requires full driver attention. At Level 3 (conditional driving automation), the driver does not drive the vehicle while the automated system is engaged, under certain conditions; however, the driver must be ready at any time to take over if the system comes disengaged. At Level 4, there is no need for a driver, and no need for a steering wheel and pedals in the vehicle. Level 4 vehicles are ODD specific: they operate only within a specific geofenced area, and the vehicle disengages and comes to a stop on its own if it encounters a problem. Level 5 is fully self-driving and does not require human involvement. Unlike Level 4, Level 5 is not ODD specific because it can operate autonomously at all locations and under all conditions.

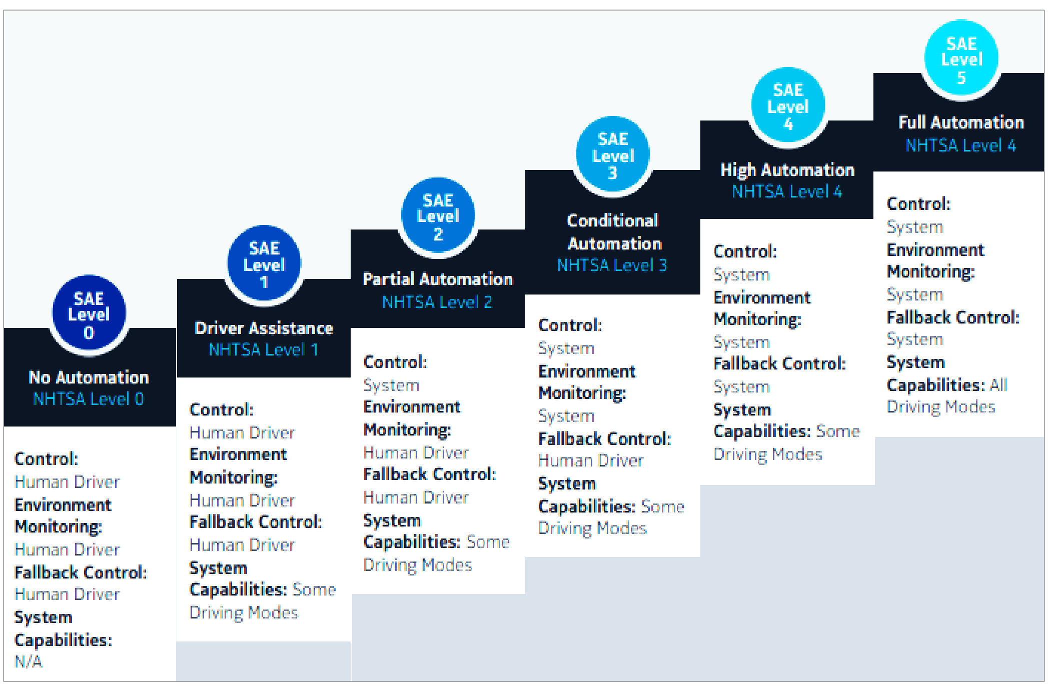


Figure 2.1 SAE vs. NHTSA classifications of automated driving systems

Subsequently, these guidelines were questioned for being vague and confusing, for example, the technology leap from Level 2 upward is not as linear as the guidelines suggest, and some vehicle manufacturers considered Level 2 to be too broad. As such, in 2021, SAE released updated descriptions of the levels of driving automation. The update added terms and substantial refinement and clarification of certain concepts (that had been misunderstood by users of the previous version) and restructured the definitions into more classes that are more logical. These include additional clarity on the differences between SAE Levels 3 and 4; new terms and definitions for remote driving and remote assistance; adopting the "Driver Support Systems" moniker for SAE Levels 1 and 2; classifications of sustained driving automation and definitions for vehicle types by groups; and clarifying and defining the concept of failure mitigation strategy (SAE 2021).

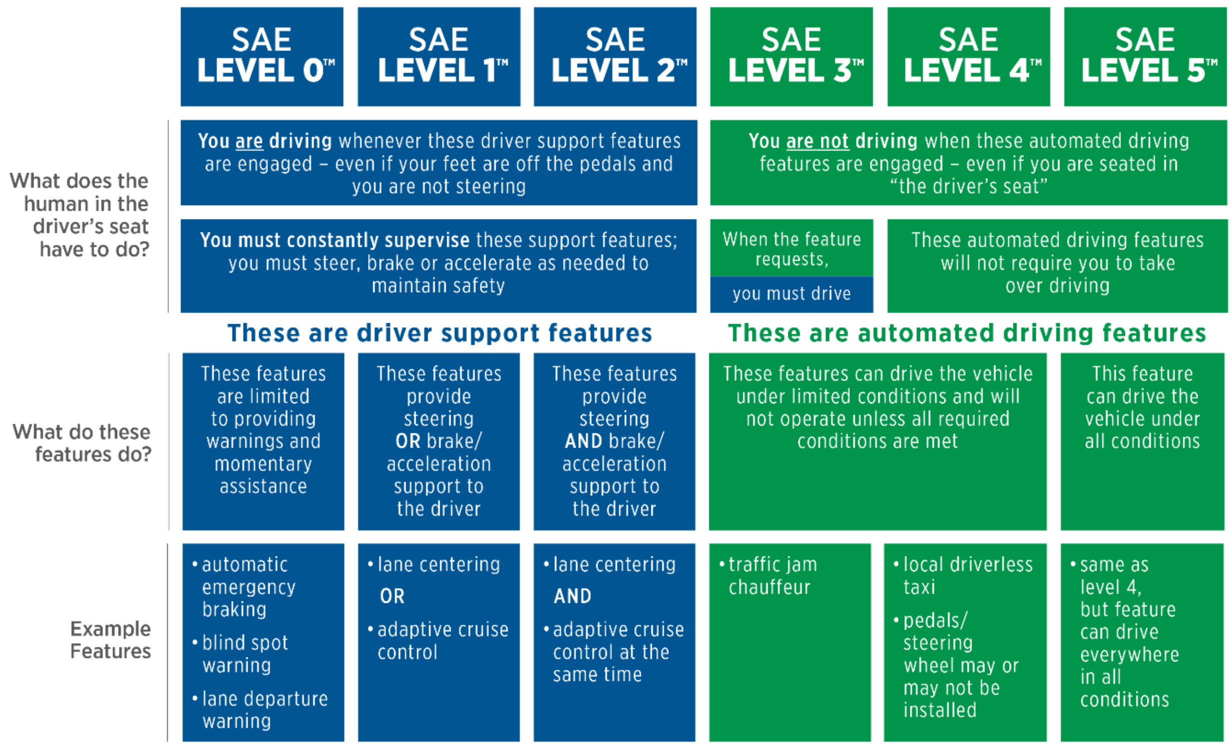


Figure 2.2 Descriptions of SAE J3016 Levels of Driving Automation
(Source: sae.org/blog/sae-j3016-update)

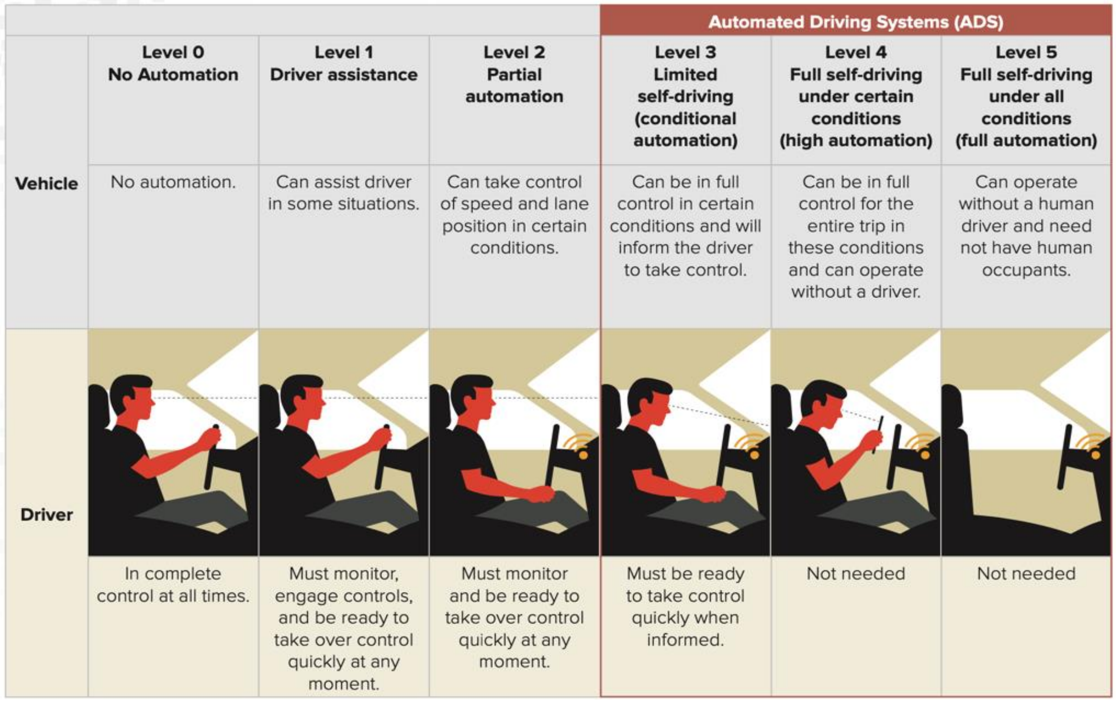


Figure 2.3 Other descriptions of the levels of automation (Source: GHSA (2018))

2.4 Features of Automation and Connectivity

AVs use sensor-based technology (camera, lidar, and radar) and AI-based image detection algorithms to develop and interpret in real-time, a 3-D characterization of the physical environment within which the vehicle operates (Figure 2.4). The cameras capture visual information, while lidar sensors use laser beams to measure distances and create detailed 3-D maps of the surroundings. Radar sensors detect objects and measure their speed and direction using radio waves. These sensors work together to provide a comprehensive view of the surrounding road and traffic environment in real time. Algorithms are then used to analyze the sensor data to identify objects, track their movements, and make informed decisions for safe navigation. As such, the combination of cameras, lidar, and radar enables the AVs to accurately detect obstacles, recognize traffic signs and signals, and respond to complex driving scenarios. This sensor-based technology is essential for the reliable and efficient operation of autonomous vehicles, ensuring an elevated level of perception and decision-making capabilities.

In addition, successful operations of AVs depend 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., 2014). 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., 2014; 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).

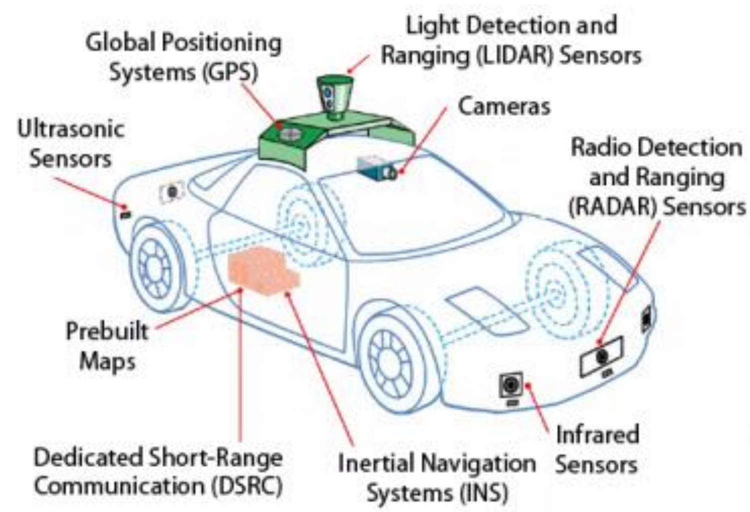


Figure 2.4 Basic hardware of a typical autonomous vehicle (Image source: Canis, 2019)

2.5 The AV Transition Period and its Phases

From the infrastructure perspective, conversations about AV demand and the transition of manual driving to autonomous driving in the traffic stream are important, because the timings of infrastructure retrofitting decision-making points will be defined by the road user needs. It is certain that fully autonomous operations will occur not spontaneously but rather incrementally over some extended period that is often referred to as the Transition Period (Figure 2.5). Several predictions have been made regarding the start year of AV deployment at public roads, their initial autonomy levels vis-à-vis the need for some driver control, and the effects of experimental or initial AV deployment into the traffic stream (AHAS, 2017). The transition process is expected to be incremental in terms of technology maturation, infrastructure modifications, and road user adoption. During this transition period, it is expected that key roadways will host a mix of vehicles, including traditional (operated by human drivers, i.e., Level 0 autonomy), automated (Level 1 to Level 3 autonomy), and fully autonomous or FAV (Levels 4 and 5 autonomy), until a time when all vehicles on the road are fully autonomous.

The period of HDV-FAV transition could be described as consisting of four phases:

- Phase I, low FAV-HDV ratio: up to 25% of vehicles in the traffic stream are FAV.
- Phase II, low-to-medium FAV-HDV ratio: 25-50% of vehicles in the stream are FAV.
- Phase III, mid-to-high FAV-HDV ratio, 50%-75% of vehicles in the traffic stream are FAV.
- Phase IV, high HDV-FAV ratio, 50%-75% of vehicles in the traffic stream are FAV.
- Fully autonomous phase (FAP) – 100% of vehicles in the traffic stream are FAVs.

Within these phases, there could exist sub-phases depending on the share of each level of autonomy. At the early years of the transition phase, the market penetrations of Levels 4-5 AVs will be low (as they are being tested for commercial use) and Levels 1-2 will be dominant in the traffic stream. With time, the market penetration of AVs will increase gradually to a point where AVs will dominate the traffic stream. This will be similar to the period in the early twentieth century when motor cars became dominant and horse carriages became obsolete and thus no longer considered in road design.

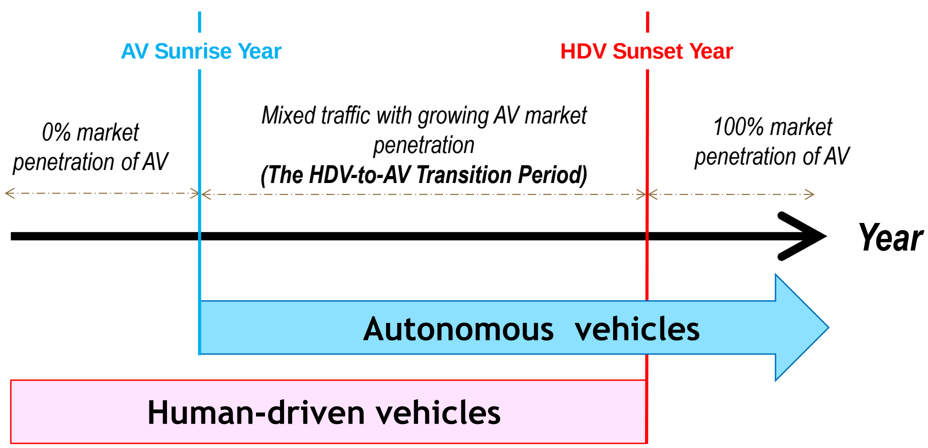


Figure 2.5 Timeline of HDV-only traffic, mixed traffic, and AV-only traffic (adapted from Labi, 2019)

There exist different untested hypotheses regarding the initiation and length of the transition period. An IHS Automotive (2014) study expects the entire global fleet to be fully autonomous by 2050. Litman (2014) suggests that human driving will be restricted after 2060 if AV benefits are realized. It has been reported that the CEO of an automotive industry giant, has suggested 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). It may very well be the case that as AV demand grows, governments might be compelled to make policies prohibiting HDVs from certain corridors or classes of highways. 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 2018 study 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 AVs – self-owned, hired, or shared use (Saeed et al., 2018).

The uncertainty in the expected length of the transition phase is governed by several factors. Many of these factors are related to an underlying cause – lack of trust in automation. The first factor is road user/driver attitudes. It seems obvious that there will be marked variability across market segments (demographic groups, personal vs. commercial interests, etc.) in their willingness to give up their traditional vehicles at the onset. This is discussed further in Section 2.6. The second factor is AV policy: some jurisdictions will be slow to provide supporting policies for AV operations and some may even pass policy to inhibit AV operations, both likely to be due to lack of trust in automation. For example, a few years ago, Krok (2016) reported that Chicago's City Council members considered an ordinance that would ban autonomous car development in Chicago's city limits, citing safety risk particularly to pedestrians. The third factor that could elongate the transition period is inadequate preparation to accommodate AVs: in some cases, IOOs might be unable to provide the infrastructure funding needed to support AVs due to already strained budgets. It will be important for public-sector IOOs to continue to cultivate skills of communicating to legislatures to open the purse strings to support AV-related infrastructure development. The fourth factor represents the outcomes of experimental AV deployments at public roads (AHAS, 2017) and the press and media coverage in the event of any AV crashes. AV successes seem to receive far less press reporting compared to AV mishaps.

As more AVs get deployed gradually, the number of crashes (not crash rates) are also expected to increase. Every adverse AV incident may receive extensive coverage, thereby: exacerbating the fears of an already skeptical public, increasing the reluctance of potential customers to patronize AVs, and leaving policymakers even more cautious to pass AV-supporting policy. In addition, any crash involving an HDV and AV will likely be blamed on the AV as it is the newcomer to the traffic stream, and the public mood might be governed by the maxim "it was not as bad until you came along." These situations may further lengthen the AV transition phase. As the safety and mobility benefits of AV become obvious, skepticism towards AVs will likely reduce, and may lead to reduced length of the transition phase, with the introduction of AVs in the traffic stream, there might be a jumping the crash rate as both vehicle types "learn" how to adjust to each other. After such a period of learning and thus, more cognizant and accommodative during actions by both parties, the crash rate will likely decrease (Figure 2.6).

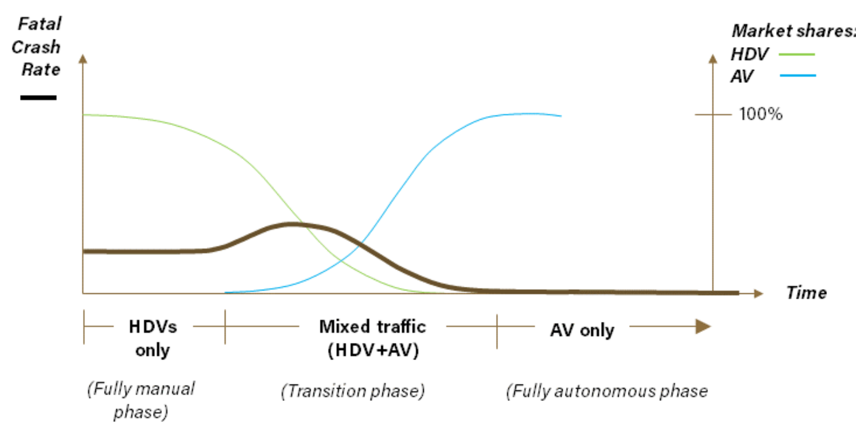


Figure 2.6 Hypothetical AV Safety Bump (TIRG, 2023)

Notwithstanding the effects of these factors, it is generally agreed that the transition to a era of full autonomy will be gradual and evolutionary and will be punctuated with hiccups from technological, policy or consumer attitudes perspectives. Then, from an IOO perspective, the nature of AV market penetration trends will continue to be a key issue because it will drive the demand for AV-supporting infrastructure, and consequently, the expected impact of the required pace of AV-related road infrastructure investments. 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 3 autonomy), autonomous (Level 4 and 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 public sector IOOs, the retrofitting of roadway infrastructure can be expected to be incremental and stepwise. Infrastructure retrofitting will be both proactive and responsive because it will be both a cause and an effect of AV demand.

2.6 Discussion on the Influence of Road User Attitudes on the Transition Period Duration

User attitudes represent a critical factor of the length of the AV transition period. As explained earlier in this chapter, favorable user attitudes will drive up AV demand, which will in turn spur IOOs to provide the supporting infrastructure and motivate governments (at all levels) to pass favorable policy. As prospective AV users increasingly comprehend the wide range of capabilities that this technology offers for making transportation safer, more efficient, more accessible, and more responsive to mobility needs (Abraham et al., 2017), they will become more receptive to this emerging technology. Public perceptions are expected to change over time as road users become more aware of the technology, its potential, emergence patterns, and expected implementation scenarios and, more importantly, as their personal experience of AV operations in experimental public use. User perceptions are likely to be negative when AV crashes during test deployment become highly publicized. Overall, user perceptions will become stable with wider cognizance of the impacts (both positive and negative) that AV technology might have based on travelers' personal experiences. User trust is expected to increase over time as users witness increasing volumes of AV operations on roadways (The Economist, 2018) and as they continue to have positive personal experiences (Figure 2.7).

Figure 2.7 As travelers continue to have positive personal experiences in autonomous vehicles, user trust in AVs is expected to increase *(Source: Matt York, AP Photo)*

2.7 Technology Development and Adoption Scenarios

Currently, AV technology is undergoing testing at several laboratories, test tracks, and pilot corridors or cities worldwide, and this is being done under different operational design domains and roadway environments. Keeney (2018) noted that Waymo, Tesla, and Cruise are operating fleets of test AVs. AV technology acceptance and adoption will require continual evolution in several areas (Forni, 2017) including (a) accurate sensing for enabling vehicles to perceive their roadway and traffic environments; (b) high-definition internal vehicle maps to pinpoint exact vehicle location in the roadway;, (c) 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. Expectations of the scale and types of AV-supporting infrastructure requirements can be expected to vary as AV technology evolves.

Some AV advocates have predicted that by 2030, AVs will be sufficiently reliable and affordable 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 due to the realities and limitations of the current technology. Some pundits have argued that most of the optimistic predictions of AV market penetration are made (a) by those that seem to have commercial interests in the AV industry, and (b) based on experience with earlier technological innovation including smartphones, cameras, and the Internet (NetworkNewsWire, 2018). In most cases, such analysis is overly sanguine and could have benefitted from realistic assumptions regarding costs and reliability. Several complex technical issues must be resolved before AVs can be operated in all conditions. For example, AVs must undergo significant testing before they are approved for public use, and AVs must be affordable and attractive to consumers.

At the current time, most existing vehicles have Level 1 and 2 technologies at a maximum – hazard warning, cruise control, and automated parallel parking. The “Autopilot” developed by Tesla has automated steering and acceleration features that can be deployed under restricted circumstances; however, its deployment was delayed after a Tesla car got engaged in a fatal crash in 2016 (Hawkins, 2017). Some companies are conducting Level 4 pilot projects; and in the 2022-2023 period, Uber and other AV manufacturers announced partnerships to commence autonomous taxi service operations in a number of US cities (Korn, 2022; Capoot and Piazza, 2023). Notwithstanding this advancement, substantial technical developments are needed before AVs are capable of driving under all operational design domains (Simonite, 2016) including snow, heavy rain, unpaved roads, and heterogenous traffic. In some cases, the environment could have unpredicted obstacles including stray animals, potholes, errant vehicles and cyclists, and inattentive pedestrians. In such cases, AV operation on public roads could become even more challenging (Mervis, 2017) and the AV would need even more complex sending and detection technology to be recognize these threats.

The proponents of AV technology acknowledge the need for substantial technical advancement before Levels 4-5 vehicles are evaluated, approved, and declared dependable (Mervis, 2017). It has been noted that the Michigan Mobility Transformation Center director anticipates that it will be decades before the technology is dependable enough to allow the vehicle to drive on its own safely on any road at any speed and in any weather (Truett, 2016). Similarly, researchers at the Toyota Research Institute believe 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 a few years ago that self-driving vehicle technology that is safe and dependable enough to operate in all operating domains is not expected to be available in the next few years (Marowits, 2017).

In addition, it has been reported that AI experts perceive 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) went further, opining that AV technology development (as a replication of the human driver without replicating human error propensity) is far in the future.

2.8 Key Stakeholders and their Roles

It is expected that the successful development and deployment of AVs will be driven by decisions and actions of four key stakeholders (Figure 2.8):

- 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),
- Government legislatures and the executive branch (at various levels of government) responsible for regulations and policy formulation,
- Road agencies and private-sector IOOs are responsible for infrastructure development.

The roles of all these (and other) stakeholders are complementary in nature; in other words, their individual efforts are expected to complement one another and therefore form a tapestry towards the realization of AV operations. The rest of this section discusses a specific stakeholder – road users – because of their critical role in infrastructure preparedness.

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. To address these concerns, investigating user acceptance of this technology at every phase of its development and deployment is critical for at least three reasons:

- to ascertain the extent to which users will embrace this technology, thereby reliably measuring the AV demand.
- to inform agencies to make user-responsive decisions regarding AV investments and policies.
- to advise technology developers on AV design.

Road user perspectives (and ultimately, consumer demand) will drive the scale of AV market growth and vice versa. The anticipated societal benefits may not be attained unless a critical mass of consumers adopt this technology. Government legislatures will likely mandate (or prohibit) the use of AVs in certain areas, which could generally accelerate (or diminish) AV market penetration. However, the timing of AV deployment and the state of AV technology are still uncertain. Moreover, any measures from government agencies, such as promoting the use of AV-related ride-hailing or ridesharing services or restricting the use of private AVs or even prohibiting them from certain areas, could be unpopular (The Economist, 2018). For this reason, it is important to ensure road users involvement in AV infrastructure preparations.

In a national dialogue on highway automation held by 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 direction. 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: 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 life cycles 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-related 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.

There exists significant endogeneity and simultaneity of the roles of key stakeholders (the IOOs, the government, the road users, and the OEMs) as shown in Figure 2.8. The rate of change of road infrastructure will depend on the rate of maturation of AV technology and rate of user acceptance of AV technology. Also, the rate of maturation of AV technology will depend on the rate of change of road infrastructure and rate of user acceptance of AV technology. Further, the rate of user acceptance of AV technology will depend on the rate of change of road infrastructure and rate of maturation of AV technology. The symbol *t* refers to a given time period; *k* is the time lag and may be different for each equation and/or each variable. A simultaneous equation could be specified as follows:

$$RI_t = f_1(UA_{t-k}, MA_{t-k}, SP_{t-k})$$
$$UA_t = f_2(RI_{t-k}, MA_{t-k}, SP_{t-k})$$
$$MA_t = f_3(RI_{t-k}, UA_{t-k}, SP_{t-k})$$
$$SP_t = f_4(RI_{t-k}, UA_{t-k}, MA_{t-k})$$

Where:

RI_t = level of road infrastructure; *MA* = level of AV technology maturation

UA = level of AV user acceptance or demand; *SP* = level of AV-supporting policy

All 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 AV deployment.

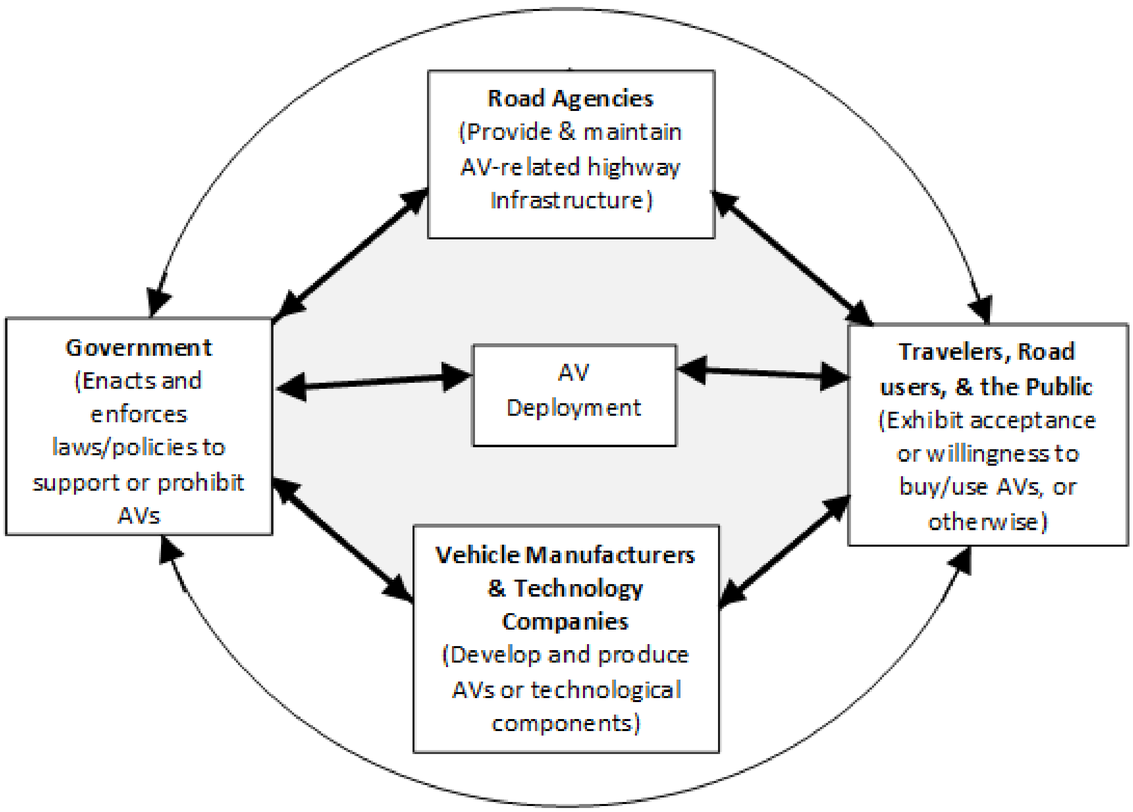


Figure 2.8 The stakeholder quad

2.9 The Stakeholder Participation Model (SPM)

The complementary roles of key stakeholders in AV deployment are described in the previous section. However, the nature of the required changes to road infrastructure to support AV operations, is still in question. The Stakeholder Participation Model (SPM) (Saeed, 2019) 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 involves acquiring input from key stakeholders (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.

The OEMs lead the technology development efforts. However, AV demand is dictated by the preferences of the road users. From the IOO perspective, road user demand is what drives their decisions regarding the expansion or development of new or existing infrastructure systems. Therefore, IOOs routinely conduct estimates of travel demand for various purposes including infrastructures in response to trends in the socio-economic and technological environment. Currently, the best available tool to gauge user demand for AVs is a survey questionnaire. For example, if a city agency seeks knowledge of 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 carried out 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 questionnaire surveys 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 AV transition period, IOOs will seek to develop and maintain roadways that are compatible with both types of road users. As such, non-AV users could be surveyed about their comfort level in sharing the road space with AVs. Their perspectives could be collated for subsequent consideration in IOO decisions regarding AV-related road infrastructure decisions(for example, whether to separate AVs from other vehicles through AV-exclusive lanes and whether to protect the AV exclusive lane using barriers).

Furthermore, information collected through survey tools could be leveraged to investigate the user acceptance and potential effectiveness of various alternative infrastructure retrofitting strategies under consideration by IOO. For example, surveys could be used to 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 survey question could be: "During the initial deployment of autonomous vehicles at freeways, which of the following roadway design changes would elevate your trust and comfort level regarding an AV-inclusive highway operating environment". Responses could include (a) a dedicated lane for AVs; (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 appear on the road in significant numbers and prospective survey respondents have personal experience with the technology, public preferences cannot be captured with certainty. Consequently, any such surveys should be conducted periodically to feel the prevailing market pulse. Conversely, 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 impede AV market penetration. Furthermore, this entire process of transitioning to a new era of infrastructure needs to be regulated through favorable regulations and policies issued by government institutions.

2.10 ODD and its Relationship with Infrastructure

Operational Design Domain (ODD) can be defined as the operating conditions under which a given driving automation system (or its feature) is specifically designed to function (British Standards Institution, 2020). For example, the Level 3 conditional automated traffic jam drive feature works on freeways and at speeds less than 38 mph (Gopalkrishnan et al., 2015). ODD includes the road class, speed, and specific traffic and weather conditions. Coupled with the SAE level of automation, the ODD provides a basis upon which AV development and deployment can be planned. ODDs are particularly critical for SAE Levels above 3 because these vehicles have an autonomous-only driving mode. García et al. (2020) hinted that the number of AV-to-human takeover requests (TOR) could serve as a useful indicator of the adequacy of the road infrastructure in the future era of AV operations.

It has been acknowledged that ODD is inherently dynamic because it is based on elements that change with time, for example, the weather, time of day, and traffic conditions. For example, some AV lane-keeping systems depend on pavement marking detection, but the detectability of pavement markings could be impaired by aging, tire-induced abrasion, ice cover. Also, the type of marking and the sun's position could enhance/degrade the ADS's marking detection capabilities.

Gopalkrishnan et al. (2015) stated that for some ADAS and ADS features, the relative performance of roadway infrastructure may influence how an ADS developer defines an ODD. The researchers emphasized the strong link between automated driving features and roadway infrastructure, and offered the following suggestions for ADS developers:

- Consider how the infrastructure elements of an ODD support the technologies that provide ADAS and ADS features.
- Examine what is needed from an ODD's infrastructure elements to make ADAS and ADS more dependable within the intended ODD.
- Consider the infrastructure elements that could be addressed to improve the performance of ADAS and ADS features.
- Help identify the roles that infrastructure could serve in preparing/expanding an ODD from transitioning from HDVs to AVs.

The researchers noted that as the transition from human-driven to ADS takes shape, additional infrastructure areas may be affected. Therefore, there is a need to promote coordination of IOOs and ADS developers to better understand how ADS performance may impact the total transportation system, including infrastructure.

Given the multi-faceted and time-varying nature of the ODD-infrastructure relationship, it seems clear that it can be rather difficult to define an ODD. Thorn et al. (2018) presented an ODD framework (Figure 2.9) which recommends and categorizes the elements worthy of consideration in establishing an ODD.

There also exists the issue of standardization. Researchers have argued that in practice, there exist serious limitations in ODD applications due to inadequate standardization. There is no universal specification of all combinations of the possible factors, conditions, and thresholds for which an AV should be able to operate autonomously. In addition, irrespective of how well an ODD is defined, each individual vehicle presents a different ODD (Gopalkrishnan et al. 2015), and this is a key challenge from the viewpoint of road infrastructure preparations. The time-varying nature of ODD elements exacerbates the problems of inadequate standardization and the complexity of the ODD-infrastructure relationship and highlights the importance of roadway design and management to successful AV operations.

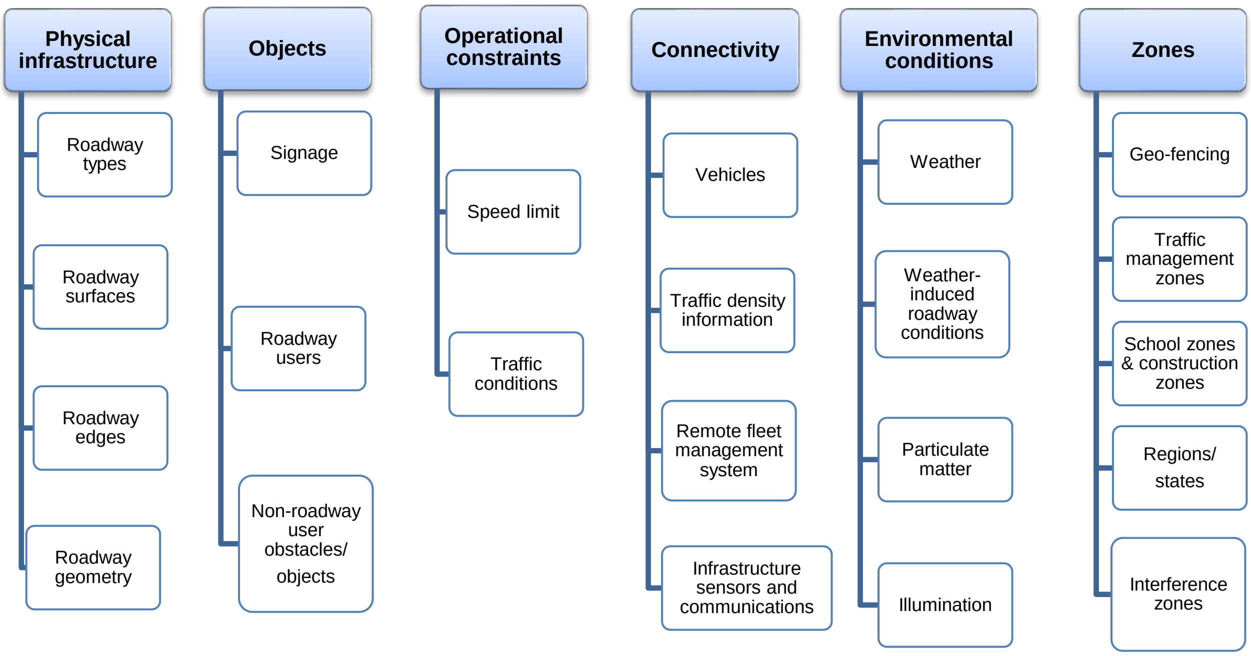


Figure 2.9 Conceptual ODD elements (adapted from Thorn et al. 2018)

In addition, Gopalkrishnan et al. (2015) exhorted the OEMs to work with IOOs to resolve these issues. Garcia et al. (2022) noted that OEMs typically design their automated systems unilaterally without explicit awareness of the adequacy of the physical infrastructure and the requisite infrastructure improvements to enhance the ODD robustness, and cautioned that in this regard, IOOs cannot afford to be either “subservient” or “oblivious” to OEMs. The authors proposed a novel Operational Road Section (ORS) concept – a road section where all automated systems can operate safely, considering the existing physical and cyber infrastructure. The IOO could install road signs and cell phone alerts for the benefit of the AV as it enters or exits the ORS and encourage the AV driver to activate their automated systems or to disable/supervise them with greater attention, with due recognition of the temporary limitation posed to automation by certain conditions in the roadway environment.

In other related research, Reddy et al. (2020 developed operational design domain requirements for improved performance of lane assistance systems: a field test study in The Netherlands. Taxonomy-related issues related to ODDs have received some attention. For example, Chen et al. (2023) proposed a modified taxonomy for autonomous vehicles considering ambient road infrastructure, and Mendiboure et al. (2023) discussed the taxonomy, definitions, and applications of ODD for automated driving systems. In the United Kingdom, the Center for Connected and Autonomous Vehicles (2020) presented specifications for Operational Design Domain (ODD) taxonomy for an automated driving system (ADS) that shed much light on the relationships between ODD and autonomous driving.

2.11 Some Initiatives at Various State in the US

Table 2.1 presents a few AV-related initiatives programs, policies, and other executive and legislative actions, and infrastructure-related reports at a sample of US states. These initiatives include legislation, executive actions, and reports from sponsored research studies. Also, CAVita (2017) presented the outcomes of a state DOT CEO Leadership Forum on Connected & Autonomous Vehicles and Transportation Infrastructure Readiness in conjunction with the 2017 ITS world congress in Montreal, Canada. These outcomes are generally consistent with the concerns of state DOTs regarding the provision of infrastructure for the era of AVs.

Table 2.1 AV-related initiatives at a sample of US states

State	Examples of DOT initiatives (programs, policies, and other executive and legislative actions, and sponsorship of AV infrastructure-related studies)	Source(s)
Arizona	Is the state currently with the most testing and commercial deployment. 2022. SB 1333 passes. This is regarding a new low speed "Neighborhood Occupantless Electric Vehicle (NOEV)". 2021. HB 2813 passes. This codifies most of Executive Order 2018-04 into state law. 2019. HB 2132 passes. This allows "personal mobile cargo carrying device" operations 2018. HB 2422 passes allowing for "personal delivery devices" to operate in Arizona. 2018. Executive Order issued. Reflected advancements in technology and testing. 2017. HB 2159 passes. Allowed truck platooning technology demos on AZ highways. 2015. Executive Order issued. Outlined CAV technology development/testing process.	Arizona DOT (2023)
California	2018. Approved driverless testing regulations. 2018. Published revised regulations on driverless testing and deployment of AVs. 2017. Published proposed regulations to establish a path for the testing and deployment of fully autonomous vehicles. 2016. Released revised draft deployment regulations and held a public workshop. 2015. Released the draft deployment regulations for review.	The State of California (2023)
Connecticut	2021. Released document "Preparing for Connected & Automated Vehicles Strategic Plan"	Connecticut DOT (2021)
Delaware	2017. Report published: "Autonomous vehicles in Delaware: Analyzing the impact and readiness for the first state"	Barnes (2017)
Iowa	2017. "Automated Vehicle Technologies Project, Vision Document Final"	Iowa DOT (2017)
Maryland	2021. "2021-2025 MDOT SHA Connected and Automated Vehicle Implementation Plan"	Maryland DOT (2021)
North Carolina	2016. "NC Readiness for Connected and Autonomous Vehicles (CAV) Final Report"	Kimley Horn (2016)
Texas	2017. "An Assessment of Autonomous Vehicles: Traffic Impacts and Infrastructure Needs—Final Report"	Kockelman et al., 2017

CHAPTER 3 AV DEMAND FORECASTS

3.1 Introduction

Any research on AV infrastructure preparations must necessarily consider existing AV demand and its future projections. The previous chapter, addressing the key concepts, stakeholders, and phenomena related to AV operations, set the stage for the present chapter which discusses AV demand in the context of market penetration. The current chapter presents forecasts of AV market penetration not only for all levels of autonomy combined but also for each level of autonomy, and the factors that influence AV market penetration. The research mechanisms used include a questionnaire survey of the relevant stakeholders, desk interviews of experts, and a review of existing literature.

3.2 Market Penetration (MP)

As discussed in the previous chapter, demand (AV market penetration in this case) is the most critical decision factor that governs IOO decisions regarding AV-related infrastructure investment. These investment decisions are related to the renewal, retrofitting, rightsizing, expansion, or upgrading of infrastructural elements. The IOOs are responsible for the upkeep of highway infrastructure and traditionally develop time-based or performance-based schedules to facilitate their decisions (see Lamptey et al., 2008). The development of these schedules assume that an asset-related parameter of volatility will exhibit a peculiar pattern (increasing, decreasing, or otherwise) based on observed historical trends or in certain cases, expert opinion.

There exist no documented historical trends for AV market penetration, due to the novelty of the technology. Therefore, the uncertainty surrounding AV demand is expected to be particularly pronounced during the early phase transition period. The early 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 period, user acceptance of this technology (and hence, the demand) is expected to be highly susceptible to fluctuation partly due to any widely publicized crash events involving test AVs. To capture any such fluctuation in the demand, it is important to conduct periodic surveys to gauge user perceptions and hence, AV potential demand and market penetration. 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 experiences are positive.

For IOOs to make more informed investment decisions related to AV-related 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 worthy consideration. The market penetration rates will vary across states, regions, or countries.

Table 3.1 summarizes the forecasts for AV market penetration rates developed by past studies based on consumer surveys. Some glowing forecasts reported by earlier studies have been proven to be not very reliable. This may be because they were based on speculation and probably erroneous implicit postulates regarding AV technology, timing evolution, and maturation. Litman (2018) cautioned that independent testing and regulatory approval will require additional time even after Level 5 vehicles are fully dependable and functional. In contrast to other technological innovations, AVs are expected to require higher regulation and testing standards due to their potential risk of imposing substantial external costs in terms of road crashes and delay 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 inherently unsafe and unreliable (i.e., if they incessantly lead to high-profile crashes), several more years of technology development and testing will be needed (Bhuiyan, 2017). It is also important to note that different jurisdictions may implement different testing protocols, approvals, and regulations, (as is the case with other governance issues) and this will cause different 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, purchasing a vehicle is a significant investment for the average person, and not all travelers can afford to do this. As such, AV technology may take decades to penetrate travel markets (Litman, 2018). Some AV advocates believe that some consumers including shared-ride fleet companies may be willing to prematurely scrap their traditional vehicles given the magnitude and nature (prospectively) of AV benefits. It is hoped that such decisions will be based on realistic estimates and assumptions of the costs and benefits.

In the recent past, surveys have been used heavily to develop fairly reliable AV market penetration forecasts (Gkartzonikas and Gkritza, 2019; Iacobucci et al., 2023; Bala et al., 2023; Othman, 2021). 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, due to the rapid evolution of AV technology. Furthermore, these forecasts may be area-specific and time-specific and thus cannot be generalized for all geographical locations. 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 ODDs operational design domains (Grush, 2017). However, as Wharton (2017) noted, it is difficult to attain a high target of operability.

Most importantly, it is critical to duly acknowledge and account for the volatility of market penetration and then make flexible infrastructure investment decisions that are responsive to the evolving trends in market penetration. 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 trend, and this is suggestive of the existence of significant volatility in AV market penetration.

Table 3.1 AV market penetration forecasts (made in 2014-2018)

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. Approx. 1 million AVs are likely to be sold in 2025 as self-owned cars and shared fleets. AV sales are likely to surpass 33 million annually in 2040, corresponding to over 26% 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 assume 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 (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); Goldman Sachs-Cars Forecasts	100% of the North American, European, and Japanese vehicle fleet to have Level 4 autonomy by 2050. Level 3 and Level 4 vehicles to be officially launched first in 2025
Harrop & 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)	100% of U.S. light-duty vehicles will be Level 3 and 4 vehicles by 2030 and 2055, respectively

3.3 Statistical Modeling of AV Adoption Potential

3.3.1 Prelude

With the advent of AVs, it can be expected that new mobility services and modes will emerge. For example, private ownership of vehicles may become increasingly obsolete as society approaches the era of full autonomy. However, during the time when both HDVs and AVs share the road, AVs must be considered in the context of a wider transportation system with competing alternatives, and it is important to consider the impact of travel attributes including safety, comfort, reliability, convenience, privacy, and security (Barff et al., 1982) on mobility choice decisions. AVs will potentially free people from persistent urban transport ills of congestion, parking, the driving task, and vehicle ownership but this may come at the expense of flexibility associated with personal vehicles. AVs, particularly where they are shared, generate concerns about the ease of personal movement, privacy, and exposure to transmittable diseases (Gkritza and Chahine, 2023). As such, it is hard to envision future mobility trends with much accuracy due to many known and unknown uncertainties. It is important to explore public acceptance of the AV modes in relation to the conventional mode during the AV transition phase. In this study, the user concerns and travel preferences are studied through an experiment that involved a questionnaire survey of prospective AV users.

The existing literature contains evidence of growing interest in understanding consumer preferences and opinions related to AV adoption in the context of general interest and attitudes (Iacobucci et al., 2023; Bala et al., 2023; Nair et al., 2018; Saeed, 2018; Soteropoulos et al., 2018; Gkartzonikas and Gkritza, 2019). Some researchers have investigated AV adoption based on vehicle ownership and diffusion models (Lavasani et al., 2016; Daziano et al., 2017; Talebian and Mishra, 2018). Others 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). Some researchers, however, have expressed concerns about responses to open-ended questions, in the context of willingness to pay (Arrow et al., 1993) and it has been stated that choice experiments and consumer attitudes and preferences without explicit willingness to pay may be considered more suitable (Nair et al., 2018). For example, a fairly 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).

Past studies threw much light on the issue of AV demand from a diagnostic perspective. However, opportunities exist to address the issue from a few more additional perspectives, including: (a) expansion of the target population or geographical coverage to extend beyond localized areas or small regions, (b) inclusion of HDV as an option, (c) use of outcomes other than a Likert scale (e.g., Nair et al., 2018 and Nazari et al., 2018), (d) exploration of consumer preferences regarding an expanded list of the forms of the built environment (city center, urban, suburban, and rural), (e) going beyond basic descriptive statistics to conduct in-depth econometric analysis to earn more insights, (f) expanded and representative sample sizes.

To address these gaps in the literature, this part of the study 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, the experiment 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 set of travel-choice alternatives was deliberately kept small to avoid complexity of the questionnaire and prevent respondent fatigue. This study did not include modes related to public transport and AV-transit integration in the choices – this is suggested for future research.

There exists a common 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; 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 such hypothesis. As such this study assessed the hypothesis using empirical data from the questionnaire survey. The survey instrument is published in Saeed (2019).

The results of the experiment pertain to SMMAs but could be extrapolated to the wider population of prospective AV users in the country. In this report, important insights are provided regarding the consumers' potential adoption and usage of these modes, which could be indicative of future mobility trends during the transition period. The experiment culminated in the development of a random-parameters logit model that helped throw light on 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 the built-environment features.

3.3.2 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 responses. 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 was also excluded from the analysis.

Prior to its dissemination, the survey 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. The university respondents were at two different academic levels: undergraduate and graduate. The pilot survey was conducted 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 both academic levels. The number of questions was kept low (37) but enough to study the key phenomena. There was a concern that a lengthy survey would affect the quality of the responses. The questionnaire was checked for comprehensibility and revised accordingly. 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 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. They 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 report, 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 based upon the dwelling density as: city center, urban, suburban, and rural.

Table 3.2 presents a summary of the responses used to create a large set of explanatory variables investigated in the study. The data presented here were used to create many new derived variables, interaction terms, and indicators. The survey sample included responses from 43% male and 57% female respondents. Regarding 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 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 higher awareness about AVs could be attributed to the fact that the media discuss this technology more often compared to CVs.

Table 3.2 Summary of road user responses

Questions	Responses	Percent
Respondents	Drivers	91
	Passengers	9
Distance to work/school	≤ 1 mile	4
	≤ 5 miles	30
	≤ 10 miles	54
	≤ 15 miles	68
	≤ 20 miles	77
	≤ 25 miles	83
	≤ 50 miles	94
	≥ 50 miles	
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
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
Household size including respondent	1 person	24
	2 persons	42

	3 persons	16
	4 persons	13
	> 4 persons	5
Nr. of household members of age < 16 yrs	0 person	77
	1 person	12
	2 persons	> 3
	3 persons	2
Highest education level	Less than high school	1
	High school (includes equivalency)	17
	Some college	32
	Bachelor's degree	30
	Professional school degree	3
	Master's degree	15
	Doctorate degree	3
Annual income of 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

3.3.3 Descriptive Statistics – Assessing AV Demand Potential using User Survey

Table 3.3 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:

i. continue using a self-owned traditional vehicle,
ii. using a self-owned AV,
iii. using a hired AV service (like Zipcar or Car2Go), and
iv. 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 3.1, there is 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. Such 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 (more certain and dependable).

Table 3.3 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 > 2.5 miles, 0 otherwise)	0.892	0.310
Awareness factors		
Autonomous vehicle awareness indicator (1 if respondent has heard about AV, 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

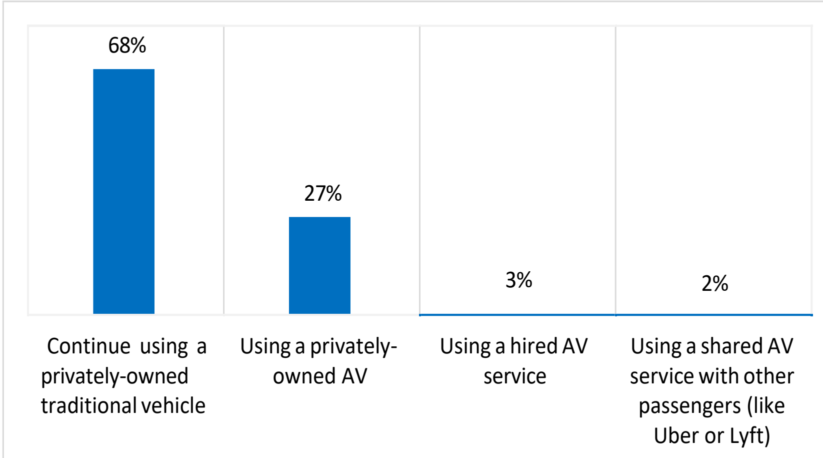


Figure 3.1 Consumers' prospective mobility preferences (from the 2018 survey)

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 3.4 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. Technology is still evolving; road infrastructure is still not ready to host this technology, and few steps have been taken towards the development of regulations and policy formulation. This is due to the evolutionary nature of technological advancement and the uncertainty associated with consumer acceptance or demand (Federal Highway Administration, 2018).

Car sharing using AVs has often been 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 among 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 consumer perspectives.

Table 3.4 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 (e.g., Uber, Lyft)	5%	1%	2%	1%

3.3.4 Model Specification

Due to the non-ordinal discrete nature of the response variable (that is, travel mode choice), 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., 2020). Using the framework discussed in McFadden and Train (2000) and Train (2003):

$$Z_{mn} = \beta_m X_{mn} + \varepsilon_{mn} \quad (3.1)$$

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., 2020):

$$P_n(m \mid \varphi) = \int_X \frac{EXP[\beta_m X_{mn}]}{\sum_m EXP[\beta_m X_{Mn}]} f(\beta \mid \varphi) d\beta \quad (3.2)$$

$Pn(m|\varphi)$ 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. A continuous form of the density function, $f(\beta|\varphi)$ is used herein. Several functional forms (log-normal, uniform, and exponential) were investigated, and the normal distribution was identified as the best functional form based on statistical fit and statistical significance, and engineering interpretability. φ is a vector of parameters, which 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 responses. The marginal effect of a predictor variable gives the effect that a one-unit increase in that variable has on the response. For the indicator variables, the marginal effects show the effect of a predictor moving from zero to one (Washington et al., 2020). Each respondent had an individual marginal effect; the marginal effects averaged over all respondents is presented in this report.

3.3.5 Model Estimation Results—Interpretation of the Variable Signs

Table 3.5 presents the results of the random-parameter logit model that was estimated to explore the respondents' mobility preferences. These include the parameter estimates and z-statistics. The random parameters model accounts for unobserved heterogeneity in the data and the possibility of variation of the parameter estimates across the observations (in this case, the survey respondents). All the random parameters identified in the final model were found to follow a normal distribution. Other distributions (lognormal, uniform, exponential and Weibull) were also evaluated for significance but were found to be statistically inferior compared to the normal distribution. The average marginal effects are presented in Table 3.6 and illustrated in Figure 3.2.

The variable representing the joy associated with driving a vehicle using manual control was found to be normally distributed with a significant random parameter: 67% of the respondents who enjoy driving were more likely to continue using a privately-owned HDV 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 that enjoy driving are more likely to prefer their regular vehicle for travel; however, our study identified a heterogeneous effect of this variable 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 results for the variable representing age suggests that the respondents aged over 55 years were highly likely to choose the continued use of a privately-owned HDV (as evidenced by a 0.0438 higher probability compared to others (see the average marginal effect in Table 3.6)). This result could be attributed to the fact that people in this age group are less savvy in technology or less flexible in adapting to modern technology, reluctance, or inability to learn new things, and thus, lower propensity to accept new technologies. On the other hand, older individuals (who are no longer able to drive) may welcome AV technology that could help them regain their personal mobility.

The results for the variable representing gender indicate that females are more likely to continue using HDVs during the transition phase (with a 0.0369 higher probability as indicated by the marginal effect value in Table 3.6 and Figure 3.2). The female respondents indicated low preference towards using AV-related modes. This observation could be attributed to the uncertain state of AV technology, lack of individual consumer experience with this technology, and inadequate user trust in automation, against the background of the fact that females generally have higher risk aversion compared to males (Filippin, 2022; Sundheim, 2013; Charness and Gneezy, 2012). The observation in our study is consistent with findings of past AV-related studies which reported that men are more likely to adopt AVs 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 are more likely to accept to use or buy AVs compared to women (Payre et al., 2014; Weigl et al., 2022).

The study results also suggest that more educated respondents indicated a proclivity towards automation. Respondents whose highest education level is a bachelor's degree or higher were found to be less likely to continue using a privately-owned HDV. This finding could be because these respondents are more aware of the potential benefits of AV technology compared to other less educated respondents. As noted by Agrawal and Prasad (1999), individuals at higher levels of educational attainment are more receptive and broad-minded about technical innovations. Another study found a higher preference for private HDVs over automated modes among people without a high school degree (Pakusch et al., 2018). These results are in accord with those of Haboucha et al. (2017) who found that female, older, and less educated individuals were more likely to continue using their existing vehicles (HDVs) compared to automated modes.

The model results also show that the variable representing AV familiarity has a positive association with AV use. This positive sign of this variable coefficient 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 3.6 and Figure 3.4). This result is intuitive: respondents that are more aware of the envisioned benefits of AVs are more likely to use a self-owned AV. Regarding the household size variable, the model results suggest that 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 rely on other modes that are less flexible, families could find that a privately-owned AV might be a more efficient and less costly option. This could be particularly true for large households if the vehicle is used as a shared vehicle by the household members for commuting, shopping, religious, grocery or other trips of shared or overlapping interests. They would not have to deal with concerns regarding 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 (HDVs) in a mixed-stream traffic environment for a longer distance every day or to use a shared AV service with strangers for longer periods.

The variable representing car-sharing service familiarity 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 have a good understanding of how car-sharing works and are 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 would offer flexibility and independence to all the household members traveling around freely without having to rely on each other. A past study found that individuals whose households had more than one child are more likely to use SAVs (Haboucha et al., 2017). There seems to exist consistency in the results regarding the preference of using a shared AV service with higher numbers of noticeably young household members. However, Haboucha et al (2017) study lacked 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 model results suggest that younger respondents (between 18 and 24 years of age) are more likely to use car-sharing and ride-sharing AV services. This finding is not only consistent with past studies (Krueger et al., 2016) but also is highly intuitive because that age group tends to be uninclined towards vehicle ownership and generally prefer shared modes (ride-hailing, ridesharing, public transit) that keep their hands free for smartphones and other personal communication devices (Cottam, 2017). The results also suggest that individuals living in urban areas are more likely to use AV car-sharing service. There is widespread and frequent coverage of car-sharing options in urban areas, thereby making it a popular mode choice. With the multiplicity of mobility options at urban areas, there is lower tendency towards personal vehicle (HDV) ownership and greater inclination toward AV car-sharing service. In addition, this observation could be due to travelers seeking to avoid the stress of urban driving.

The results also suggest that respondents who currently live in suburban or urban areas (city centers) are more likely to use SAV services. People prefer SAVs because they seek not only to avoid congestion on city roads but also reliable travel times (Barbour et al., 2019). In addition, respondents who are retired from full-time employment indicated greater propensity to use SAV service, which is an intuitive finding. Lastly, respondents that indicated discomfort driving a regular vehicle in a mixed-traffic stream of HDVs and AVs, are more likely to use an SAV service. Having other passengers on board in an SAV service could help mitigate the anxiety of being in a mixed-traffic stream.

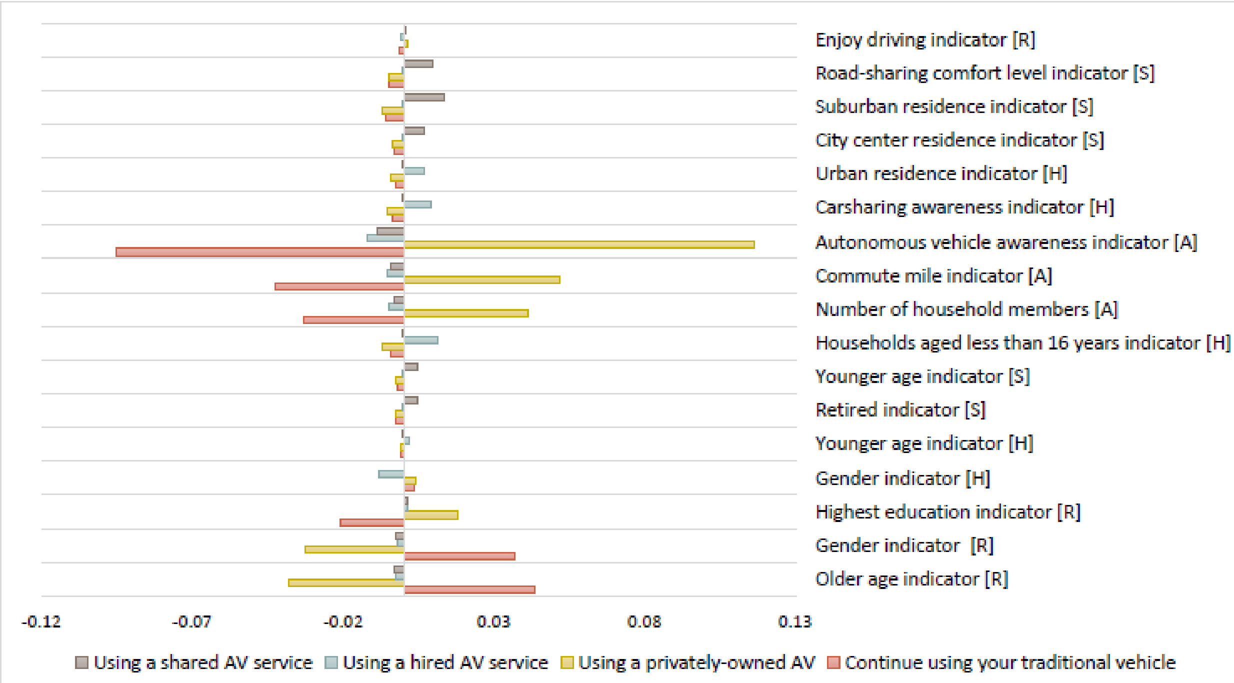
Table 3.5 Model estimation results for mode preferences

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 > 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 18-24 yrs, 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 18-24 yrs, 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 lives in urban location, 0 otherwise) [H]	0.858	2.7	0.318	0.007	0.236	1.481
City center residence indicator (1 if respondent lives in city center, 0 otherwise) [S]	1.753	3.15	0.557	0.002	0.662	2.844
Suburban residence indicator (1 if respondent lives in suburb, 0 otherwise) [S]	1.120	2.38	0.470	0.017	0.199	2.041
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 (3.566)	3.06 (3.33)	0.512 (1.07)	0.002 (0.0009)	0.569 (1.468)	2.604 (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					

Table 3.6 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] use privately-owned AV; [H] use hired AV service; [S] use shared AV service.*



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

Figure 3.2 Marginal effect of factors that influence mobility preferences.

3.3.6 Further Discussion of the Results

It is expected that ride-hailing will serve as the basis for a business model for AVs. However, based on the findings of this study, such hypothesis may not hold true for small- and medium-sized metropolitan areas of the U.S. during the early phase of the AV transition period. In evaluating the consumers' interest across three AV-related modes, 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 always whenever needed, and the flexibility to carry out activities regarding a self-owned vehicle. In addition, some consumers might consider SAV service to be costly. These preferences regarding AV modes might change over time when a substantial majority of vehicles on the road network are SAVs. Initially, consumers might try out SAV rides for experimental purposes. However, the findings of this report suggest that during the early phase of the AV transition period, consumers might continue to prefer their traditional vehicles (HDVs) over other AV-related modes, which could be due to the flexibility associated with owning a vehicle.

It is widely speculated that AVs will enable mobility for elderly travelers and could attract patronage from aging seniors. In the survey of this study, however, it was observed that respondents over 55 years indicated preference to use their traditional vehicles (HDVs) compared to the AV mode options. Travelers of this age group tend to be resistant to change and any disruption of their lifestyle. It may very well be the case that the older respondents that were surveyed have not yet reached an age where they are no longer able (or allowed) to drive. The survey results also suggest that travelers with longer commutes (specified in this study as distances exceeding 2.5 miles) tend to prefer self-owned AVs; this could be indirectly indicative of the respondents' realization of in-vehicle travel time benefits of AVs – their hands will be freed up so they can spend their time more productively, through other activities including reading, working, eating, resting, and so on. This could cause unintended impacts on land use: housing locations distant from workplaces thereby exacerbating urban sprawl and causing an increase in vehicle-miles of travel. To forestall these consequences, land-use policy makers and urban designers may need to undertake requisite initiatives.

In this study, we identify 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, particularly those residing at SMMAs. In addition, the study provided a better understanding of the inclinations of prospective AV users in various mode-choice scenarios (self-owned, car-sharing, or ridesharing). Policymakers, transport planners, highway agencies, and regulators who seek public opinions regarding AVs, will be better positioned to carry out AV related policy development, land use planning, infrastructure preparedness, and regulations that facilitate successful introduction and evolution of automated AV technology. The findings from this study offer useful preliminary insights into this process.

One of the more important findings of this study was the lower propensity for AV use observed for responder 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 constitute an interconnected network; and AVs will be expected to operate at different highway classes (freeways, arterials, collectors/distributors, and local roads). Therefore, for successful integration of these vehicles into the road transport system, policymakers, 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 study do not reflect exactly the actual modal split because 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 study 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 subject could utilize a more comprehensive inventory of modal 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 AV-related preferences might be different across consumers that patronize these modes.

3.4 Predicted market penetration – for all levels and each level of automation

Predictions of the anticipated market penetrations of the various SAE levels of CAVs have been made using interviews and market research surveys (Saeed et al., 2020). It may be estimated that by the year 2030, AV Level 0 (currently the dominant share) may likely gradually decrease to 50-70%, while Levels 1 and 2 will increase to 20-35%, and Levels 3 and 4 will increase to 10-15% and 2-5%, respectively. Other researchers have addressed AV market growth from the perspectives of vehicle sales, on-road fleet share, and amount of travel, and have suggested that it may probably be Year 2045 before 50% of all new vehicles are autonomous and Year 2060 before 50% of the vehicle fleet is autonomous, or possibly longer due to technological challenges or consumer preferences, as shown in Figure 3.3 (Litman, 2022).

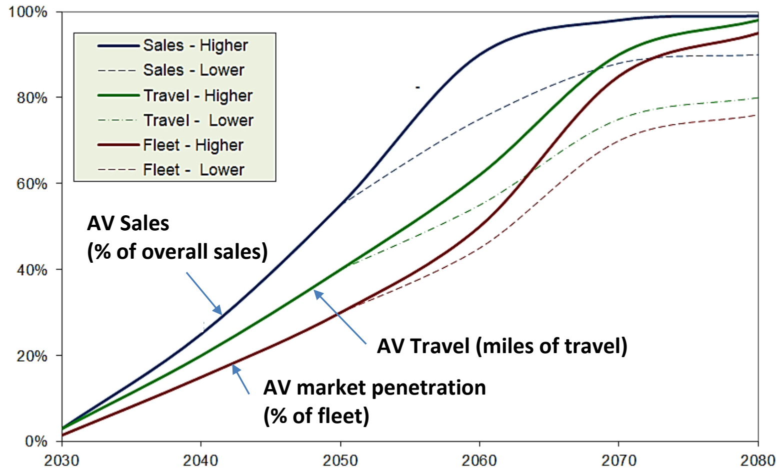


Figure 3.3 Predictions of AV Trends – Percentages of market penetration, sales, and travel (reproduced from Litman, 2022)

In addition, AV predictions could be made from the perspective of the levels of autonomy. The MPLA diagram (Figure 3.4) presents rough projections of the anticipated initiation and progression of market penetration rates and levels of automation over the next few decades. This chart was developed through a series of interviews with AV stakeholders nationwide (US). This is an updated version of a similar chart developed by Labi (2019). That 2019 study used a limited questionnaire survey. Also, that study predicted a 2020 peak for Level 2 and a rapid growth of Level 3 after 2021. These trends have not been realized as that study had predicted, possibly due to lack of road infrastructure preparations and supporting policy.

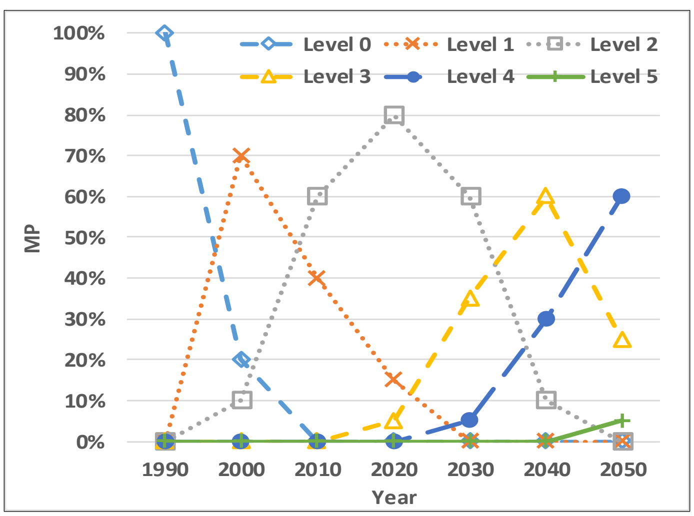


Figure 3.4 Market penetration and level of autonomy (MPLA) diagram (Adapted from Labi, 2019)

CHAPTER 4. STAKEHOLDER PERSPECTIVES

4.1 Introduction

This chapter discusses the perspectives of three of the four key stakeholders of AV deployment (IOOs, OEMs, and road users) gathered through a questionnaire survey. The road users include AV users and HDV users that will share the road space with AVs. The roles of these stakeholders towards AV operations have already been described briefly in Chapter 2 of this report, where the stakeholder participation model identified the major elements and tasks of the stakeholders regarding AV implementation. This chapter demonstrates how some of these perspectives could be considered in IOO decisions regarding AV-related infrastructure preparations. The chapter describes questionnaire surveys that were used to capture the stakeholder's perspectives and preferences and discusses the results of models developed from the surveys. This chapter also discusses the spatial and temporal limitations of the survey findings.

4.2 OEMs (AV Technology Developers)

4.2.1 Prelude

In this report, AV technology developers are defined as entities that develop autonomous vehicle technology. These include vehicle manufacturers, software developers, and experts and companies in other industries that contribute to innovation, enhancement and testing of various AV capabilities and technological components, for example, radar, camera, LiDAR, machine vision systems, data fusion algorithms, and artificial intelligence software. Therefore, in this study, it was considered relevant to ask OEM representatives to comment on the potential timing of AV deployment and their commercial availability. It was assumed that these experts are fully aware of the current state of the technology, its potential evolution, plans for improvement, and the ongoing state of AV technology testing (and current test outcomes in terms of performance and reliability). The current state and capabilities of AV technology and the timing of commercial deployment are expected to have implications on AV market penetration. As such, the OEMs were also asked about their expectations of market penetration trends.

4.2.2 Survey Questionnaire, Findings and Discussion

Table 4.1 presents the questions posed to the OEM representatives and their responses. Eighty-three (83) technology developers were surveyed through either an online survey tool or the distribution of a paper-based questionnaire at AV-related events. One such occasion was the 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 represented. The questions asked and the responses recorded are discussed in the following sections.

<u>(a) First time of AV availability for public use</u>

The OEM respondents were asked to comment on the first time that AVs are expected to be available for public use (Question 1 in Table 4.1). They were also allowed to indicate a response of their own in case they chose not to select any of the options offered. Twenty-nine percent (29%) of respondents had believed that AVs would be available for public use the following year (in 2020), whereas 24% thought it may happen in 2023. Litman (2018) stated that Level 4 or 5 vehicles might be commercially available in the 2020s. In the survey, thirty-five percent of respondents provided a short narrative to support their responses, for example, “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 because it reflects the notion that the OEMs are aware that the inception of AV operations will depend on road infrastructure readiness, as Johnson (2017) had noted. The initial 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 report, the AV technology industry has expressed serious concerns regarding the lack of readiness of road infrastructure, particularly the poor road surface conditions and markings which prevent AV technology from reliably characterizing lane positions. 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, Waymo already had a plan to initiate their commercial service by the end of 2018. Waymo had started a trial program for a 24-hour commercial driverless taxi service (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. 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) reported on the plans of Waymo, Uber, and General Motors to deploy AV fleets to provide on-demand ride services in various U.S. cities.

(b) Timing of road infrastructure investments to accommodate AV operations

Another important question for the technology developers was related to the timing of major AV-related road infrastructure changes in relation to AV market penetration (Question 2 in Table 4.1). Forty-one percent (41%) of the respondents suggested making major infrastructure changes when AVs reach 25% of the traffic stream. Seventeen percent (17%) of the respondents provided a short narrative as their response: “the sooner the better; it will accelerate market penetration,” “unclear if that will be necessary/feasible,” and “25-50%.” The first response is indicative of the suppositions from the stakeholder participation model (Chapter 2 of this report) which posits that the adequacy of infrastructure readiness will likely influence AV market penetration.

Adequate infrastructure readiness is expected to address several of the concerns of prospective users who are apprehensive about riding in AVs. As such, with adequate infrastructure in place more travelers are likely to use the technology. One such example of infrastructure readiness could be the provision of protected, exclusive lanes for AVs. This 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 write-in response, “unclear if that will be necessary/feasible,” is suggestive of some uncertainty as 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 could be a formidable challenge. Furthermore, this response could be attributed to the uncertainty of length of the AV transition period. During a meeting of the National Governors Association, the CEO of Waymo urged the state governors to continue their current infrastructure investments, mainly because of the expected lengthiness of the transition period where both personally-owned HDVs and AVs will be using the roadways (Abuelsamid, 2018).

(c) Freeway readiness for AV operations

Another important question asked of the OEMs is related to the road infrastructure modifications needed to support AV operations on freeways (particularly Interstate highways) in the initial stages of AV deployment. Forty-one percent (41%) of the 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 dichotomy in the OEM responses is suggestive of two possible scenarios of AV infrastructure investment that could be analyzed for their economic implications: (a) no changes made to the corridor in question; only the basic maintenance is carried out to ensure all-weather-visible pavement markings, and (b) a dedicated lane for AV operations is provided at the corridor in question.

Table 4.1 Questions to OEMs and their responses

#	Question(s)	Responses	Percent
1	In your opinion, about how many years from now will driverless cars be FIRST available for public use?	Next 2 years Next 3 years Next 4 years Next 5 years Other (please specify)	29% 6% 6% 24% 35%
2	In your opinion, at which the minimum level of market penetration of driverless vehicles, should MAJOR changes be made to roadway design? For example, lane-width changes.	When 25% of vehicles on roads are driverless When half of the vehicles on roads are driverless When 75% of vehicles on roads are driverless Other (specify)	41% 24% 18% 17%
3	At the INITIAL deployment of driverless vehicles on a FREEWAY, which of the following design changes would you suggest?	A dedicated/exclusive lane for driverless vehicles A dedicated lane for trucks and other lane(s) for driverless and traditional automobiles. No change is necessary	41% 6% 53%
4	In your opinion, which of the following locations should be the first for deploying driverless vehicles?	High-speed roadways (freeways, expressways) Urban highways Central business districts Restricted residential neighborhoods Rural roadways Other (please specify)	53% 0% 18% 12% 6% 11%

(d) Likely locations for initial AV deployment

The fourth question to the OEMs was to identify the most conducive locations for initial deployment of AVs. For this, most respondents (53%) favored high-speed roadways (freeways), 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 as brief narratives, some of which included: “non-open road venues” and “private campus environments”. Overall, the responses to this question indicated OEM support of the notion that freeways will likely serve as the first point of mass AV deployment, and therefore could receive priority in retrofit investments. In a subsequent chapter of this report, A case study, addresses this context as an evaluation case study.

4.2.3 Market Penetration Trends

The OEMs were also asked about the evolution of AV market penetration rates over time (years). Specifically, they were asked to provide the times (years) when AVs will be expected to constitute the following fractions of the traffic stream: 25%, 50%, 75% and 100%. 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 responses (Figure 4.1) present quite disparate opinions regarding the expected rates of market penetration of AVs in the near future. This is evidential of the uncertainty and volatility associated with AV market penetration. The actual market penetration rates will depend on customers' adoption and use of AV technology. Nevertheless, these responses from the technology developers could serve as a fair reflection of the industry's expectations regarding the timing of user adoption of AV technology. Additionally, these responses could be an implicit indication of how soon the industry expects to achieve certain levels of market penetration based on ongoing technological advancements and testing. Two trends of market penetration rates were established based on the survey responses, as shown in Figure 4.2. 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 suggests 100% market penetration by 2088 while the pessimistic trend indicates full market penetration by 2118.

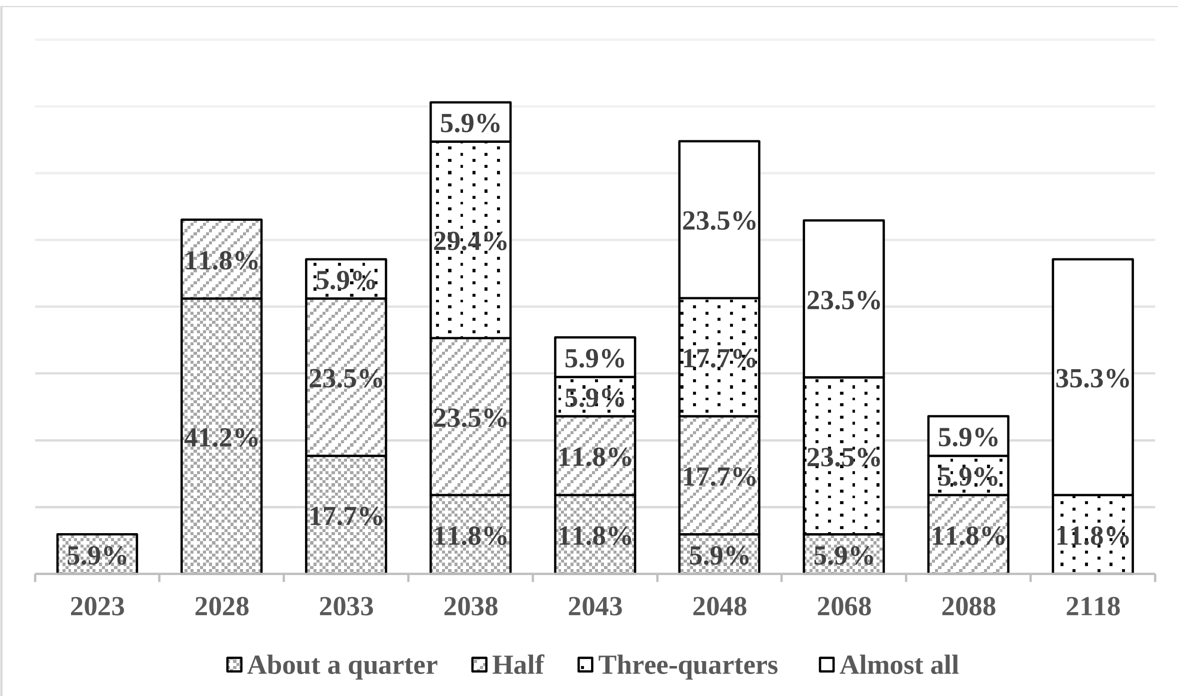


Figure 4.1 Years at which AVs are expected to constitute specific fractions of the traffic stream, (OEM perspectives)

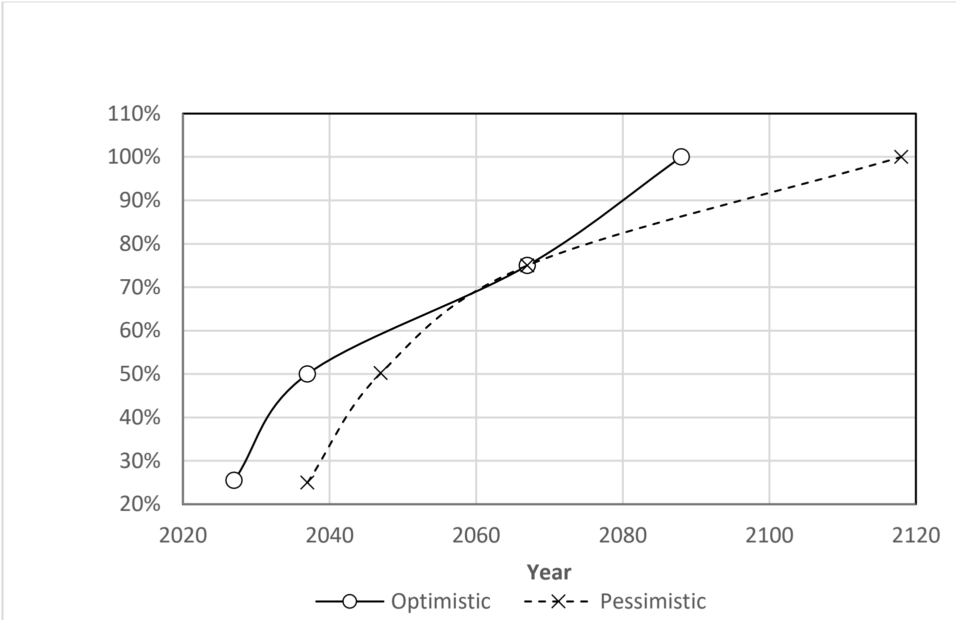


Figure 4.2 AV market penetration trends (optimistic and pessimistic) (OEM perspectives)

4.3 Public-sector IOOs

4.3.1 Prelude

As the stewards of road infrastructure, public sector IOOs (which mostly comprise highway agencies) are responsible for developing new road facilities and expanding, retrofitting, rightsizing, modernizing, maintenance, rehabilitating, and reconstructing existing facilities. Chapter 2 of this report discussed the critical role of IOOs in AV implementation through their provision of supporting infrastructure. The current section of the report describes the responses of IOOs (at state and local levels) to a survey questionnaire that was intended to capture their perspectives and opinions regarding the emergence of AVs and the implications on the current and the future road infrastructure and design features. Table 4.2 presents the questions. In all thirty- nine (39) responses were obtained from agencies across the United States. These were collected through an online survey distributed by the American Association of State Highway and Transportation Officials (AASHTO). AASHTO is a nonprofit association of highway and transportation departments in the fifty states, the District of Columbia, and Puerto Rico. The organization, among other things, develops and publishes guidelines used in highway geometric design and construction across the country. Details of the survey instrument are published in Saeed (2019). The remainder of this section discusses the questions and the responses provided.

4.3.2 Survey Questionnaire, Findings and Discussion

Fifteen (15) questions were posed to the IOOs. The respondents were offered the choice of selecting one of the responses offered by the survey instrument and the opportunity to note the reasons for their choice or other thoughts related to their selection of a specific response. We noted the enthusiasm with which the IOOs participated in the survey. The quality and comprehensiveness of the responses are suggestive of the respondents' keen interest and thoughtfulness in answering the questions. Their responses, which provided valuable insights, are discussed below.

(a) Timing of road infrastructure readiness to accommodate AV operations

In a response to the question on the level of AV market penetration at which AV-related infrastructure retrofits and related investments should be triggered, 20% of responding IOOs indicated 25% market penetration, 20% indicated 75% market penetration, and 8% indicated 50% market penetration. Fifty-two percent (52%) of the respondents provided short narratives instead of (or to support) their response: One response emphasized the need to proceed to plan the provision of AV-related road infrastructure without delay because "it is not possible to stop the future from coming; if agencies are not planning ahead now, they will fall behind quickly". Another respondent indicated high expectations of AV technology, capability stating 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." The respondent is correct in asserted that AV technology can be developed to be sophisticated enough to navigate in any standard terrain, however, such sophistication may lead to higher costs to consumers and consequently, 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 response belies a preference to adopt a "wait and see" approach and start making concrete AV supporting infrastructure investment plans only when the technology progresses adequately to enable AV operations. Other responses noted that AV-related infrastructure planning should be initiated "when the first AV is deployed" and "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 upgraded as soon as any deployed AVs encounter problems using existing infrastructure, such as work zones. Another response suggested that infrastructure improvements should be made when it is understood with some reasonable degree of certainty which specific infrastructure changes will be required to serve AVs without jeopardizing the operational efficiency of HDVs in the traffic stream.

One of the responses noted that even at 10% market penetration, certain aspects of automated driving – cooperative adaptive cruise control – will start showing benefits in terms of traffic throughput. It is therefore important for public-sector IOOs to start engaging the OEMs so they can collaboratively identify the infrastructure improvements that are needed. It has been recommended that after the needs have been identified, the IOOs should start planning their construction right away, because of the notoriously lengthy period of project development. Another respondent noted that infrastructure improvements should be made when AVs become imminent, as it will 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 an initiative-taking measure to avoid delays in AV deployment.

A respondent narrated that "determining infrastructure needs for AVs is an ongoing iterative process that has already started and will parallel the development and deployment of the technology. The State of California has recently adopted new striping standards that improve pavement contrast and visibility for all drivers, including automated driving systems. As of the time of reporting, there is inadequate clarity on exact initiatives needed to accommodate AVs. A respondent noted that "some auto manufacturers have taken the stance that their vehicles must function safely regardless of infrastructure deficiencies such as poor condition of the pavement or the pavement marking, 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 emerge, possibly through the Federal Highway Administration's Manual on Uniform Traffic Control Devices (MUTCD)." The respondent also commented that there often exists speculation regarding the ways in which AVs could motivate modifications in infrastructure. For example, in the future, some road lanes could be made narrower because AVs are expected to avoid excessive wander from their tracks. **It is important to recognize that where both HDVs and AV share the traffic stream, the infrastructure designs must be conservative enough to accommodate even a small fraction of either party (HDVs or AVs)**. It is expected that the mixed traffic environment (of AVs and HDVs) will last for several decades. Any infrastructure design changes should be defined and planned based only on the party that requires a more conservative design due to their physical or operational features. In other words, within such transition period, certain road features must be designed conservatively so they can also serve HDVs, and other features must be designed conservatively so that they can also serve AVs.

Obviously, from the 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. Nevertheless, it seems obvious that identifying AV-related infrastructure needs and measuring their extent (and, in some cases, retrofitting to support AV operations) is an ongoing, iterative process that will need to occur in parallel to the development and deployment of AV technology.

<u>(b) Likely locations for initial AV deployment</u>

The IOO respondents were asked for their opinions regarding the roadway environments for initial deployment of AVs (the second question in Table 4.2), 32% of respondents indicated high-speed roadways (freeways, expressways), followed by central business districts as the next most likely location (24%). Twenty-eight percent (28%) provided narratives on this issue. The responses 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 any typical trip involves an origin and destination whose path includes 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 operate at only a single class of roadways. However, high-speed roadways are typically cited as the top preference for initial AV deployment, particularly during the early stages of the transition phase. At high-speed roadways that possess controlled access, there are fewer chances of encounters and interactions with HDVs, compared to other road classes.

Two similar responses suggested the initial deployment of AVs at 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 could envision this as 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 to place a geo-fence for areas where AVs may be allowed to operate given there is adequate infrastructure to support AV operations."

Another pair of 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 for those who plan to use AVs and 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 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 which technology 'should' be deployed first based on achieving a sufficiently safe roadway operation?"

Additionally, many respondents offered comments to provide additional thoughts or reasons for the selection of their choices. One respondent chose urban highways because he witnessed AV testing on freeways in Arizona. Another selected CBDs and stated the belief that these areas will have the most "action" for an AV. By deploying AVs in these areas, one could investigate vehicle reaction times in busy environments.

Respondents who chose high-speed freeways as the prime 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 be more advanced in urban areas, and the public living and working in central districts will gain more from AV operations. By the words “gain more”, the respondent meant that residents and workers would benefit from the “absence of parking fees, reduced congestion, and 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 at low-volume open roads for safety reasons and then at 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.

(c) Freeway readiness for AV operations

In response to the question on roadway design changes that will be needed to support AV operations at freeways during the transition phase, 44% of the IOO respondents suggested providing a dedicated/separate/exclusive lane for AVs. Respondents stated that they selected this choice for 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-AV traffic but will also let agencies determine whether automated technologies are providing any improvement in safety and mobility.”
- “To minimize conflict 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 these viewpoints indicate IOOs realization by that not only AV users but also the users of traditional vehicles should be duly regarded in the AV infrastructure decision-making process. IOOs seek to provide a roadway infrastructure that is friendly to 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. The respondents’ reasons include (reproduced here unedited):

- “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 provided a narrative to express or support their opinion. One respondent did not support dedicated lane deployment in 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. Yet another respondent doubted whether their state agency would be able to devote lanes for AVs or trucks and concluded that the agency would have mixed lanes for foreseeable future. Another respondent from an IOO foresaw a need only for improved pavement markings and signage.

A particularly interesting response from an IOO respondent was "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 report, namely, pavement markings that can easily be sensed by the AV in all weather conditions.

<u>(d) Minimum MP rates for making major roadway design changes</u>

Twenty-eight percent (28%) of the respondents, when asked about the minimum level of AV market penetration needed to make major roadway design modifications (for example, lane width reconfiguration), 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 short narratives which are summarized below.

One IOO 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."

Another respondent suggested making changes to roadway design and infrastructure only in response to the issues experienced by AVs upon their first deployment. Another IOO respondent did not anticipate any change for the future because currently there is 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, a 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."

(e) Changes in the amount of vehicle travel

With regard to the question on the expected changes in the amount of vehicle travel (VMT) with the increased use of AVs during the transition phase, 42% of respondents expect an increase, for the following reasons (reproduced 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 the IOO respondents expect VMT to remain the same, and seventeen percent were unsure about the changes in VMT, for the following reasons (reproduced 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 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."

(f) Change in the amount of passenger travel

In response to the question on 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 (reproduced 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 IOO respondents expect PMT to stay the same, 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. Based on these responses, it could be argued that the agency respondents unable to effectively comprehend the nature of PMT in the era of AVs. It is quite possible that transportation IOOs were not the right subjects for this question; the question should probably 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 not certain how AVs will be used in the future by individual travelers and transportation businesses.

(g) Infrastructure funding needs

When asked about the highway infrastructure funding needs to accommodate AVs, 63% of IOO respondents expect an increase in such needs, for the following reasons (reproduced 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 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 have not been 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 IOO 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 number of resources. Another reason provided was that roadway projects can maintain the same costs while simply using modified designs to manage the needs of AVs. The respondents commenting on the resources did not 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. Such uncertainty could be attributed to the many unknowns at this time and the possibility that funding may increase (due to expanding equipment needs) but also may decrease (if AVs are able to increase throughput using existing lanes or even decrease the number of needed lanes).

<u>(h) Overall parking needs</u>

In response to the question on the direction of change of 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 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 IOO 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 IOO respondents suggested that parking infrastructure needs will be eliminated completely in the AV era.

(i) Shoulder widths on arterials and freeways

In response to the question on the expected direction of change of road shoulder widths on arterials and freeways with increased AV operations, 13% of IOO 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 manage road conditions better; therefore, the need for a shoulder on a road may decrease."
- "Driverless vehicles drive more precisely."
- "Shoulders are used for people with vehicle issues, people who need to check on something, or people making a call. Since an AV function 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 IOO 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 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 the IOO respondents were unsure whether shoulder widths would change with increased AV operations. The most plausible explanation provided was to the effect that, on the one hand, shoulder widths could 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 will likely stay the same because vehicle breakdowns will continue to occur, and space will be needed for refuge.

<u>(j) Superelevation for new roadways with AV operations only</u>
In response to the question on the expected change in superelevation for new roads containing only AVs, 70% of respondents expressed the opinion that superelevation will stay the same for the following reasons (reproduced 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 (21%) of IOO respondents were not sure whether superelevation would change because they were unsure whether vehicle designs and dynamics would change over time. However, they agreed that driver and passengers’ safety and comfort, which continue to drive the design of highway horizontal curve superelevation, should not be compromised.

<u>(k) Radius of horizontal curves on roadways dedicated to AV operations only.</u>
Regarding the question on the expected radius of horizontal curves for new roadways containing only AVs, 74% of respondents did not foresee any change, 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 likely be smaller and more efficient than human driven vehicles. It is not certain the extent to which these predictions will become manifest.

(l) Gradient of vertical curves for new roadways with AV operations only

In a question on the expected change in the gradient of vertical curves for new roads containing only AVs, 65% of the IOO respondents indicated an expectation that gradients will stay the same. Respondents expect AVs to react similarly to human-driven vehicles. Additionally, one respondent commented that in the case of extreme weather, AV occupants may tolerate steeper vertical curves. However, 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 (22%) of the IOO respondents were uncertain 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.

(m) Asset types needed and required changes across various road classes, for AV operations

In addition to providing their responses to the questions above regarding expected changes in road infrastructure and design, the IOO respondents provided 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."

The IOO respondents also mentioned the following possibilities:

- "The elimination of traffic signals"
- "The elimination of most, if not all, signs"
- "Smart infrastructure"
- "New types of pavements marking."
- "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, the IOO 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 expressed 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 4.2 IOO Respondents – Questions and Summary of Responses

#	Questions	Possible Responses	%
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 When half of the vehicles on roads are driverless When three-quarter vehicles on roads are driverless Other (please specify)	20% 8% 20% 52%
2	In your view, which of the following locations should be the first for deploying driverless vehicles?	High-speed roadways (freeways, expressways) Urban highways Rural roadways Central business districts Selected residential neighborhoods. Other (please share your thoughts)	32% 8% 8% 24% 0% 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 A dedicated lane for trucks whereas other lane(s) for driverless and traditional automobiles. Other (please specify)	44% 24% 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. When about a quarter of vehicles on roads are driverless When half of the vehicles on roads are driverless When three-quarter vehicles on roads are driverless Other (please specify)	28% 16% 4% 16% 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 It will decrease It will stay the same Unsure	42% 21% 20% 17%
5	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 It will decrease It will stay the same Unsure	50% 8% 29% 13%
7	What do you expect to be the impact on infrastructure funding needs to accommodate driverless vehicles on roads?	It will increase It will decrease It will stay the same Unsure	63% 8% 17% 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 It will decrease It will stay the same It will be eliminated completely Unsure	9% 65% 9% 0% 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 It will decrease It will stay the same Unsure	13% 35% 39% 13%
10	In your opinion, how will superelevation on horizontal curve change for NEW roads containing only driverless vehicles?	It will increase It will decrease It will stay the same Unsure	0% 9% 70% 21%
11	In your opinion, how will the radius of horizontal curves change for NEW roads containing only driverless vehicles?	It will increase It will decrease It will stay the same Unsure	0% 17% 74% 9%
12	In your opinion, how will the gradient of vertical curves change for NEW roads containing only driverless vehicles?	It will increase It will decrease It will stay the same Unsure	0% 13% 65% 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 No Unsure	100% 0% 0%
14	How do you expect speed limits to change when roads will host both traditional and driverless vehicles?	They will increase They will decrease They will stay the same Unsure	0% 9% 91% 0%
15	How do you expect speed limits to change when ONLY driverless vehicles will be operating on roads?	They will increase They will decrease They will stay the same They will no longer be required Unsure	57% 13% 22% 0% 8%
16	Agency	State Local	90% 10%

4.4 Road Users

4.4.1 Prelude

As discussed earlier in Chapter 2 of this report, accounting for the feedback from the prospective road users in era of AV operations, can be valuable. Fairly recently, the Federal Highway Administration 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 report, 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. Feedback from both classes of road users is pivotal to successful implementation of AVs. The survey of road users presented in this report demonstrates the relevance of the input and how the survey outcomes may be used to inform the decision-making process at agency level. Road agencies could develop and conduct similar surveys in their respective jurisdictions to capture the road users' perspectives for subsequent consideration in AV-related infrastructure development decisions.

The business models of the industry may initially define the deployment scenarios of AVs (discussed earlier in Chapter 2), this uncertainty may persist 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 important. Moreover, the transition phase is expected to span several decades; therefore, the perspectives of road users (who will continue to drive their traditional vehicles and share roads with AVs) are as important as those of 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 report is how to capture the preferences and perspectives of these road users. At the current time where no historical data are available in the aforementioned context, a questionnaire survey was chosen as a tool to collect this information at either state level (for state DOTs) or other administrative jurisdictions (county, city, or town agencies). In this study, 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, it can be argued that the sample is representative of at least 75% of the population.

The data collection for the road user questionnaire survey is described in Section 3.3.2 of Chapter 3 of this report, and the descriptive statistics are presented in Table 3.3. The first part of the survey is more directly relevant to demand estimation and therefore is presented in Chapter 3 of this report. The second part of the questionnaire relates to AV user comfort and is presented in this chapter of the report. The question to the road user is: If there were AVs in traffic, how comfortable would you feel about driving your own traditional vehicle? Responses to this question were ordered on a Likert scale: very comfortable, moderately comfortable, neutral, moderately uncomfortable, and very uncomfortable. As shown in Figure 4.3, 24% of the respondents indicated 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.

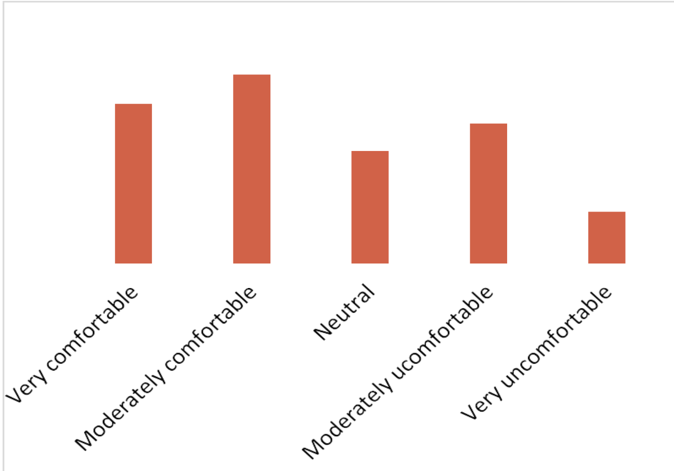


Figure 4.3 HDV drivers' comfort levels regarding road sharing with AVs

4.4.2 Background information on AV safety perceptions

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; Le Vine et al., 2015; 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. As AV technology continues undergoing development and experimentation, any reports of crashes involving AVs are likely to impair positive public 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 report. Advocates for Highway and Auto Safety (2017), 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; 34% were unconcerned and 2% chose the option of "don't know." A survey by the American Automobile Association (2018) found that half (46%) of 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%).

4.4.3 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 (Washington et al., 2020). 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; and Washington et al., 2020).

Consider the following model that is based on latent regression:

$$y' = \beta X + \varepsilon \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.1)$$

and

$$\begin{aligned} y &= 1 \; if \; y' \leq \mu_0 \\ y &= 2 \; if \; \mu_0 < y' \leq \mu_1 \\ y &= 3 \; if \; \mu_1 < y' \leq \mu_2 \\ y &= 4 \; if \; \mu_2 < y' \leq \mu_3 \\ y &= 5 \; if \; y' \geq \mu_3\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.2) \end{aligned}$$

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 experiment, as follows:

$$\begin{aligned} P[y=1] &= \Phi[-\beta X] \\ P[y=2] &= \Phi[\mu_1-\beta X] - \Phi[-\beta X] \\ P[y=3] &= \Phi[\mu_2-\beta X] - \Phi[\mu_1-\beta X] \\ P[y=4] &= \Phi[\mu_3-\beta X] - \Phi[\mu_2-\beta X] \\ P[y=5] &= 1 - \Phi[\mu_3-\beta X]\} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.3) \end{aligned}$$

Where: Φ(.) 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 (+ve, -ve) of that effect on interior categories (in this case $y = 2, 3, 4$) (Washington et al., 2020). 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:

$$\partial P(y=m)/\partial X = [\phi(\mu_n - 1 - \beta X) - \phi(\mu_n - \beta X)]\beta' \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.4)$$

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 report is estimated with random parameter specification (Ahmed et al., 2017). Failing to account for unobserved potentially leads to inefficient, biased, and inconsistent estimates (Washington et al., 2020). The random parameter formulation used in this report is given as Equation 4.5 as provided in standard literature:

$\beta = \beta_n + \varphi_n$ ……………………………………………………….(4.5)

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 using a likelihood ratio test. The random parameters model was found to be superior and therefore is presented in this report.

4.4.4 Discussion of Model Estimation Results

This section discusses the results of the econometric model presented in Table 4.3 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 4.3 and illustrated in Figure 4.4.

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. Respondents who were aware of car-sharing services (Zipcar, Car2Go) were found to be 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 smaller road traffic and therefore lower congestion, potentially contributing to a higher comfort level for them while driving their traditional vehicle and sharing the road with AVs.

The results (Table 4.3) 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 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 the early phases of the transition period when the state of AV technology will be uncertain.

The respondent's age is 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. Respondents between 18 and 24 years of age 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 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 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 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 tend to be more risk-averse with higher levels of concern (Kyriakidis et al. 2015; AAA, 2018) and prefer a less uncertain and safer roadway environment; and their perceptions indicate a 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 will follow the news about the development and testing of AVs more closely and have a better understanding of how this technology works and its current state. 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 84% 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.

Respondents that 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 4.3 and Figure 4.4, 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 4.3 Model estimation results for User comfort level in sharing the road with AVs.

Explanatory Variables	**Parameter Estimates**	**VC**	**MC**	**N**	**MU**	**VU**
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)	0.196b	-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					

VC— Very comfortable, MC— Moderately comfortable; N— Neutral; MU— Moderately uncomfortable, VU — Very uncomfortable. a, b, c represent significance at 1%, 5%, 10% levels.

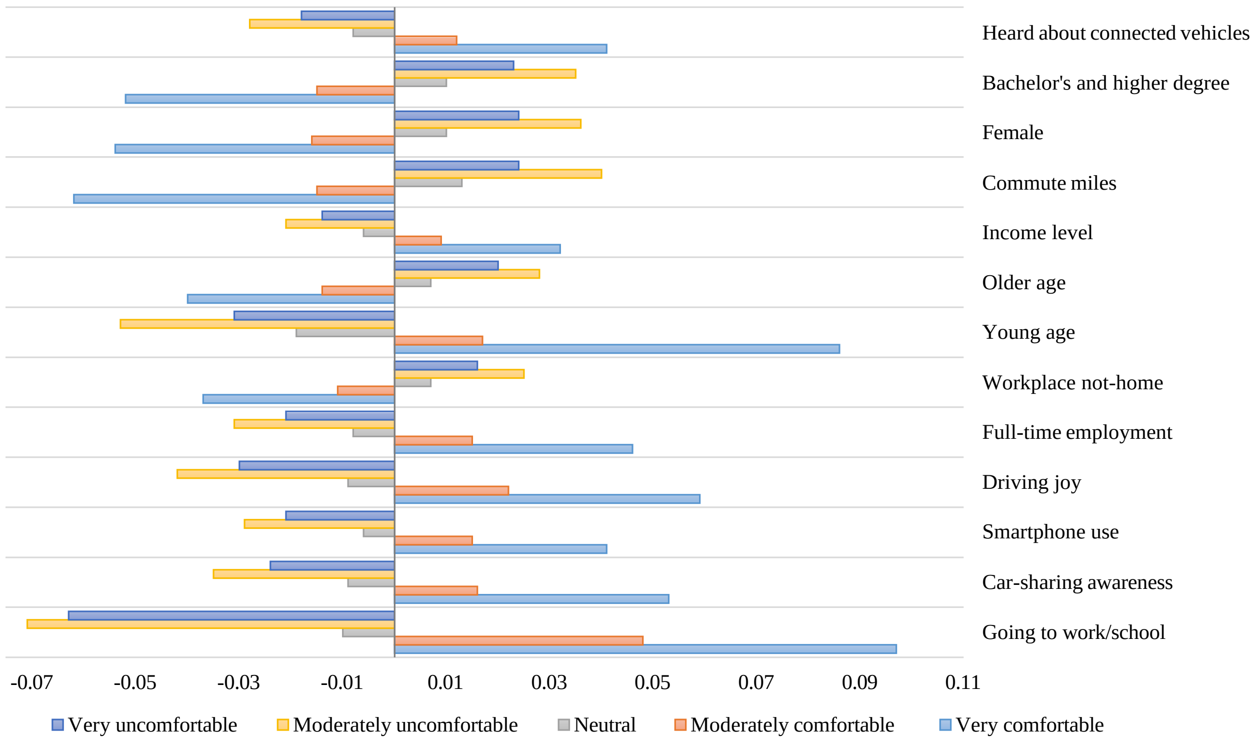


Figure 4.4 Illustration of marginal effects for road user comfort level

4.4.5 Implications of the Road-users' Road-sharing Comfort

This section explores the factors that influence the respondents' comfort level in driving a regular vehicle while sharing the road with AVs. The data suggested that respondent of certain characteristics (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 of age, or had an annual income between $25,000 and $49,000) were more likely to feel comfortable while others (those that did not work at home and drove more than a mile to work/school daily, or were over 55 years old) indicated that they are 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 AV technology, it is important to understand the road user trust in these systems to support their assimilation into the mainstream marketplace and their deployment at public roadways. One of the key questions investigated in this experiment 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 decisions. The findings also could be used by IOOs 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 road user concerns and preferences.

It was determined that 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 redesign and retrofit strategies under consideration for highway infrastructure and design. To do so, the information from the road-sharing comfort-level could be leveraged to investigate the public acceptability of proposed redesign and retrofitting options. For example, future studies could investigate how the levels of road users' road-sharing comfort would change across various retrofitting options, such as the provision for exclusive lanes for AVs, heavy vehicles, and so on.

4.5 Summary and Discussion

The three key stakeholders – OEMs, IOOs, and road users – were surveyed with the intent to capture their opinions and preferences regarding AV infrastructure and related issues. The OEMs 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) locations for the initial AV deployment, and
e) the emergence of market penetration trends.

Due to their leadership of AV technology developing and testing, the industry (OEMs) represents the most appropriate stakeholder to comment on the potential timing of the deployment and commercial availability of AVs for public use. Also, OEMs 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.

The IOOs hold the stewardship of road infrastructure and are responsible for the development of new road facilities, and expansion, retrofitting, rightsizing, modernizing, maintenance, rehabilitation, and reconstruction of the existing infrastructure facilities. IOOs including state highway agencies and a few local agencies were surveyed, with the help of AASHTO, to capture their perspectives and opinions regarding the emergence of AV operations and its implications for the road infrastructure and design.

The questions asked from IOOs 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.

The questions also covered the expected changes in highway geometric design features, i.e., shoulder width of arterials and freeways, superelevation of new roads containing only AVs, radius of horizontal curves and gradient of vertical curves for new roadways with AV operations only, for new roadways with AV operations only, need for real-time monitoring of traffic and cyber-physical infrastructure, speed limits in a transition phase, and speed limits in a fully autonomous era.

The respondents emphasized an immediate need for:

(a) equal implementation of infrastructure and information technology nationwide, for example, 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 classes,
(f) an modernization and retrofitting of local roadway networks.

Table 4.4 summarizes the viewpoints of industry and agencies. An important finding 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 the provision of an AV-dedicated lane in this regard. This indicates 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 findings render additional evidence in support of one of the scenarios that are being analyzed later in this report 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 particularly 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 on on-road or cab-simulated AV operations and their outcomes, these surveys could be used as an effective tool to generate consumer data. The road user survey demonstrates how highway agencies could collect road user feedback on infrastructure modifications in their jurisdictions. Such information could be leveraged to investigate the user acceptance of AV technology, hence, defining the demand. Such demand information could 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 stakeholder survey tools could be useful to agencies in decision-making particularly during the early stages of the transition period.

In sum, stakeholder surveys help highlight the need for closer interaction among the key stakeholders of AV operations. Such interactions could be mutually beneficial and help discern the 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 intentions and limitations, a state of full knowledge and awareness can be maintained among all stakeholders, thus helping to reduce uncertainty and to enhance confidence in decision making.

Table 4.4 Responses of the OEMs and IOOs – A Comparison

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%

4.6 Limitations

The results presented in this chapter explain current preferences; however, today's perspectives may be of rather limited use in discerning future preferences. Without the full and mostly unrestricted deployment of AVs it may not be possible to measure, public perceptions and perspectives with much certainty. As such, the actual level of AV demand in any specific market may deviate from what is predicted initially. Since AVs are an emerging technology, public perceptions about these emerging vehicle technologies are still at a nascent stage. Consequently, similar surveys should be conducted periodically to feel the fluctuating pulse of the market and unveil consumers' preferences instantaneously. 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.

Regarding the road user survey, a limitation is that it uses cross-sectional data. A superior approach could be to collect longitudinal data (perspectives over a period) and track the changing perspectives. 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 report 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. only, and therefore, 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.

CHAPTER 5. AV CONSIDERATIONS AT THE PLANNING PHASE OF INFRASTRUCTURE DEVELOPMENT CYCLE

5.1 Introduction

The management of road infrastructure including AV infrastructure can be viewed generally within the context of a systems development life cycle (Figure 5.1). The cycle starts with an assessment of the need for the AV-related infrastructure followed by planning, design, construction, operations (including maintenance and monitoring), and end of life. This chapter focuses on the planning phase, and we identify some issues that IOOs could contend with as they proceed toward infrastructure readiness for the AV era.

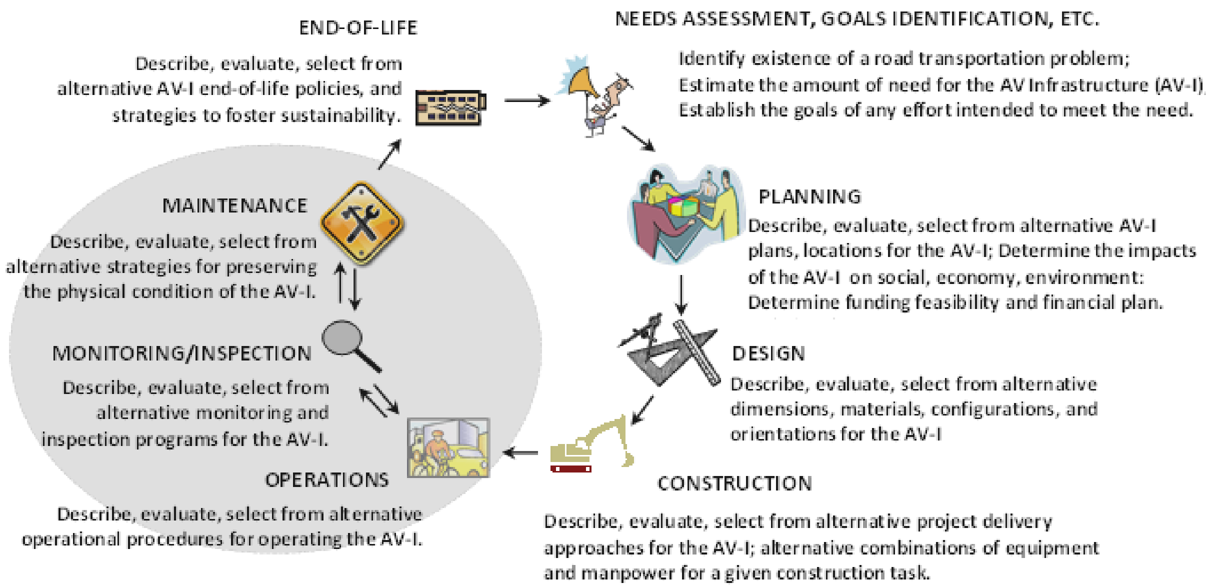


Figure 5.1. Phases of road development and typical tasks at each phase (shaded phases are synchronous)

Planning is considered one of the most critical phases of road infrastructure development and will continue to play a dominant role as society gears up for the era of automated vehicles. Planning is typically conducted by agencies that have been granted salutary authority to oversee a specific class or classes of infrastructure. At certain countries, there is a formal and distinct national governmental organization that conducts or supervises planning for public infrastructure at a national level, and these are often referred to as National Development Planning Commission or National Infrastructure Planning Agency. In other countries, such as the United States, the responsibility for most infrastructure planning is borne by regional, state, or local governments (including metropolitan planning organizations), and the federal government's role is to provide the funds and to ascertain that all the subsequent phases of the infrastructure system development are consistent with legislation.

Road planners develop AV-infrastructure planning alternatives, evaluate each alternative in terms of social, environmental, economic, physical, locational, and political criteria, and the best alternative is selected. Also, planners decide the location of the new infrastructure, identifying and measuring the functional relationships between the road and its built-up and natural environments; and establishing the scope of the plan (planning that considers the infrastructure only vs planning of the infrastructure in the context of a wider system of infrastructure systems), identifying the stakeholders, developing a list of impact criteria, and specifying the temporal scope of the plan. In the context of roadways, planning also involves provisions (dedicated lanes) for a specific class of road users (for example, those that are prepared to pay a price to reduce their travel time, use a specific fuel type, have extra-legal dimensions or weight, have autonomous and/or connected systems, and so on). Further planning includes the development of a financial plan and establishing high-level cost estimates of the proposed intervention.

According to Goodman & Hastak (2007), the planning task can be divided into four different levels as shown in Figure 5.2 below. This chapter considers criteria associated with some of these levels including the location of the system and expected users, capacities and, in some cases, the revenues generated by the road users.

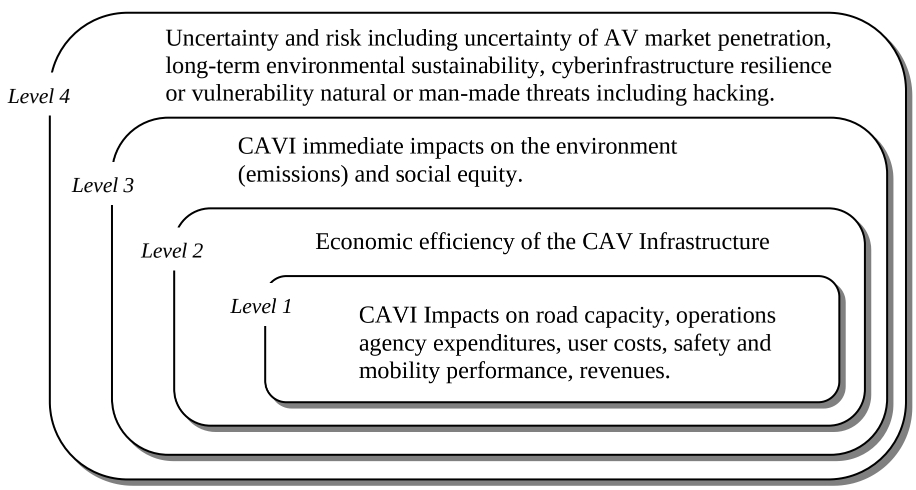


Figure 5.2 Suggested Criteria at Various Planning Levels of AV-related Investment(AV-I)

Government agencies at all levels continue to seek frameworks that account for the need to support autonomous vehicle operations in their planning processes. For example, long-range transportation planning by metropolitan planning organizations is gradually considering the emergence and impacts of driverless vehicles. This includes the consideration of the potential outcomes of autonomous vehicles, such as a scenario where vehicle miles of travel (VMT) rise substantially, and another scenario where shared AVs replace private automobiles, hence possibly reducing VMT.

5.2 PSCCAR Guidance on Infrastructure Planning in the AV Era

Regarding AV related infrastructure preparations, the Public Sector Consultants and Center for Automotive Research (PSCCAR) recommended that government agencies in charge of transportation planning consider the following issues (PSCCAR, 2017):

Legal issues

Legislative bodies will need to restructure rules and laws that govern road user operations particularly those that are expected to influence (or be influenced by) the transition from human-driving to autonomous driving. It is worth noting that some existing regulations for HDV-related infrastructure might not be applicable to AV-related infrastructure.

Partnerships with private companies to improve transit conditions

It is assumed that AVs will also function as components in an overall shared mobility ecosystem particularly as first-mile last-mile (FMLM) vehicles. Therefore, some form of planning and preparation will be needed to ensure smooth AV operations. During the initial stages of the transition period, AVs will likely be used as public transit such as shuttle services on university or corporation campuses or confined neighborhoods. It is useful for infrastructure planners to help transit agencies partner with private ride-hailing companies including Uber and Lyft, in onovative ways, to facilitate the reflective role of AVs in the wider transport ecosystem.

Changes in zoning requirements

Connected and autonomous vehicle operations will likely engender changes in zoning (planning) and building requirements, and parking. AVs will likely reduce the need for in-city parking as their owners will seek less expensive out in-city parking (Labi et al., 2022). This will free up more space downtown which could then be used for other developments. Also, more staging areas (pickup and drop-off zones) which might require a change to the curb-side design. Further, parking infrastructures currently consume a vast amount of land (approximately 6500 square miles in the United States, surpassing the area of the entire state of Connecticut (Thompson, 2016).) With the implementation of AV-facilitated automated parking systems, existing parking facilities could accommodate more vehicles.

Nonmotorized users

The implementation of AVs could prospectively improve the safety of other road users, particularly, nonmotorized and vulnerable roads users at least in the long term. However, there is concern that in the short term, AVs could pose a threat to other road users because the new designs of supporting infrastructure may lead to fragmentation of nonmotorized networks, particularly where the designs involve dedicated AV-only lanes/zones. Infrastructure planners will need to address such concerns in their plans and designs for AV-supporting infrastructure.

Lane-keeping technology

The poor state of road markings is motivating OEMs to reduce the dependence AV navigation on lane markings. It will be good practice for infrastructure planning agencies to be fully cognizant of AV perception capabilities.

Funding

AVs operations are expected to influence how funds are raised and disbursed for transportation infrastructure for development and maintenance. For example, reduced parking leads to loss in parking revenue; AV growth will lead to reduced fuel tax revenues because AVs are likely to be electric; reduced need for driver’s license due to reduced vehicle ownership and hence, registrations. It will be useful for local agencies to start seeking other mechanisms to raise funds to support the infrastructure needs of AVs.

Communication infrastructure

Autonomous vehicle operations always require connectivity between the vehicles and even the infrastructure. It would be good practice for transportation infrastructure planners to consider the inclusion of publicly or privately owned and/or operated communication infrastructures needed by AVs. It will be necessary to ensure accurate and secure data exchange.

5.3 AV-related Legislation, Policy, and Regulations related to Road Infrastructure Planning

In the United States, new vehicles conform to Federal Motor Vehicle Safety Standards (FMVSS). The FMVSS was written/designed for human driven vehicles and will need to be revised to accommodate CAVs . Another important question is the responsibility for vehicle infractions. For example, issuing out a ticket to a CAV or validating vehicle ownership/registration. This section, which discusses these issues, is based on guidelines, laws and policies published in:

(a) Governors Highway Safety Association (GHSA) report on preparing for automated vehicles: traffic safety issues for states (GHSA, 2018).
(b) American Association of Motor Vehicle Administrators, AAMVA's guidelines for motor vehicle administrators and law enforcement on ADS testing, registration and licensing, driver licensing, and law enforcement considerations (AAMVA, 2022).
(c) The National Governors Association's issue paper with recommended policy guidance for governors on ADS testing and deployment (Hill et al., 2018).
(d) National Highway Traffic Safety Administration, government support of AV technology growth and leadership, in NHTSA's ADS policy 4.0 (NHTSA, 2020).
(e) NCHRP Report 2020 on the impacts of CAV technologies on the highway infrastructure (NCHRP, 2020).
(f) Uniform Law Commission's Automated Operation of Vehicles Act (ULC, 2019).

It had been recommended in this literature that the following activities should be considered when setting up a management structure to manage AV testing and development:

(a) A state ADS testing and deployment plan should be established, and a lead state agency should be appointed to supervise the plan.
(b) An AV task force should be created, and the representatives of the State Highway Safety Offices (SHSO) and law enforcement should be members of this task force.
(c) Agencies should be abreast of AV developments and stay in touch with the technology developers.

To help regulate the deployment and testing of AVs in the various states, there need to be policies, rules, laws, regulations, and guidelines to ensure safety and smooth operations of AVs. As of 2022, at least thirty-seven (37) states and the District of Columbia had implemented legislation or issued orders regarding AVs; at least 13 states have authorized a study, defined key terms or state contacts, or authorized funding; at least 8 states had authorized testing; at least 11 states and the District of Columbia had authorized full deployment. Of the 19 states that had authorized testing or deployment, at least 12 states had allowed testing or deployment without a human operator in the vehicle, although some states limit it to certain defined conditions; at least 5 states have regulated truck platooning. The NHTSA has developed policies to regulate AV operations. The policies serve as guidelines and are not enforced by law. A sample list of policies in NHTSA's Preliminary Statement of Policy Concerning Automated Vehicles (2016) is provided below:

(a) Introduction of a voluntary 15-point safety assessment to be submitted to NHTSA prior to testing or deploying highly automated vehicles.
(b) Acknowledgement that manufacturers are responsible for determining capability of a driving automation system with respect to the SAE 0–5 taxonomy.
(c) Request to states to require local testers to submit a 15-point safety assessment to NHTSA.

Planning for infrastructure to support CAV should also review the extent of traffic laws particularly in the context of the potential adverse effect (or obsolescence) of these laws on safe and efficient CAV operations. Also, traffic laws must be adjusted to accommodate AVs deployment and testing, with and without a test driver. Examples of new laws that may need to be passed and existing laws that may need to be modified, are listed as follows:

(a) Authorizing Level 4 and 5 AV operations at limited lanes/ zones.
(b) Requiring that a licensed driver is present and maintains situational awareness in each vehicle, for AV levels 2 and 3.
(c) Establishing legal responsibility for incidents involving AV Levels 4 or 5.
(d) Regulating emergency control of an AV, such as remote control.
(e) Distracted driving laws, in particular, for Level 3 AV drivers that are required to quickly take control of the AV in the event of a road hazard.
(f) Impaired driving.
(g) Following other vehicles too closely.
(h) Non-AV Road user behavior in the neighborhood of an AV.

Michigan is one of the states that have amended their legal codes to account for AV operations and to allow AV testing and deployment. In 2013, they restricted the use of AVs to testing purposes only, until 2016 when they introduced additional bills which allowed AVs to operate on Michigan roadways. The additional bill also allowed for automated truck platooning at predetermined speeds on the state's roadways. Figure 5.3 indicates the implementation levels at various states in terms of laws and legislation relating to AVs, as of 2018.

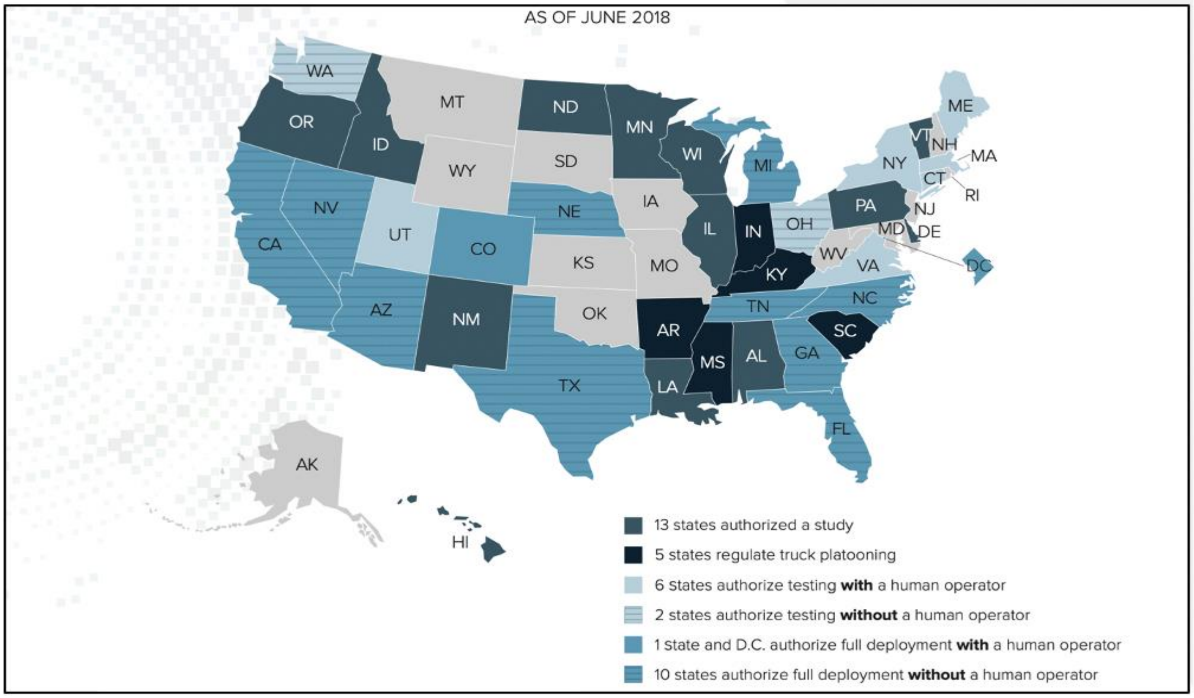


Figure 5.3 AV implementation levels at various states (Source: (GHSA, 2018))

5.4 Revenue Challenges Facing Infrastructure Planning in AV Era

According to the American Society of Civil Engineers (ASCE), there exists a backlog of approximately $836 billion worth of highway and bridge capital needs in the United States. This large size of infrastructure funding need could be reflecting the gap between highway expenditure needs and revenue. The gap could be further exacerbated by the introduction of AVs that will generally not only reduce revenues but also increase expenditures. For example, AVs are expected to be mostly electric (hence, no gas tax revenues). Highway infrastructure planners are already searching for new ways of raising funds to replace gas tax and driver licensing fees. This could be done by taxing the electricity used to charge the electric AVs. Fagnant & Kockelman (2015) and Mwamba et al. (2023) suggested a shift from gas tax to a VMT fee or the use of another innovative funding mechanisms to generate revenue for road agencies in the prospective era of AVs.

The trends stated above are general in nature. The direction of specific impacts of contributory forces may be upward or downward. For example, AV operations could lead to increased travel (vehicle miles traveled) due to the increase in travel opportunities for the elderly, people with disabilities and youth below the driving age. With such perspective increase in VMT, it is expected that the government revenues may increase if revenues are tied to VMT. Even though this might be true, it might also lead to congestion and accelerated pavement deterioration. Therefore, highway infrastructure planners will need to implement policy that balances any increase in revenue with the addition to pavement consumption. This could be done using a VMT fee that would not only raise revenue efficiently but also restrict unnecessary travel and reduce ghost trips, which would in turn reduce the VMT levels.

5.5 Cost Allocation and User Equity in the AV Era

Highway infrastructure managers continue to seek answers on the additional (or reduced) expenditures, and the additional (or reduced) revenues in the era of AVs. Changes in expenditures can be estimated through identification of the physical infrastructure investments (or decommission of existing facilities) needed to accommodate vehicle connectivity and automation, as well as the sibling technologies including vehicle electrification. The repair of travel-related infrastructure damage, provision of new infrastructure, and modification of existing infrastructure will involve a significant capital investment. Secondly, with the changing patterns of travel that will be engendered by the new technologies and the increase in electric connected and autonomous vehicle operations (ECAVs), vehicle registration and fuel tax revenues will be impacted. These revenue and expenditure changes will happen disproportionately across the highway user groups (vehicle classes), and therefore will impact road user responsibilities, fees, and fee equity across the user groups. For these reasons, infrastructure managers seek the extent to which ECAV operations will cause changes in highway expenditures, highway revenues, and user equity across the highway user groups.

Mwamba et al. (2023) investigated these issues and found that ECAVs are expected to significantly change the highway system usage, travel volumes, and ultimately, changing rates of highway infrastructure deterioration. Coupled with new infrastructure needs to support the new technologies, such deterioration increases will lead to increased highway expenditure. At the same time, ECAVs are expected to have significantly reduce fuel tax- based revenues. In anticipation of the agency expenditure increases and revenue shortfalls in the ECAV era, Mwamba et al. (2023) proposed a revision to the current fee structure of highway users in that era. Their objective was in a bid to address highway system efficiency and equity in both near term and long term. With regard to the near term, their study developed a novel variable tax scheme under which each vehicle class pays a different fuel tax rate and showed that this could promote user equity and system efficiency in the ECAV era. Regarding the long term, their study recommended the extent to which the fuel tax could be supplemented with a mileage based VMT tax applicable to electric vehicles.

5.6 Inconsistency of Road Design and Operations Standards

At the planning phase of road infrastructure development, IOOs will need to consider the variations of road designs across jurisdiction and what this could mean in terms of AV operational efficiency and safety. Road infrastructure, regulations, and driving customs vary from country to country, state to state, and even city to city, and are overseen by a multiplicity of bodies. Thus, in the case of road transportation, it may be unclear which regulations supersede others (unlike airspaces which are governed by well-organized global regulatory bodies, has lower levels of traffic congestion, and maintains high licensing standards for its "drivers", i.e., pilots). Road spaces lack standardized and consistent design and operational policies across borders. Human drivers are naturally equipped to handle such cross-state traffic and design differences in the driving environment. On the other hand, AVs may not possess such capabilities.

5.7 Planning for Integration of AV-related Infrastructure with Existing Infrastructure

It is important that any AV-related infrastructure plan considers duly the nature of existing surface transportation infrastructure, as the new infrastructure may require demolition-and-replacement, modification, or repurposing the existing infrastructure. Researchers including Duvall et al. (2019)

have established roadmaps that can help stakeholders prepare infrastructure for the prospective era of autonomous mobility. Similar recommendations can be found in these roadmaps as well as other literature including Duvall et al. (2019), GHSA (2015), AAMVA (2022), NCHRP (2020), Othman, (2021). Examples are provided below:

(a) Function-related recommendations

- Monitoring of AV demand trends.
- Monitoring of the growth in sibling technologies (connectivity, electrification, shared mobility, airborne vehicles).

(b) Infrastructure-related recommendations

- Converting existing curb areas into PUDO (Pick-up drop-off) zones where AV fleets and shared-ride services pick up or drop passengers. Curb spaces may be equipped with beacons that send signals to AVs, and dynamic pricing (of the curb space) at areas and times of congestion.
- Converting existing parking spots into staging areas where AV fleets and shared-ride services wait until it is their turn to proceed to the PUDO areas.
- Provide mobility hubs (near mass transit stations) where travelers headed for the same destination could access shared mobility vehicles, including AVs and personal transport units (PTUs) including bicycles and scooters.

5.8 Planning for AV Supporting Infrastructure

To help support AV operations, road infrastructure should be planned to be equipped with intelligent capabilities. This means that the infrastructure will need to be equipped with sensors and communication devices. For example, traffic signals equipped with (or, prospectively in the long run, replaced by) radio transmitters, devices that facilitate data transmission, fusion, and dissemination with minimal latency, for purposes of V2I communication, and roadside units providing real-time data on weather, traffic, and other conditions (Oliver et al., 2018).

5.9 Planning that Considers Potential Inequities

As discussed earlier in this chapter, a key task at the planning phase of infrastructure development is to consider not only the prospective benefits but also the potential disbenefits in terms of the environment, economy, and social capital of the target jurisdiction. AV operations at some areas and not at others, may lead to "spatial segregation" (Oliver et al., 2018). At the current time, such spatial segregation is rather benign as it is driven by test/deployment area availability and opportunity. However, as AV market penetration grows, it will become more common place to see more severe cases of inequity in AV related infrastructure availability. For example, AV dedicated lanes at existing corridors (Ramzi Rad et al., 2020) and dedicated zones for AVs. Such segregation will emanate from good intentions – to protect human-driven vehicles, pedestrians, and other road users from the limitations of AVs (Oliver et al., 2018). On the other hand, this will cause unintended consequences where certain areas may not see such investments (for reasons including expectations of low returns) and therefore may be denied the benefits of AV operations. This will exacerbate existing issues regarding equity in infrastructure planning.

CHAPTER 6. AV CONSIDERATIONS AT THE DESIGN PHASE OF INFRASTRUCTURE DEVELOPMENT

6.1 Introduction

The previous chapter addressed AV considerations and challenges at the planning phase of road development and offered a few directions for the practice. The present chapter identifies and discusses the types of highway infrastructure readiness and roadway design changes that may be required to support AV operations. The required level of infrastructure readiness (IRL) for AVs is expected to be different across the various stages of AV operations, primarily the transition period, and the fully autonomous period, for example, road geometric design features. Finally, Design for Changeability (DfC), a systems engineering concept, is proposed for consideration by IOOs to promote their infrastructure readiness. Road designers typically carry out analysis, description, and evaluation of design alternatives, and select the best design. In doing this, they draw on analytical tools including simulation, optimization, evaluation, risk and uncertainty analysis, and life cycle analysis of the costs and the performance benefits. In the AV era, designers of road infrastructure systems will continue to be guided by these tasks and will use these tools.

Currently, highway infrastructure is designed for human drivers who are prone to variety of driving errors, exhibit errant behaviors, distraction, impairment, fatigue, and inexperience. For example, roadway and shoulder widths are designed to exceed vehicle widths significantly so that they can serve as correction areas or 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 in cognizance of the inherently errant nature of human driving. AV operations will likely offer more precise and low-error operations compared to human driving. This could lead to the reduction or elimination of certain infrastructure elements and the need for new infrastructure elements.

As such, it is imperative that highway agencies are able to clearly measure the extent of their existing infrastructure design needs at each stage of AV operations over the transition period. During this period, roadways will be expected to host a mixed stream (both HDVs and AVs) and highway infrastructure must accommodate both vehicle types. In the ensuing sections, five main types of infrastructure readiness are discussed. Some of these changes are applicable to only the period of fully autonomous operations. Some of these changes are expected to be incremental and will initiate as the scale of AV operations increases at roadways. The likely changes may be categorized as follows: Enhanced maintenance; Introduction of new infrastructure elements; Removal of some of the existing elements; Redistribution of some elements; Redesign of some elements.

The road design process involves development of alternative designs based on the driver attributes and the existing natural features of the intended road environment on one hand, and the desired outcomes in terms of travel safety and mobility, on the other hand. The existing road infrastructure is designed for human drivers to provide a “forgiving” roadway environment for those that are inclined to make driving errors due to personal impairments including inattentiveness, fatigue, drunkenness, distraction, and inexperience. With fully autonomous driverless vehicles, this design approach would be rendered unnecessary because the human driver is eliminated from the driving task. It is expected that the extent to which highway design will be affected by CAVs will depend on the market penetration and level of automation (MPLA) of the CAVs. Governments of countries including Norway espouse updating road design handbooks to incorporate the features of autonomous vehicles (Paulsen & Pitera, 2018). Figure 6.1 presents some infrastructure options that could facilitate shared ridership (Duvall et al, 2023). Table 6.1 presents the types of roadway infrastructure needs that are associated with the existing and anticipated AV technologies. These are discussed in some detail in the following sections.

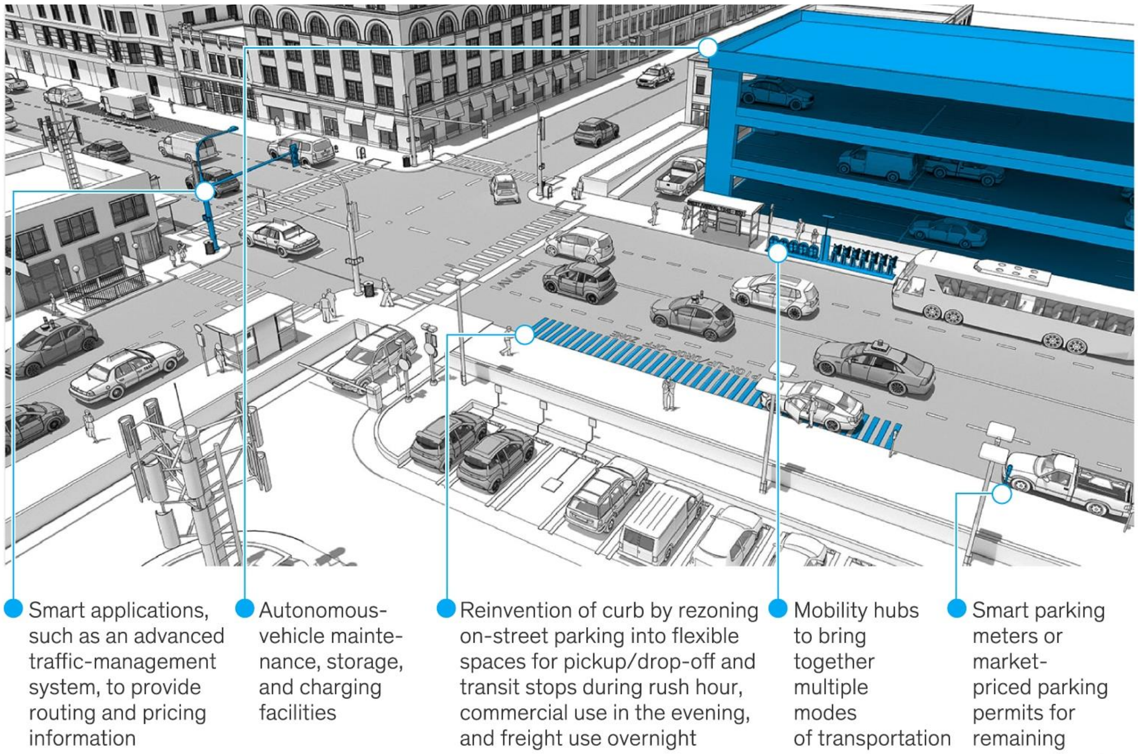


Figure 6.1 Infrastructure Options that could Facilitate Shared Ridership (Duval et al, 2019)

6.2 Establishment of a New Hierarchy of Infrastructure Classes in the AV Era

According to Saeed et al. (2021), CAV-related infrastructure needs can be divided into four classes: modifications to existing infrastructure, new infrastructure needs, and existing infrastructures being reduced or becoming obsolete (Figure 6.1). The figure presents the four categories of CAV-related infrastructure. Class 1 is the base infrastructure that is currently used by human-driven vehicles (HDVs): pavements, bridges, tunnels, retaining walls, guardrails, median cables, pavement markings, traffic signs, traffic signals, curbs. Class 2 refers to traditional infrastructure whose modifications will be needed to support CAV operations, and new infrastructure types. Class 3 is the set of infrastructure types dedicated to AVs, e.g., in-pavement and sign-mounted sensors, and Connected Vehicles (CVs) (e.g., DSRC installations, fiber optic conduits and cables to facilitate 5G connectivity). Also, recognizing that CAVs will be most likely to be propelled by electricity, it is reasonable to assume that EV infrastructure (charging stations and guideways) will be needed to support AV operations. The fourth class of infrastructure is that which will see reduced dimensions of their design elements, (such as road lane and shoulder widths), thicker pavements in the wheel tracks, and reduced quantities of other road elements (such as road signs). Also, in the post-transition period where CAV market penetration is 100% and the level of autonomy is 5, certain traditional infrastructure types will be retired due to obsolescence.

The need distribution of the classes shown in Figure 6.2 will change with time as the CAV market penetration increases. At the current time, Level 1 has the highest share, (almost 100%,) but this is expected to change with increased AV market penetration. The timing of this change is not known with certainty as doubt remains regarding the initial public road deployment year of AVs. This has been a challenge faced by IOOs responsible for AV infrastructure planning.

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

Sources: 1.Shladover (2018); 2. Kockelman et al. (2017); 3. NHTSA (2013); 4. NHTSA (2016); 5. Parent control: for example, (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 the case of trucks. Therefore, road pavements will be required to be designed to a much higher standard to enable them to withstand these traffic loads. 7. None means "there is no need for readiness."

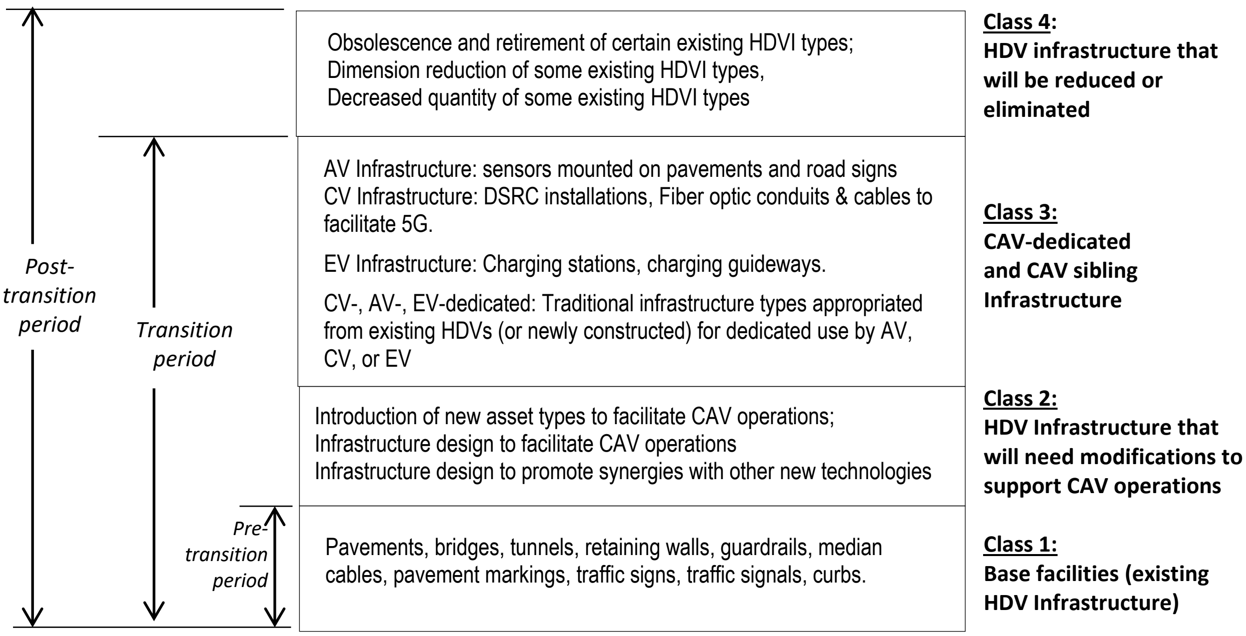


Figure 6.2 Classes of CAV-related infrastructure

As Table 6.1 suggests, 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. This is consistent with the survey results presented an earlier chapter of this report. Pavement markings with high contrast and enhanced reflectivity help improve lane detection by human drivers and AVs (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, IOOs will need to be vigilant about their roadway surfaces and make any surface markings legible to the AV's 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. On the other hand, such AV features 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 to the survey questionnaire, pavement marking will need to be carried out regularly because the current need and levels of road maintenance are also based on human perception. Frequent maintenance will also be needed for new types of infrastructure assets including cyber infrastructure that support V2X communication but 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 climate and traffic loading conditions on degradation of pavement marking.

6.2.1 *Introduction of new infrastructure elements*

(a)Pick-up-Drop-off (PUDO) Areas and Staging Areas

With self-driving vehicles, passengers would like to be picked up or dropped close to their origin or destination respectively, as these vehicles can drive themselves back to the residence or to find a parking spot close to their destination. Existing bus stops could therefore be converted into pickup and drop-off areas. Staging area refers to a facility close to PUDO areas, to avoid congestion at the PUDO area. The AV waits at the staging area until the passenger is ready to be picked up. Staging areas may or may not be associated with a fee, to discourage lengthy occupancy of the staging area. Staging areas located close to the PUDO zones could help prevent congestion caused by vehicles backing up into the main roadway and slowing down traffic. Pick-up and drop-off operations are expected to last for a few seconds only. However, as AV demand continues to grow, a large volume of AVs may need to be served at a staging area per hour. To prevent clogging up of these areas, severe penalties could be imposed for AVs that exhibit unduly excessive PUDO zone occupancy delay in loading or unloading their passengers.

(b) Lanes

The classes of new lanes that may be needed to support AV operations include a dedicated lane for:

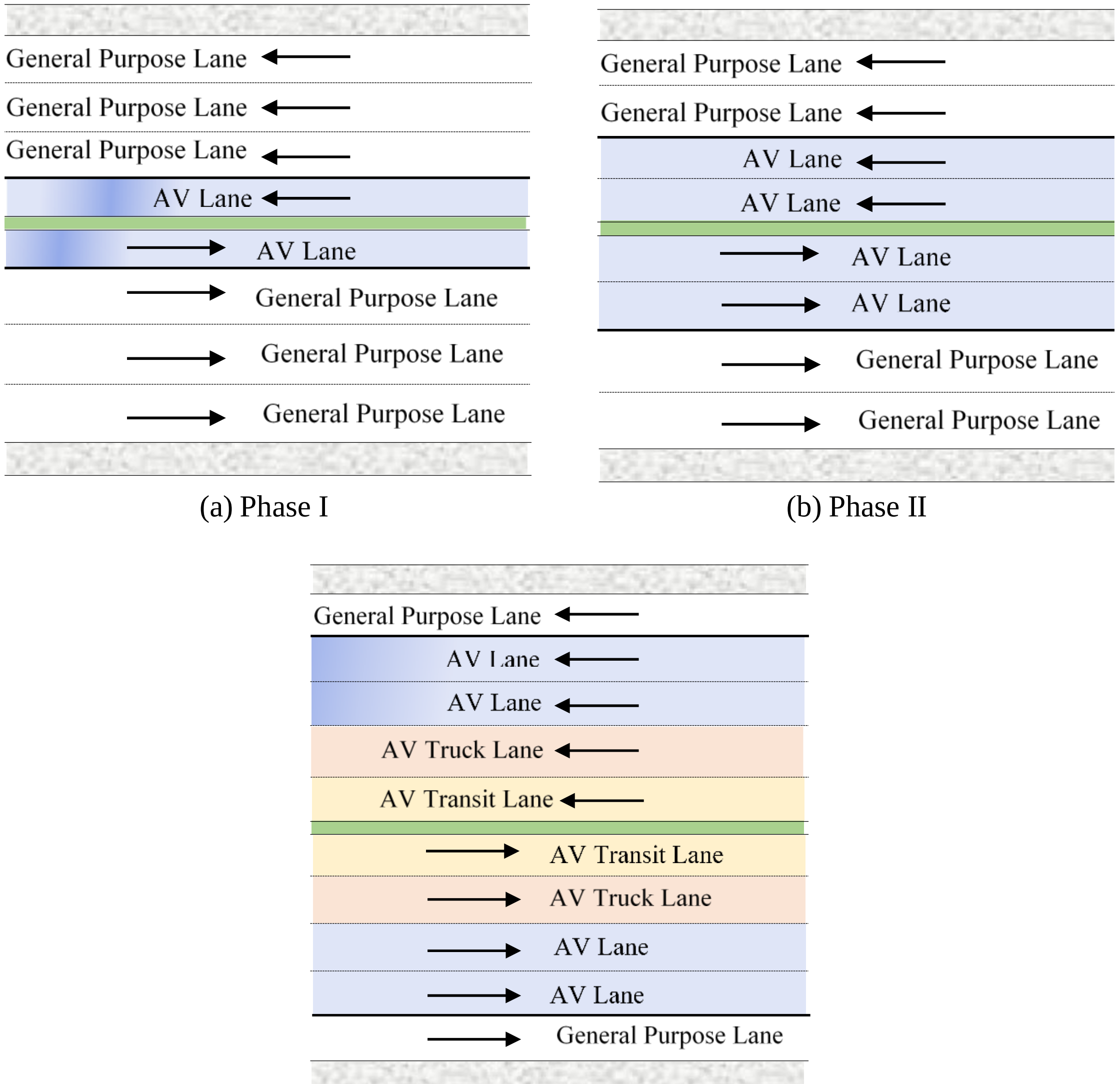
- AVs during the transition phase particularly during the period of initial AV deployment when it is expected that both traditional vehicles and AVs will share the road corridor.
- HDVs of a specific characteristic that could impair AV operations, for example trucks, vehicles lacking connectivity (non-connected HDVs), and so on.
- freight transport vehicles (trucks) to allow truck platooning; and
- autonomous buses and other high-occupancy vehicles.

It is worth commenting on the provision of exclusive lanes to facilitate AV platooning. Simko (2016), using a simulation framework, predicted an increase in carriageway capacity by up to 500 percent through AV platooning. During the transition phase, AVs with the ability to platoon in exclusive express lanes could offer significantly efficient corridor travel. Separating AVs from traditional (HDV) traffic by providing exclusive AV lanes, could generate significant benefits in terms of fuel consumption and travel time efficiency. With increased AV market penetration, the number of special freeway purpose lanes could be increased incrementally (Figure 6.3).

As AV market penetration grows, the number of AV exclusive lanes will likely increase until phase III is reached. At this phase, traditional vehicles are constrained to the general-purpose lanes. With increased AV operations, improvement in traffic efficiency is anticipated and a resultant increase in capacity. Consequently, it may not be necessary to acquire additional right-of-way for road (additional lanes) in the future, to accommodate growing traffic including AVs.

(d) Charging facilities (stations or lanes) for elective AVs

These are facilities needed for charging electric autonomous vehicles (EAVs). These will be designed differently compared to existing human driven EVs, EAV charging facilities that are stationary must be designed to be easily accessible to vehicles that have no drivers, to enter, park and charge. Some interesting research efforts have investigated wireless dynamic charging, which include placing wireless charging mats within or along the road pavement for the vehicles to charge as they drive. Some researchers have expressed skepticism regarding the efficiency of wireless charging because the charge may tend to drain relatively quickly.



(a) Phase I

(b) Phase II

(b) Phase III

Figure 6.3 A phasing plan example for roadway lane-assignment transition to accommodate AVs

<u>(e) Cyber-infrastructure for CAV operations</u>

Vehicle to infrastructure (V2I) communication is essential for CAV operations (Figure 6.4) to ensure the efficient exchange of information between the vehicle and its surroundings, such as traffic conditions and intersections. IOOs will need to manage the cyber infrastructure required by the connected portion of CAV technology. The operation of cyber infrastructure includes transfer of information on congestion, construction zones, detours, and other road traffic conditions. The infrastructure needed to support these operations are listed below:

Roadway (agency)-related:

(a) Roadside units (RSUs): Equipment that transfer and receive data from nearby connected vehicles. The RSU could be fixed or portable, and contains a processor, data storage, and communications capabilities. Currently, RSUs use Dedicated Short-Range Communications (DSRC) or other wireless communications technologies.
(b) Traffic signal controllers: Devices that generate the Signal Phase and Timing (SPaT) message (green, yellow, red, and the amount of time left until the next phase) and transmit that signal to the RSUs.
(c) Traffic management center: A physical location where staff collect, process, and disseminate data from/ to infrastructure and vehicles.
(d) Backhaul communications infrastructure: A secure communications network between the highway agency and RSUs (typically fiber optic).
(e) Infrastructure for Support functions: that ensure security of data transmission and maintenance.

In-vehicle or User-related:

(a) Onboard communication equipment: Devices located in the vehicle (standard equipment or after-market device) that communicate to the RSUs, and process and store the data.
(b) Nomadic device: Device carried by a pedestrian, bicyclist, or wheelchair user that provides information to the drivers of connected vehicles.

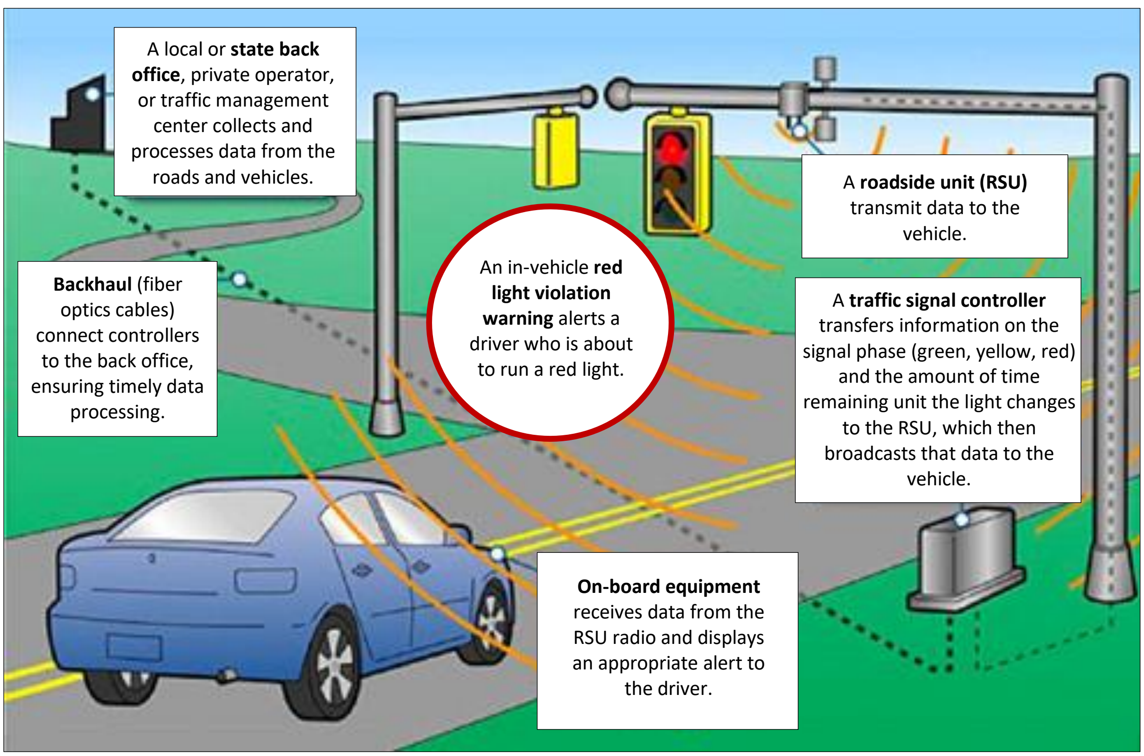


Figure 6.4 Sample communication setup (reproduced from GAO, 2015)

6.2.2. Modification of existing infrastructure elements through changes in standards

As mentioned in an earlier part of this report, existing roads were designed for human driving, and therefore, for smooth transition from human driving to automated driving, requisite adjustments need to be made to road design through changes in design standards. In addition, the designs (orientations, dimensions, positions, etc.) of existing infrastructure such as lane markings and traffic signals must be made consistent across jurisdictions, to avoid causing confusion of the automated driving systems (Sage, 2016). This is because AVs characterize the roadway environment based on a predefined library of images; thus, deviations from what the AV is trained to comprehend, impairs the AV's operations (Knight, 2016). This section identifies some design modifications that could help IOOs prepare adequately for the emerging era of AV operations.

<u>(a) Road and lane markings</u>

Automated vehicles significantly rely on sensors that detect road markings, for use in road navigation. Therefore, poorly-marked roads will generally pose a challenge for autonomous vehicle operations. For example, a retro-reflective road marking is preferred to the traditional white painted stripes. According to Caltrans Director Malcolm Dougherty, lane markings will need to be six inches wide (Ayre, 2017). In supporting this assertion, the FHWA has stated that lane marking width of six inches can reduce fatalities and injury-related accidents by 15 to 35 percent. Davies (2016) indicated that regarding nighttime driving, aside from contrast ratio and width of pavement marking, retroreflectivity is an important factor of pavement marking performance. With regard to daytime driving, contrast ratio was found to be the most important, with retroreflectivity having only a little effect. The retroreflectivity level of lane markings is suggested to be 35mcd for AVs to easily recognize and guide their positioning (Hallmark, Veneziano, & Litteral, 2019). It has been proposed to install road marking tape that provides a black edge with white or yellow markings (3M, 2018) as shown in Figure 6.5 below.

Figure 6.5 High-contrast markings (Source: 3M, 2019)

In an Intervision (2019) article online, it was stated that for a machine vision algorithm to effectively detect pavement marking, it needs to discern the contrast between the pixels of the unmarked pavement and the marked pavement, and identified four examples of machine vision schemes typically used to calculate contrast and detect the pavement markings: (a) corner detection, (a) difference in light and dark pixels, (b) edge detection, and a Convolutional Neural Network (CNN) which uses machine deep learning to train the AV's computer to detect and classify objects (including pavement markings) in its field of view. Pike et al. (2019) commented on how wet retroreflective pavement markings might facilitate enhanced machine vision.

(b) Road signage and traffic signalization

With the use of vehicle-to-infrastructure communication and 3D mapping by AVs, road signs and traffic signalization might become obsolete in the long term where (if) Level 5 autonomous vehicles or approaches reach penetration 100% market penetration (Duarte and Ratti, 2018). Until then, during the transition period of mixed traffic stream (HDVs and AV) operations, signage and signalization will still be needed. It is expected that by the year 2040, 80% of signalized intersections in the United States would be equipped with DSRC to transmit Signal Phasing and Timing (SPaT) messages to on-board units inside vehicles, to ensure adequate V2I communication (Hendrickson et al., 2014). For example, MnDOT has started to incorporate SPaT into the operations of snow and ice maintenance (WSP, 2018). Additionally, Slot-based Intersections (SI) are already in use in place of traffic lights at certain areas (Tachet et al., 2016). In the fully autonomous era, SIs could be used by CAVs to communicate with each other and allow them "book" a slot at the intersection ahead of time, based on their speed, location and direction.

Work zones need to be considered seriously in terms of communicating information to autonomous vehicles. With highly-detailed digital vehicle navigation maps, certain infrastructure types including signage, signalization, and other message boards may be eliminated from the road design when there is 100% penetration level of Level 5 AVs (Hayeri et al., 2015). However, during the transition period (where HDVs and AVs will share the roadway), road signs will still be needed but might be modified to include features that can be read by both human drivers and autonomous vehicles. The USDOT has indicated that the Manual on Uniform Traffic Control Devices (MUTCD) may need to be revised to accommodate AV needs and capabilities (USDOT, 2018). For example, prototype street signs capable of identifying on-coming vehicles and then conveying roadway information have been tested (O'Keefe, 2017). Also, signs with embedded smart codes have been developed to enable detection by vehicle sensors (Moylan, 2018). For example, AV cameras can be made to read digital information posted on road signs (Figure 6.6).

Figure 6.6 Example of road sign with barcode
(Source: https://www.qr-code-generator.com/qr-codes-on/street-signs/)

(c) Platooning impact on pavements

It has been shown through research that truck platooning can increase fatigue damage (Noorvand et al., 2017) at the bottom of pavement asphalt layers by as much as 146% (Chen et al 2019a). This could lead to rutting and road deterioration (Yeganeh et al., 2022). With superior pavement design (materials and thickness) and controlled positioning of platooning autonomous trucks, it is possible to protect pavement condition and longevity from fatigue failure (Al Qadi et al.,2021).

(d) Curbside modifications

Curb spaces should be designed to have varying purposes and pricing depending on the traffic condition or time of day. For example, it can be used as a pick-up and drop-off (PUDO zone, that is, for picking up and dropping passengers.

6.2.3 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 agencies asset inventories. This is likely to occur mostly when all the vehicles on the roads are fully autonomous. In that era, some infrastructure elements, such as traffic lights, may become obsolete and no longer required (Duarte and Ratti, 2018). As Tachet et al. (2016) noted, traffic lights, a more than century-old intersection communication device, could potentially be removed by implementing the distributed networks of traffic data exchange. The authors proposed a slot-based solution at intersections where approaching vehicles autonomously work out their rights-of-way priority by exchanging data on their individual speeds, directions, and locations. The authors suggest that such slot-based operations at intersections could probably produce twice as much throughput in a given time compared to intersections with traditional equipment.

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. AVs may discern how to avoid conflicts with other vehicles using artificial intelligence, and traffic control signals and signs may no longer be needed to direct human operators and help negotiate the right-of-way. However, this is mainly true for the fully autonomous era. In the transition phase, the existing traffic control systems will be needed. Also, at low-volume and rural roads where traffic control systems do not exist, requisite signage, marking, and traffic control devices may still be needed. Further, in the fully autonomous era, speed-calming devices will become obsolete. Speed humps/bumps, rumble strips, raised pavements, and so on, may be no longer necessary as AVs could be programmed to not exceed the speed limit inadvertently.

6.2.4 Redistribution of some elements

Some infrastructure elements may require locational redistribution. For example, city parking garages may need to be redistributed due to the anticipated reduction in city-center parking demand and increased demand for passenger pick-up and drop-off (PUDO) zones. As Duarte and Ratti (2018) noted, cities will likely be able to recover much of the land occupied by large parking garages, particularly in downtown areas. It is expected that private ownership of vehicles will reduce as the demand for shared AVs rises. If that prediction becomes a reality, AVs will have a high vehicle utilization rate of (this has been estimated to reach as high as 75% in the AV era, compared to the current 4% average utilization rate of self-owned human-driven vehicles (The Economist, 2015)). As such, increased use of shared AVs will cause reduced need for parking infrastructure, parking meters, and handicap parking and the long-term storage of mostly unused vehicles will reduce over time. Such reduced need will translate into demolition of parking lots/garages at Central Business Districts and repurposing the land they currently occupy. The sites formerly occupied by old parking spaces could be repurposed for recreational spaces, parks, sidewalk space, or green areas. These anticipated developments in the urban landscape will require urban planners to consider rezoning large areas within cities. The recent COVID-19 pandemic and its aftermath already provided some indication of such developments (New York Times. 2023) and shifts in land use, as a significant fraction of commuters have chosen to work from home or quit their jobs in the CBD area.

6.2.5 Redesign of geometric and other design elements

A key factor of road design is the nature or behavior of human drivers and the need to protect vehicles and their passengers from unsafe maneuvers or situations. Examples include the driver's eye height, perception and reaction time, passenger feeling of comfort and safety, and so on. Some of these attributes may differ across HDVs and AVs. As such, it has been postulated that in the era of AVs, certain road design elements will need to be redesigned (MacDonald, 2018; Labi, 2019; Sinha et al., 2028; Saeed, 2019). It is anticipated that AVs will have far superior safety performance and therefore, the era of full automation and full market penetration of automation, will obviate the need for certain safety assets such as shoulders, guardrails, and rumble strips. The physical dimensions of some infrastructure elements may change; for example, the design dimensional features of certain assets will likely decrease (e.g., narrower lanes and smaller lateral clearance).

With regard to the impacts of AVs on road geometric design, one of the most informative sources of information is the work of Othman (2021) published in Designs journal. Also, Aryal (2020) discussed optimization of geometric road design for autonomous vehicles. Specific potential geometric design impacts of AVs are discussed in this section of the report. The criteria governing the geometric design of roadways generally include 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, geometric designers specify the sharpness of a horizontal curve measuring the degree of banking required on a horizontal curve, the vertical slope degree, and so on. The roadside safety aspect of the geometric design includes features including shy distances and clear zones. The shy distance is the distance from the edge of the traveled roadway beyond which a roadside object will not be perceived by the typical driver as an obstacle to the extent that the driver will change the vehicle's speed or location on the carriageway. Ye et al. (2021) carried out a feasibility study of highway alignment design controls for autonomous vehicles.

Further, in the AV era, it is expected that highway and street geometric designers will continue to seek to (i) ensure the comfort and security of the AV driver and passengers by maintaining design policies that keep vehicle lateral acceleration below levels that may cause discomfort; (ii) help avoid encounters and conflicts through adequate stopping sight distance and sight lines at intersections; and (iii) define vehicle trackways through lane width configurations, and float and drift between lane markings (AASHTO, 2018). In the AV era, horizontal alignment design will continue to address curve dynamics and forces, and the horizontal offset sight distance and vertical alignment will be designed to provide adequate sight distance and with reduced emphasis on driver comfort at crest curves or headlight related requirements at sag curves.

As stated earlier in this section, the underlying factors that guide roadway geometric design 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 expected to not have any considerable impact on the geometric design standards, because the 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). 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. Similarly, 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, it is anticipated that human needs and tolerance levels will continue to govern this aspect of geometric design. Therefore, the emergence of AVs is not expected to cause any changes in this area of geometric design.

<u>6.2.5(a) Stopping Sight Distance (level road section)</u>

Stopping sight distance (SSD) (Figure 6.7) refers to the distance that is needed to comprehend an object in a roadway and bring the vehicle to a stop and indicates how far (distance) a driver can perceive an obstacle in the roadway (AASHTO, 2018). The sight distance at every point along a roadway should be at least that needed for a below-average driver or vehicle to stop. The design of horizontal and vertical curves is predicated on the sight distance together with the design speed and reaction time of human drivers, as shown in Equation (6.1). The braking distance, also called the stopping distance, is the distance a vehicle covers from the time of the full application of its brakes to the complete stop of the vehicle.

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

Where: SSD = stopping sight distance in ft; V = design speed in mph; t = personal reaction time (PRT) (2.5 seconds); and a = deceleration rate in ft/s^2.

$$SSD = Braking\ Distance + Reaction\ Distance \quad (6.1)$$

where reaction distance refers to the distance a driver covers from the point of detecting a hazard to the point of applying brakes or swerving.

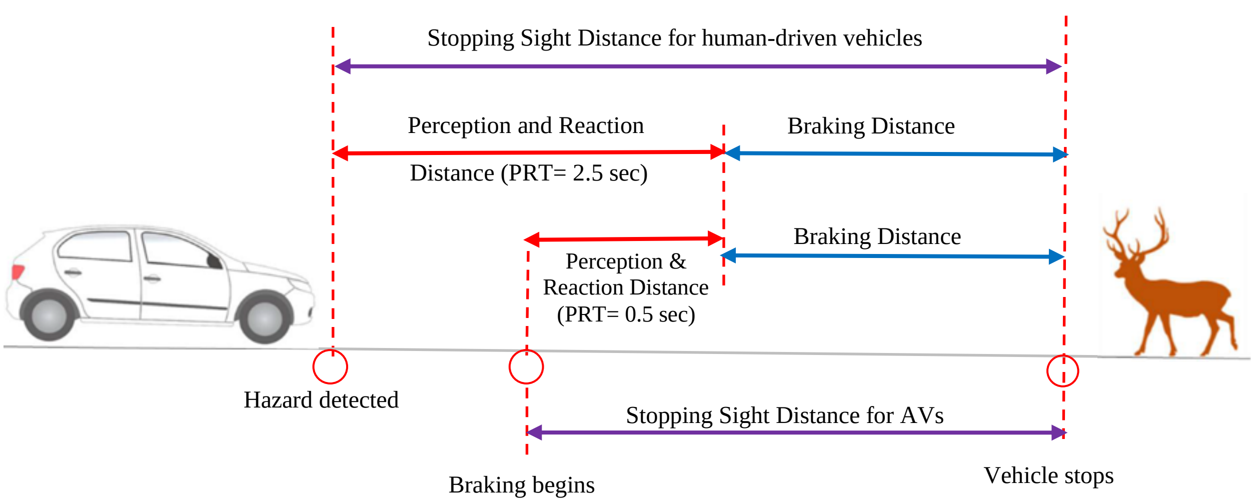


Figure 6.7 Stopping sight distance: HDV vs. AV (adapted from Othman, 2021)

The reaction distance is influenced by two factors: vehicle speed and driver reaction time. Generally, AASHTO (2018) recommends 2.5 seconds for personal (brake) reaction time, but this time duration increases with age, fatigue, complexity of the task, physical impairment, and alcohol drug use. These are specific to individual human drivers. Additionally, events that are unexpected event could 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 slower reaction time. Although younger people have sharper senses, older drivers are more experienced. The reaction time could be reduced in two ways: (1) greater preparedness and (2) better situational awareness that promotes quicker anticipation of hazards. AVs are generally independent of human-specific design-related traits. Simulation tests have shown that AV perception/reaction time could be reduced to 0.83-0.84 seconds (Dixit et al., 2016) that is, 0.5 seconds from the 2.5 seconds of perception/reaction time of human drivers. If the perception/reaction time for AVs in Equation (6.1) falls to 0.5 seconds, then the stopping sight distance at different design speeds can be calculated as shown in Table 6.2. The table indicates a higher percentage reduction in the SSD of AVs compared to HDVs, at lower design speeds.

Table 6.2 Stopping sight distance: HDV vs. AV

Design speed, mph	Reaction time for HDV & AV (secs)	Stopping sight distance, ft	AV SSD (% reduction of HDV SSD)
40	2.5	301	39
	(0.5)	183	
45	2.5	360	37
	(0.5)	227	
50	2.5	424	35
	(0.5)	277	
55	2.5	493	33
	(0.5)	331	
60	2.5	566	31
	(0.5)	390	
65	2.5	644	30
	(0.5)	453	
70	2.5	728	28
	(0.5)	522	
75	2.5	816	27
	(0.5)	595	
80	2.5	908	26
	(0.5)	673	

(1) The computations in this table are predicated on a deceleration rate of 11.2 ft/sec2 recommended by AASHTO (2018) for level roadways. (2) Percent reduction of SSD for AV relative to HDV. (3)Assumption: Reaction times for human driving and AV are 2.5s and 0.5s, respectively.

<u>6.2.5(b) Stopping Sight Distance (considering grade)</u>

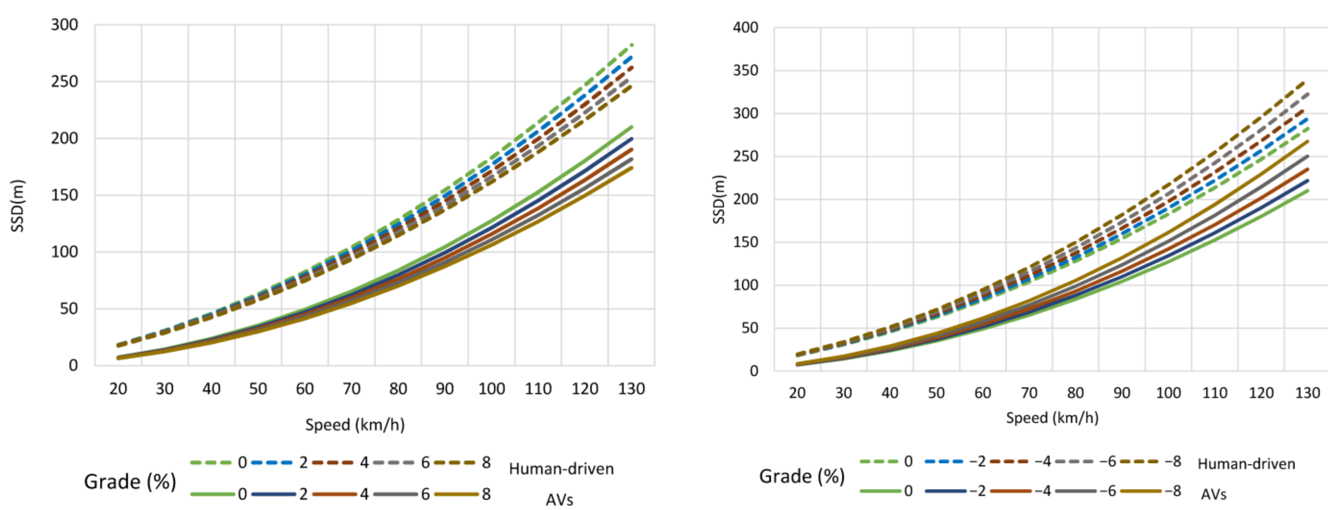
In the AASHTO Green Book, the stopping sight distance considering the road grade is given by:

$$SSD = 0.278 * V * t + \frac{V^2}{254\left[\left(\frac{a}{9.81}\right) \pm G\right]}$$

Where: *SSD* = Stopping sight distance (m); *V* = Design speed (km/h); *t* = Perception and reation time (s) (Typically 2.5 s); *a* = Deceleration rate = 3.4 m/s^2, typically. *G* = Grade. See Figure 6.8.

Table 6.3 SSD on level roads for human-driven vehicles and AVs (Othman, 2021)

Design Speed (km/h)	Human-Driven Vehicles				AVs				SSD Difference (m)
	PRD (m)	Braking Distance (m)	SSD (m)		PRD (m)	Braking Distance (m)	SSD (m)		
			Calculated	Design			Calculated	Design	
20	13.9	4.6	18.5	20	2.78	4.6	7.38	5	15
30	20.9	10.3	31.2	30	4.17	10.3	14.5	15	15
40	27.8	18.2	46	45	5.56	18.2	23.8	25	20
50	34.8	28.5	63.3	65	6.95	28.5	35.5	35	30
60	41.7	41	82.7	85	8.34	41	49.3	50	35
70	48.7	55.9	105	105	9.73	55.9	65.6	65	40
80	55.6	73	129	130	11.1	73	84.1	85	45
90	62.6	92.3	155	155	12.5	92.3	105	105	50
100	69.5	114	184	185	13.9	114	128	130	55
110	76.5	138	214	215	15.3	138	153	155	60
120	83.4	164	248	250	16.7	164	181	180	70
130	90.4	193	283	285	18.1	193	211	210	75



(a)Upward grades

(b) Downward grades

Figure 6.8 SSD for different upward grades for HDVs and AVs (Othman, 2021)

6.2.5(c) Lane Width

It has been frequently mentioned in the literature that the standards regarding the lane width can be reduced when all vehicles become automated and connected because of the lane-keeping system (Hayeri et al., 2016). Thus, additional lanes can be created and dedicated for other purposes such as platooning lanes (Somers and Weeratunga, 2015, Lumiaho and Malin, 2016). It is mentioned in multiple studies in the literature that the high communication between AVs will make it possible to minimize the lane width to reach 2.4 m (8 ft) as shown in Table 6.4.

Table 6.4 Proposed lane width for AVs: A synthesis of recommendations

Proposed lane width	**Reference**
8-9 ft.	Machiani et al. (2021)
8 ft.	Schlossberg et al. (2018)
8-9 ft (9 ft at freeways)	Aryal (2020)
20-25% of the current road width	Snyder (2018)
8-9 ft.	Heinrichs (2016)
2.5 m	Hafiz and Zohdy (2021)
8 ft.	McCarville (2019)

6.2.5(d) Maximum Length of Straight Segments on Horizontal Alignments

Roads consist of curved and straight sections. Lengthy straight sections introduce safety risks because long periods of straight driving could make the driver feel bored, tired or fall asleep (Adam, 2005). Therefore, for HDVs, roads should not be designed to be lengthy. It has been shown in the literature that at speeds exceeding 60 km/h, the maximum straight-line length should not allow the vehicle to travel more than 70 s on the design speed, which is equivalent to '20 × V' (design speed) [Pei et al., 2020]. The human driver is the main reason why the straight section lengths are constrained. For AV-based design, such human factor will cease to be a limiting factor.

6.2.5(e) Acceleration lengths for entrance terminals with flat grades

In the case of 100% market penetration of AVs on freeways, merging maneuver lengths for entrances with flat grades (≤2%) will likely to be the same for tapered and parallel design types. Due to real-time communication capability, AVs in the target lane could adjust their speeds to allow entering autonomous vehicles. AVs in the future are expected to be electric, and electric vehicles can accelerate five times as fast as ICEVs (Leisch, 2018). This provides an opportunity to reduce the design length for merging maneuvers in the era of fully AV operations.

6.2.5(f) Revised road throughput/capacity for design

Road capacity (vehicles per hour per lane) is the maximum number of vehicles that can be accommodated on a roadway. With AV operations, there is an opportunity to significantly increase (in some cases, even double) the capacity on the roadways due to smaller headways.

6.2.5(g)) Lane-width design

The AASHTO Green Book (AASHTO, 2018) defines lane widths to significantly exceed the width of vehicles. Such extra width is provided in current design to serve as a buffer that reduces adjacent vehicle interactions due to errant human driving. In the era of fully autonomous operations, road lanes will likely have smaller widths compared to designs in the current era of human-driven vehicles. This will mean eliminating the extra width. As such, in the AV era, there will be a transition towards a more compact road design. The carriageway cross-section at current roadways could be redesigned by reconfiguring the current lane markings. In cases of roads with several lanes in each direction, such configuration could yield an increase in the overall number of lanes in the same amount of cross-section carriageway space. Further, in the case of new construction, the design of new roadways with narrower lanes would mean a reduction of the needed right-of-way and hence lower costs of new construction. Also, narrower lane width will generally translate into reduced costs of pavement construction and maintenance.

(h) Roadway safety devices

The need to feature roadside safety devices and elements (including rumble strips, guardrails, attenuators, cable median barriers, and concrete barrier) will be determined after the safety performance of AVs has been thoroughly tested through computer simulation platforms of real-life environments. These tests will include investigation of the need for shy line offsets to abutments and other fixed objects. Shy line offset refers to the distance beyond which a roadway object/obstacle is not perceived as a hazard by a driver (AASHTO, 2018). Roadside barriers, where needed, are typically designed to be placed beyond the shy line offset.

(i) Designs to accommodate more efficient acceleration and deceleration

AVs are expected to accelerate and decelerate more quickly because they can sense all other vehicles in their vicinity including their respective positions, speeds, and directions. These capabilities will lead to opportunities for more conservative designs, including steeper grades, shorter ramp terminals, shorter merge areas, smaller gap acceptance for turning and crossing vehicles, and shorter queues and shorter turn bays.

6.2.6 Strategic directions for road design in the AV era

(a) Standardization of road designs

As they continue to deploy their AVs at test areas, OEMs continue to recognize the challenge of inconsistent infrastructure designs across jurisdictions. For example, in the U.S., despite efforts by oversight agencies, there still exist significant difference in roadway designs across cities, states, and regions. The capability to read all signs and traffic signals, and detect lane-marking configurations is critical to successful operations of AVs as they move across jurisdictional borders.

(b) Infrastructure readiness for lower classes of roadways to promote AV deployment

Local roads play a vital accessibility and connectivity role that complements the mobility roles of the higher classes of roads. Therefore, it will not be enough to prepare only the higher-class roads for AV operations. As such, for successful deployment and operations of AVs on a complete road network during the transition phase, a level of retrofitting at local roads, similar to highways will be needed. This includes lane markings, signage, markings, and V2I communication devices. As noted in the IOO responses in Chapter 3 of this report, local roads typically lack such features.

(c) Adaptive approaches to roadway design

It can be assumed 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, any roadway design modifications will be made with due consideration of the comfort level of humans. Nevertheless, as technology advances, roadway designs will be adapted to benefit from more cost-effective and efficient features. This may lead to cost savings, and enhancements in safety and operational performance. The new infrastructure could be designed and constructed using "Design for Changeability" principles that facilitate adaptation to shocks (see Section 6.3).

(d) Magnitude and scope of AV related infrastructure investments

A significant amount of investment will be needed to support successful operations of AVs under all operational design domains. AV technology may be unable to operate at roadways with damaged signs, faded lane markings, or damaged lights. The quality of roads in the U.S. has been ranked 10th out of 137 countries across the globe in the World Economic Forum's 2017-18 global competitiveness report. Also, the U.S. was rated 7th in terms of infrastructure readiness to host AV operations (KPMG, 2018). An estimated 65 percent of U.S. roads are in poor condition, rendering them inadequate for AVs (Young, 2017). The investment needed to ensure AV-readiness of the road infrastructure will require substantial political will power and support to gather the needed legislation for funding.

6.3 The Concept of Design for Changeability (DfC)

In recognition of the gamut of uncertainties associated with AV operations, the systems engineering concept of "Design for Changeability (DfC)" (Fricke, 2006) has been 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., 2014; Sánchez-Silva, 2019). Other terms used in a similar context are futureproofing (Masood et al., 2015) and reconfigurability (Ferguson et al., 2007; Siddiqi and de Weck, 2008; Singh et al., 2009). Masood et al. (2015) defined it 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 6.9) (Saleh et al., 2001; Crawley and de Weck, 2003; Crawley et al., 2004; Hastings and McManus, 2004; Fricke and Schulz, 2005):

- **Robustness** refers to a system's ability to be resilient to the changing environments and withstand adversities (CEN, 1994; Canisius et al., 2011). Robust systems continue to serve their intended function under varying operating conditions without being influenced and changed (Taguchi, 1993; Clausing, 1994).
- **Adaptability** refers to the ability of a system after disruption, 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). Adaptable systems continue to serve the intended purpose under varying conditions through changing or reconfiguring themselves.
- **Agility** signifies the ability of a system to be altered rapidly to avoid or minimize the effect of disruption.
- **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 to cope with change and uncertainty.

These four attributes are not needed to exist synchronously. However, the system will work efficiently when it is flexible and adaptable (Sánchez-Silva, 2019). This is expected in the case of highway infrastructure systems particularly in the prospective era of AV operations.

The development of flexible and adaptable roadway infrastructure designed will enable them to withstand disruptions including the emergence of new and ICT- related vehicle technologies. Information technology systems typically have shorter service life (often months), and vehicles, in years. On the other hand, infrastructure is designed to operate and last for several decades. Technological advancements are occurring at breakneck speeds, posing a deep uncertainty for the relatively slower pace of highway infrastructure development. The rather cautious approach of IOO's regarding investing in infrastructure readiness for AVs could be considered apt, because of the rapidly evolving and uncertain nature of AV technology. Unfortunately, such caution of the IOOs could hinder AV deployment. Adopting a "Design for Changeability" approach could help IOOs to be better prepared for such development cycle disparities.

Highways are developed to ensure safe and efficient mobility for passengers and freight. The ability of a road network to fulfill their mission is monitored continuously and evaluated by the IOO. As and when needed, the IOO reconfigures the road infrastructure design elements, so they can respond to threats and opportunities in the operating environment. This is particularly important given the evolving nature of vehicle technology and the resulting changes/opportunities that can be expected. As such, IOOs have been encouraged to be open to design provisions in infrastructure design and development that address feedback from road users and the OEMs (Saeed, 2019).

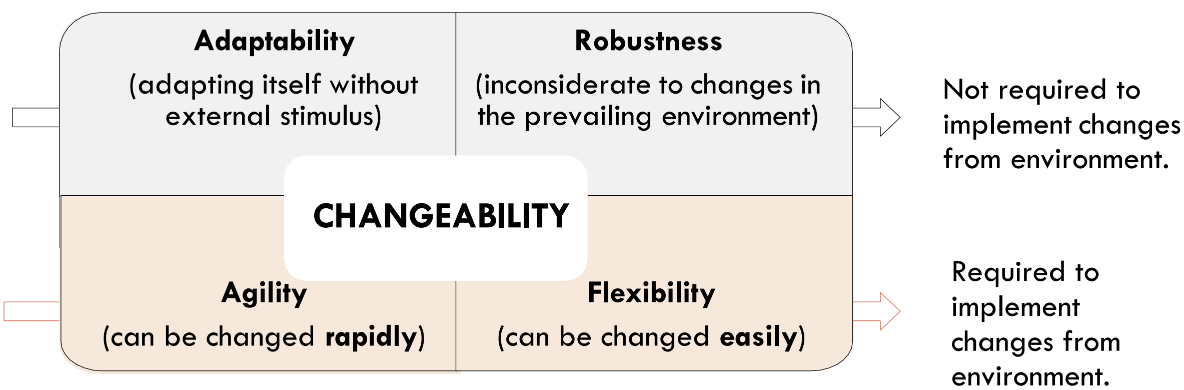


Figure 6.9 Aspects of changeability (Saeed, 2019)

6.4 Challenges and Opportunities in Design

Currently, Class 1 infrastructure (as shown in Figure 6.2) constitutes virtually 100% of all road infrastructure. Over time, as CAV operations are increasingly permitted on public roads, the share of Class 1 will diminish gradually while those of Classes 2 and 3 will increase. The temporal changes in the prevailing distribution of infrastructure classes will be guided by:

a) the initial year of CAV operations on public roads (as steered by government policy)
b) growth in CAV demand (market penetration), and

c) advancements in CAV technical capabilities.

The uncertainties inherently associated with the AV initial year, market penetration, and level of autonomy trends will collectively threaten the reliability in AV-related infrastructure planning and design. This is probably the greatest challenge faced by the IOOs as they prepare their infrastructure for AVs. Another challenge that IOOs will face is the acquisition of adequate funds for AV-related investments. At the current time, budgets are already strained due to increased traffic loading and aging traditional infrastructure. Furthermore, most IOO's current expenditures are significantly lower than their infrastructure repair, renewal, and backlog needs due to declining revenues.

Moreover, building new infrastructure for AVs at the expense of existing infrastructure might lead to equity issues and public relations problems for the agency. This is because as AVs enter the market, initial prices will be much higher than those of HDVs, and may continue until AV prices (after product maturity and scale of economies from higher production levels kick in) reduce to levels comparable with HDV prices.

As is the case with any new technology, the afore-cited challenges will be accompanied by opportunities. First, to address uncertainty in demand, real options theory can be used to characterize the uncertainty and to develop AV-investment schedules to account for the inherent flexibility in such investments. Also, regarding the issue of funding, public-private partnerships could be leveraged to help provide the infrastructure needed to support AVs. Naturally, the dependence of AV manufacturer revenues on AV market penetration (which in turn, will depend on infrastructure readiness), will serve as a motivation for the private sector to participate in AV infrastructure readiness.

Secondly, certain designs of existing roadways will become outdated in the emerging era of new vehicle technologies. The need to prepare the infrastructure for AV operations presents an unprecedented opportunity for highway agencies to redesign certain design elements of their current-day road infrastructure, and these IOOs will have a stronger case to make to legislatures to approve funding for highway renewal in general. The forecasts of the AV-related infrastructure class distributions will likely be largely influenced by the AV-related infrastructure demand (a function of market shares and level of autonomy) and supply (the physical infrastructure). The supply of AV-related infrastructure might generally lag behind the demand for such infrastructure. The infrastructure challenges of AVs will continue to resonate at areas in both urban (Campbell et al., 2010; Duarte and Ratti, 2018; Stead and Vaddadi, 2019; Malysheva, 2020; Tengilimoglu et al., 2023) and rural environments (Colonia et al., 2018). In Austria, Erhart et al. (2020) Infrastructure support for automated driving considering the various ISAD classes of infrastructure preparation. In the ISAD classification scheme, there are five classes denoted by the letters A to E, where E represents no infrastructure support and A represents the highest infrastructure support level.

Regarding the development of roadway infrastructure to support AV operations, stakeholder of AV operations faces both challenges and opportunities. For **road users** (drivers, pedestrians, two-wheel riders), there are challenges (and opportunities) regarding feedback on proposed infrastructure regarding how they may use it safely, and how it could influence their ride comfort. With regard to **technology and automobile companies**, an immense challenge is to develop technology that operates in most domains, and for the road agency there is a need to keep abreast with the rapid advancements in technology. For highway **policy makers**, their association with the government presents an opportunity to leverage existing political structures to facilitate dialogue and consensus- building towards AV deployment at all road classes.

CHAPTER 7. CONSIDERING AV FEATURES/CAPABILITIES AT THE OPERATIONS-MONITORING-MAINTENANCE PHASE OF THE INFRASTRUCTURE DEVELOPMENT CYCLE

7.1 Introduction

Physical highway infrastructure assets generally degrade overtime due to the external forces of climate and traffic loading. As such, IOOs typically monitor their road systems usage (loadings), and inspect the infrastructure physical condition to predict the initiation or progression of these defects so remedial measures can be taken before they pose life-threatening situations or becomes too costly to repair. This is critical for formulating and implementing cost-effective long-term maintenance treatments (in the short term) and the schedules (in the long term).

The operations-monitoring-maintenance phase of highway development is typically carried out fully or partially in-house by the IOO or by contract. In the AV era (at both the transition and the fully-autonomous periods), the extent and intensity of highway monitoring and inspections (and hence, the resources for this agency function) will likely be affected by the following AV-induced changes that will impact infrastructure maintenance: changes in the physical dimensions of certain highway elements; increase in the dimensions of certain assets; the obsolescence of certain existing asset types, and the introduction of new types of assets (Figure 6.2 in the previous chapter).

7.2 Road infrastructure monitoring

Road infrastructure monitoring refers to the assessment, on a cyclic or as-needed basis, of (a) the physical state or operational performance of the infrastructure, (b) the impacts of the infrastructure on the environment, and (c) the impacts of the environment on the infrastructure. CAV features that will enhance infrastructure monitoring include:

AVs could be used to monitor, fully or partially, the following attributes of road infrastructure:

- The extents and patterns of usage of the infrastructure by conducting traffic counts for different time variations (hourly, daily, weekly, monthly, or even yearly).
- The surface condition of the road assets and structural integrity of the road pavement or bridge deck .
- The stability of the infrastructure such as displacement in bridges.
- The impacts of the social, natural, and built-up environment on the infrastructure's physical structure and operating conditions: environmental threats include extreme weather and temperatures, geotechnical conditions, and human activities such vandalism and collisions), as these could affect the structural integrity or operational performance of the infrastructure.
- The impacts of infrastructure physical structure and operations on the built-up and natural environment, for example emissions from vehicles, crashes, noise, and so on.

CAVs, by virtue of their sensing and connectivity capabilities, can collect, analyze, and disseminate and distribute data obtained by sensor monitoring the road traffic and environment conditions. This data includes pavement and bridge deck surface conditions (ruts, cracks, spalling, faulting, texture, and so on), retro reflectivity of lane markings and road signs, and so on and relaying the data to a central office. The defect data to be monitored include not only their locations (mileposts and coordinates) but also their dimensions (extents and severities). Data collected in this manner will not only reduce the costs of data management but also increase the efficiency, effectiveness, and reliability of data collection. The CAVs could be specific vehicles designed and purchased for data collection, or they could be vehicles crowdsourced by the agency to carry out the monitoring task.

The use of AV for monitoring could be made to involve UAVs that have no physical limitations of the field of view. CCAT report #73 (Facilitating UAV Application for CAV Deployment) discusses the use of UAV for monitoring the operations of CAVs on roadways (Zong et al., 2023). Such UAV monitoring task could be expanded to include other targets – the physical roadway condition of pavements and bridges.

7.3 Road Maintenance and Operations

The maintenance and rehabilitation (M&R) of road pavements, bridges, and ancillary assets are a function of the inventory size and the rate of the infrastructure deterioration. The deterioration rate hinges on the traffic volume, infrastructure design type and material type, dimensions, and its traffic and natural environment including climate. It is expected that all these factors will be affected in the AV era. The advent of AVs will cause a change in the amount of travel (reduction or increase), a change in physical dimensions of highway in the infrastructure, change in the dimensions of certain asset types, asset inventory reduction due to obsolescence of certain existing asset types, and the introduction of new types of assets. These will cause changes in highway asset M&R activity types, costs, frequencies, and ultimately, the annual expenditures.

Regarding the AV impact on highway asset types, the highway agency will need to install, maintain, and operate new classes of infrastructure assets to support vehicle connectivity and autonomy. Unfortunately, unlike traditional highway assets, CAV-related assets including roadside units, road-installed sensors, and other roadside technology devices tend to (a) have relatively shorter physical lives due to lower resilience to traffic loading or climate, but also (b) become obsolete quickly to be compatible and interoperable with fast-growing vehicle technologies that support V2I communications. This will pose a challenge to road agencies in terms of manpower (trained workforce) and funding needs to inspect, test, replace, or repair these assets when they become defective. Further, because AVs are expected to be mostly electric (Pourgholamali et al., 2023), highway agencies will need to maintain and operate the infrastructure that supports electric vehicles, such as charging stations and charging lanes.

The connectivity feature of AVs will enable them to communicate with one another, leading to a high possibility of platooning. In general, platooning will benefit traffic flow. However, platooning is a double edged sword: it has been shown in the literature that when trucks platoon, infrastructure structural integrity can be compromised. With regard to pavements, this infrastructure would be subjected to repeated loading at a single point due to the autonomous trucks, lane-centering and lane keeping capabilities (Al Qadi et al., 2021). Efforts could be made through optimal design of the truck use of the carriageway cross section via truck control algorithms to spread out the tire loads more uniformly across the highway cross section. Regarding bridges, the possibility of potential damage was highlighted by Tohme and Yarnold (2020) and Elshazli et al. (2023) and will lead to more frequent bridge rehabilitation or maintenance.

More frequent maintenance and a good maintenance culture are vital for successful AV operations, for example, regular pavement striping will help ensure visible pavement marking at all times. As such, AV operations are expected to lead to more frequent maintenance, and this will translate into high maintenance expenditures.

Further, the deployment of connected AVs will present an opportunity for road agencies to utilize the AVs' connectivity capabilities to provide information that could facilitate road maintenance and operations. At wintertime, connected technologies can be leveraged for intelligent or connected snowplows towards quick and effective snow removal and deicing of bridge decks and road surfaces (Mahlberg et al., 2022; Delcan, 2022). Ødegård and Klein-Paste (2021) discussed previous research related to changes in road wintertime maintenance to accommodate automated vehicles during that season. MnDOT has started to incorporate SPaT into their snow and ice maintenance operations (WSP, 2018).

From a broad perspective, AV-related considerations will influence the outcomes of life-cycle costing, and other decision mechanisms that influence the feasibility of highway programs and projects, project appraisal, investment alternatives analysis. As Mwamba et al (2023) determined, the changes in agency maintenance and capital expenditures and user-based revenue generation caused by AV and other new technologies, will influence highway cost allocation outcomes. These outcomes are: the adequacy of the revenues to cover expenditures, and the equity of user contributions across the highway user groups (that is, the FHWA highway classes).

CHAPTER 8. A GENERAL FRAMEWORK FOR EVALUATING PROJECT-LEVEL AV-RELATED STIMULI CONSIDERING UNCERTAINTY

8.1 Introduction

A transportation stimulus could be a policy (such as, mandatory V2X connectivity in all vehicles) or physical investment in AV-only lane). The evaluation of transportation stimuli is a mater of good practice and/or is mandated by legislation or policy for at least one of the following reasons (Sinha and Labi, 2007; Berechman, 2014):

- **Evaluation of a proposed investment** — For decision-support purposes, a road agency may seek to determine the feasibility of a AV-related investment, policy, or the impacts of several AV-related alternatives. The output of such studies is typically a prediction of the expected outcomes of each alternative relative to base case scenario and identification of a superior alternative.
- **Special transportation development programs** — In some cases, the evaluation seeks to measure the effectiveness of a specific AV-related stimulus on specific outcomes of the transportation system, such as safety, mobility, equity, and so on.
- **Fulfillment of a regulatory mandate** — Regulations and policies of government often at the federal level, may require state or local agencies to carry out impact assessments for the AV-related project of a certain nature or whose cost exceeds a certain threshold.
- **Post-implementation evaluation** — While it is not common practice, it is useful to assess the actual impacts of the AV-related infrastructure project after implementation, and to evaluate such findings vis-à-vis the levels predicted at the pre-implementation stage.
- **Public education** — In case of controversial projects or for purposes of public relations, a transportation agency may carry out the evaluation of past or future stimuli to increase general public awareness of the past or future benefits of the stimulus.

Figure 8.1 presents the general framework (adapted from Sinha and Labi, 2007) that could be used to evaluate AV-related highway infrastructure investments.

8.1.1 Step 0- Pre-evaluation activities

<u>(a) Identification of stakeholders and their concerns:</u> This step identifies all stakeholders that could be (or were) potentially affected (positively or adversely) by the AV investment should be identified, and their concerns solicited. This is important because it helps refine the objectives of the investment. The "road users" refer to the vehicle operators and passengers, shippers, carriers, and truckers that will be directly affected by the AV-related transportation investment in terms of enhancement or deterioration of safety, vehicle operation, travel time, and so on. The "community" refers to those that do not necessarily use the system but may experience benefits or costs from the AV investment, for example, dislocation of homes and farms to make way for AV-dedicated lanes, land-use shifts, travel equity, and so on. The owner/ operator owns or operates the road system. The government is the entity that protects the interests of the travelers, general public and the economic development interests at all phases of the investment cycle.

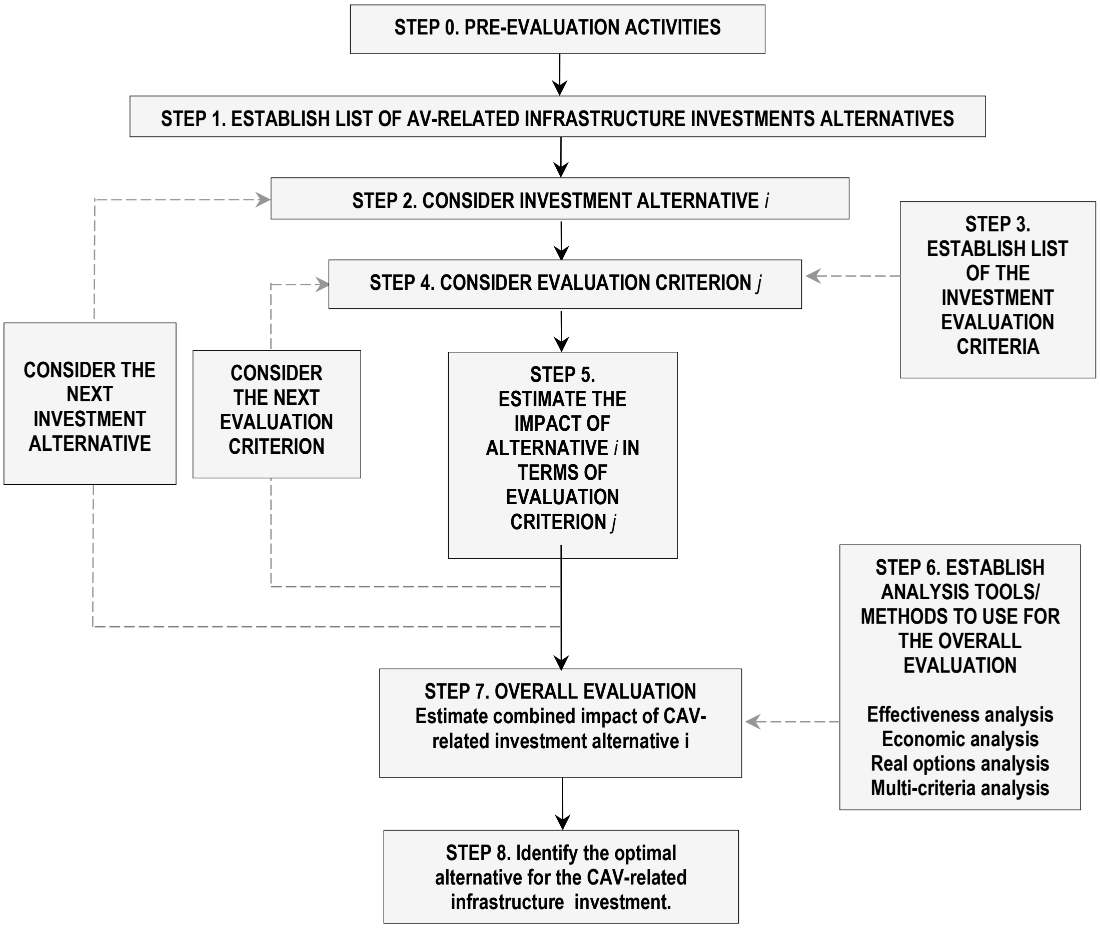


Figure 8.1 Multi-criteria Framework for Evaluating CAV-related Road Investments

(b) Confirmation of system goals and objectives: This step establishes the concerns of all the stakeholders regarding the proposed investment goals and objectives by soliciting information and viewpoints from them. The AV-related infrastructure investment goals are established not only to reflect the mission and goals of the roadway infrastructure agency, but also to accommodate the perspectives of the other stakeholder groups: the road users, the community, government officials, and the general public. For example, the most common community concerns include cybersecurity, congestion mitigation, safety enhancement, accessibility, and equity. Often, there exist past reports or white papers pertaining to regional or metropolitan plans regarding AV operations that could serve as a valuable resource for establishing the goals and objectives for a proposed system. The outcome of this step feeds into Step 3 where a list of the investment evaluation criteria is established.

(c) Establish the spatio-temporal dimensions of the evaluation: Depending on the AV investment or policy in question, it is important to establish the boundaries of the affected regions for the investment analysis (e.g., project, corridor, sub-area, system-wide, regional, or national) (for example, in road transport systems, a single point such as a ramp entrance/exit ramp or intersection, a road corridor, or an entire network of roads). The temporal scope must also be established, for example, minutes or hours (operational scope) or months or years (strategic). The relative importance of certain evaluation criteria may differ depending on the spatial or temporal scope under consideration (Sinha and Labi, 2007).

These initial steps are important for the following reasons: (i) to ensure that no stakeholder, affected party, or interest group related to the public (and their concerns) are excluded from the evaluation process; (ii) ensure that no impact of importance to the public has been overlooked; and (iii) establish the information needed to measure the impacts of interest to all stakeholders, particularly those that are marginalized or disenfranchised. The agency that oversees the evaluation must establish a proactive (and not reactive) communication program to provide information to the general public and interest groups through the media, the internet, and other channels. The agency must solicit the advice of representatives from citizen associations, interest groups, and other public bodies.

8.1.2 Step 1. Establish the AV- related infrastructure investment alternatives

This step identifies all possible alternatives and screens them to ascertain that they are appropriate. Is each specific alternative relevant to the problem at hand? Is it adequate in addressing the identified need? Are the investment alternatives too few, or too many? In answering these questions, the analysis may be guided by the following considerations: relevance of the alternative: holistic nature of the alternative (consideration of the intervention not as an independent and isolated entity but as an integral part of a larger system-of-systems) adequacy of the alternative, and whether the alternative is realistic. The number of alternatives should not be too large or too small. The range of alternatives should be wide enough to permit illustration of the trade-offs associated with the evaluation criteria, so that the best investment can be identified after duly considering the performance tradeoffs between competing alternatives (de Neufville, 1990). In developing the alternatives, inclusiveness and transparency are vital, and input from the stakeholders should be solicited. The investment analysis should collaborate with the stakeholders, and the evaluation process should be open to public scrutiny, review, and feedback.

In the context of AV, related infrastructure investments include construction of AV parking garages or lots at the outlying areas of a city, electric vehicle charging stations or guideways, roadside units, high-fidelity road markings, computer-legible road signs, staging areas, and PUDO facilities.

8.1.3 Steps 3-5. Establish list of the investment evaluation criteria

An evaluation criterion (also referred in the literature as a performance metric) is an outcome at any spatial level that is associated with some AV intervention or application. The outcome may be beneficial or adverse and may be intended or unintended. Other perspectives or dimensions include the class stakeholder affected by the outcomes (The IOOs vs. the road user and the community) and the monetary nature (monetary vs. non-monetary). Typically, the evaluation criterion is expressed in terms of these outcomes.

The evaluation criteria may be categorized in several ways, for example, the triple Es (effectiveness, efficiency, and equity) (Sinha and Labi, 2007) and the sustainability triad (economic, environmental, social) (Jeon and Amekudzi, 2012). The economic pillar of sustainability includes the life-cycle costs of maintenance and operations incurred by the road agency and the users. The user costs of operations include accident costs and operational efficiency. The social pillar of sustainability includes cyber and physical security and safety of the road users, and equity. Equity is related to fairness, an important societal value that is also strongly associated with ethics and environmental justice. When transportation agencies consider equity-related goals in their AV-related infrastructure decision-making, this helps ensure that all segments of the population have a fair share in the benefits of the project or that certain segments (regardless of their gender, age, income level, social status, disability status, residential or working location, etc.) do not suffer disproportionately from the adverse impacts of the investment. The environmental pillar includes emissions, which can be influenced by traffic stabilization and other operational efficiencies brought upon by AV operations.

The use of evaluation criteria is vital in AV-related infrastructure evaluation because road agencies and road users have a stake in knowing the extent to which the intended goals of a AV investment has achieved its intended objectives. It is preferable to have a quantitative, rather than qualitative, statement of each evaluation criterion, to minimize subjectivity, inconsistency, and bias. Such quantitative statement, often a continuous variable, index, or rating, could have linear or non-linear gradations from the least to the highest performance.

Evaluation criteria selected for a specific AV-related investment decision problem must have certain properties (Sinha and Labi, 2007). First, it should be **appropriate** (in other words, the evaluation criterion should reflect one or more goals or objective of the AV-related infrastructure or initiative). Second, the evaluation criterion should be **measurable**, in that it should allow the systems engineer to assess quantitatively the impact of each AV-related investment alternative in terms of that evaluation criterion. Third, it should possess appropriate **dimensionality**, for example, the analyst should be able to use it to measure the AV-related infrastructure effectiveness in a way that is consistent with the spatial and temporal reach of the road infrastructure's operations or performance. Fourth, it should be **consistent**, that is, comparable across different geographic regions or time periods. Fifth, the evaluation criterion should reflect the perspectives of at least one stakeholder. Sixth, the evaluation criterion should be realistic, so that it is possible to extract or generate useful and reliable data that are related to the evaluation criterion, without undue cost, effort, or time. Finally, the evaluation criterion should be **clear and concise** so that it can be used to effectively communicate the system performance to technical and nontechnical audiences including the general public.

In the context of highway automation, a few researchers have identified safety, mobility, and environmental sustainability as the three main categories of metrics of performance for evaluating the benefits of connected and automated vehicle applications. Kaparias and Bell (2011) identified performance criteria for traffic management and intelligent transport systems. Tian et al. (2017) cautioned that the performance of any AV-related infrastructure investment type could be influenced by other factors related to the vehicle, the driver/operator, the roadway, and the driving environment, particularly in mixed streams. These factors include the penetration rate of application-equipped vehicles, the maximum level of automation or connectivity of vehicles in the traffic stream, the level of sophistication of supporting roadway or roadside infrastructure, communication transmission, driver's trust in automation, and inclement weather.

8.1.4 Steps 6-9

Before this step, matrix has been constructed such as that each cell represents the impact of an alternative investment (horizontal) in terms of a specific performance criterion (vertical). In Step 6, the analysis method to use for the overall evaluation is established. These include effectiveness analysis, life cycle cost analysis, real options analysis, multi-criteria analysis, risk-based analysis and so on. These are not mutually exclusive. So, one could use, for example, risk-based multiple-criteria analysis. See Section 8.2. In Step 7. The overall utility (benefits and disbenefits) of investment alternative i, are calculated and in the last step, the optimal alternative for the CAV-related investment, is identified (step 9).

8.2 Traditional Analysis Methods (used in Step 6)

At the present time, the most dominant and popular approach for value engineering is the so-called 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, determines the time required before the investment is recovered; however, it does not consider the cash flow after the payback period (Farris et al., 2010). Two economic efficiency measures (NPV and IRR) help overcome the drawbacks of the payback period approach.

NPV. This is the most used method for investment evaluation. NPV 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). In this case, careful selection of the discount rate is required because the project life is often long and faces economic risks. As a rule of thumb, 4-6% is often used for evaluating public projects (Sinha and Labi, 2007). The investment 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 non-dynamic cash flows: the amounts earned or incurred by the investment and any decisions in the future must be predefined. Although this approach does not account for investment risks and lacks flexibility, it is used in this report as a base case approach for purposes of comparison with ROA.

Internal Rate of Return (IRR). For a given cash flow series, IRR refers to the discount rate that is associated with a zero NPV of the cash flows. 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 caution are required when using this method. First, IRR generally tends 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).

The biggest limitation of these DCF based on methods is the inadequate accounting for uncertainty. Increasing the discount rate to reflect risk and uncertainty (Kodukula and Papudesu, (2006)) 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 illustration highlights the inadequacy of traditional value engineering in capturing and quantifying the monetary value of uncertainty.

Probabilistic discounted cash flow analysis could be used to explore the effect of volatile parameters (i.e., AV Price demand and AV market penetration for example) on the stochastic distribution of the investment outcome. However, it cannot be used to estimate the value of uncertainty-driven flexibility because it may lead to decisions that are not optimal over the lifecycle of the AV 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 could be overcome by identifying the latent value of the AV-related infrastructure retrofitting decisions flexibility using a real-options approach. As such, highway agencies can make more reliable and informed decisions (Ford et al., 2002). Value engineering has been used for several years to assess the appropriateness or feasibility of interventions to construct, reconstruct, expand, defer, rehabilitate, compact, renew or "right-size" assets. Often, the investments made on these interventions are not recoverable.

The major drawback of traditional value engineering 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. This limitation could be overcome by leveraging options that account for flexibility such that decisions are deferred until the investment conditions are more certain and favorable. This approach helps mitigate any downside risks. Also, this is why the discount rate should not be kept constant but rather, adjusted 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.

8.3 Newer Approaches that account for Uncertainty and Flexibility

8.3.1 Real Options Analysis (ROA)

In a bid to determine prices of financial options, Stewart Myer (1977) extended the widely known Black-Scholes equation and coined 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 a highway agency seeks to retrofit its existing roadways for AV operations, instead of retrofitting the entire road network, a pilot project could be deployed at corridor level and then monitor the AVs market penetration. ROA can offer guidance to the decision-makers as to whether or not to scale up the investment. Continual market surveys could be carried out before deciding to increase the scale of the investment from corridor level to the entire network.

The shortcomings of traditional DCF approaches coupled with the anticipated dynamic nature of AV market penetration makes the real options analysis (ROA) a better approach to address the uncertain future of the AV demand. ROA represents actual opportunities or choices that can be exercised to add value to infrastructure (Black and Scholes, 1973), for example, decisions regarding early infrastructure intervention/modification for facilitating AV operations. Most of the future decisions related to retrofitting road infrastructure to accommodate AVs cannot be predicted reliably at the current time today.

Therefore, ROA provides an opportunity to incorporate flexibility into investment decisions. This makes available alternative decision trajectories (e.g., modifying, expanding or abandoning) at any point in time depending on the prevailing conditions (e.g., market penetration or the realization of 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, until the market penetration and safety and travel efficiency impacts are known with certitude. When AV demand and the safety and efficiency benefits are realized, the agency may choose to expand the investment scope. On the other hand, if the outcome is unfavorable, then the highway agency could choose to abandon the AV-related infrastructure project. This way, ROA can create value by managing such strategic investments and recognizing the pivotal role of flexibility in decisions under uncertainty, to ensure the success of future investments (Amram and Kulatilaka, 1999).

IOOs, i.e., agencies responsible for highway infrastructure design and operations regularly face situations where uncertainties cause a change in their intended actions initially and plans. This situation often arises throughout the lifecycle of highway infrastructure, as noted by Nembhard and Aktan (2010) and Athigakunagorn (2015).

Such revisits and revisions to investment decisions over the infrastructure lifecycle could have direct implications for the design parameters (project type, size, etc.) and the value, and hence, the feasibility of investment. Where there exist several infrastructure projects under consideration, using value-based evaluation approach could help decision-makers carry out prioritization or ranking of such alternatives. This is particularly important in the era of AV operations because infrastructure retrofitting investments could involve large sums of money.

Kodukula and Papudesu (2006) noted that, although ROA has numerous advantages it may not be appropriate 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, there could be substantial gains from a project where the decision can be adjusted to “profit” from that state (Kodukula and Papudesu (2006)). In the case of unfavorable prevailing conditions or market (e.g., lower market penetration of AVs), the project could be postponed or even abandoned, to avoid a potential loss. Under these circumstances, collection of additional information (e.g., updates on AV market penetration) could help the agency to 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 appropriate.

Moreover, it is noteworthy that in cases where the NPV 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 small because the chances for exercising an option are little. Conversely, in cases of a highly negative NPV (comprised to the option values), the option values will be unlikely able compensate for the projected loss and hence a no-investment decision is suggested.

Although the real options valuation method is derived from the financial options approach (de Neufville and Scholtes, 2011), they differ from each other in several ways. 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 (e.g., physical road infrastructure). For such tangible assets, it is rather difficult to find similar projects and extract historical data for determining the asset value. However, this could be addressed by determining the present value of the project and assuming this to be a proxy for its underlying value. In the literature, this is referred to as the “market asset disclaimer assumption” (Copeland and Antikarov (2003)).

In modeling the price of a financial option, the main assumption 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, as it has already been marketed, it can be bought and sold quickly to counter any arbitrage. In the case of real options, no market exists for trading this type of asset because of its less liquid nature. Real assets do not incorporate the arbitrage assumption. Therefore, 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. 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 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 yield a very different NPV for 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 8.1 presents a comparison of the terms and phenomena used across financial and real options.

Table 8.1 Terms used across financial and real options.

Financial Option Terms	Corresponding Terms in Real Options
Stock price	Current value of infrastructure asset
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

ROA is widely used for contract management of infrastructure systems development and construction. To address the uncertainty and risk associated with the capability of the proposed investment to 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. As such, highway asset managers seek to counter the uncertainties associated with asset attributes that may potentially impact the investment decision. This is an advantage of using ROA in infrastructure management, as evidenced in the literature (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 the case study of parking garage construction on a fixed land area (Zhao and Tseng, 2003; Wang and de Neufville, 2006; Peters, 2016). In that case study, the source of uncertainty is the demand for parking, which helps specify the size capacity (the number of floors) and ultimately, the needed structural capacity of the foundation.

8.3.2 Types of Options used in ROA.

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, and therefore, 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.

<u>(a) Call and Put Options</u>

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 price or strike price (say, *Y*). The buyer of a call option has the right, (not the obligation), to buy a security (shares) at the predetermined strike price with a non-refundable premium until the date of expiry (O'Sullivan and Sheffrin, 2003). The seller of the call (also known as the "writer") has the 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 the investment will yield some returns. 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, then it is logical not to exercise the option but rather let it expire and buy a security at the 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 within a certain period a fixed known expiry date. The buyer of a put option holds the right (but not the obligation), to sell the underlying security (e.g., shares) at the strike price. 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. 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*, up 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 (8.1) and (8.2) can be used to determine the values of the call option and the put options, respectively.

$$C = \max[S - Y, 0] \quad (8.1)$$

$$P = \max[Y - S, 0] \quad (8.2)$$

<u>(b) Option to Abandon</u>

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). This happens when the market is not in favor, or the end-product has not been completely and successfully developed. Under this option, the decision- maker abandons the project and sell the asset to recover their losses. This is also known as a termination option. The predetermined strike price should not be less than the salvage value.

(c) Option to Expand

The option to expand refers to the option of making an investment or undertaking a project in the future with the possibility of expansion (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 the case of AV-related investments. Given the enormous amount of costs often associated with infrastructure projects, the use of traditional approaches may most likely result in a negative NPV. When the IOO mulls infrastructure retrofitting to support AV operations, some funds could be given up as a premium (for example, implementing a pilot project involving AV-related road infrastructure modifications at a short stretch only) to retain the flexibility to respond as the market penetration of AVs is monitored, and retaining the option to expand as future conditions become more favorable.

(d) Option to Contract

This refers to the option of shutting down the AV-related infrastructure project at some point in the future when unfavorable outcomes or conditions are encountered, for example, a multinational corporation may suspend its operations in a country due to unstable political conditions (Lyon and Rasmusen, 2004). This is opposite of the option to expand.

(e) Option to Wait

The option to wait refers to the option to defer a decision to the future and is also termed as the option to defer (Lensink and Sterken, 2002). It allows decision-makers to wait until the project or the market conditions become more favorable. This option is relevant and adequate when the project is facing significant uncertainty. 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, regarding the construction of an AV dedicated lane, having a 20-yr service life; if the highway agency decides to defer this project for one additional year, its service life of 20 years remains the same and is not influenced by the amount of time the project is delayed.

(f) Option to Choose

The option to choose refers to the flexibility of deciding the type of option to exercise from a plethora of option alternatives (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. For example, the project cannot be expanded and contracted at the same time, and the option to choose therefore will have a reduced value.

(g) Compound Options

The compound option or the "option of an option" refers to the situations where the value of an option depends 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 are: a sequential compound option and a parallel/simultaneous compound option. The former depicts a condition where 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 using a backward induction method to determine the value of the option.

(h) Rainbow Options
The rainbow option facilitates 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.

8.3.3 Option Valuation Methods
The three well-known 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 has assumptions that significantly limit its applicability to specific option types. The major assumptions of this method are: (1) the option can be exercised only on its date of expiry (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). From a practical standpoint, it is almost impossible to identify the option type that meets these assumptions. However, this limitation could be overcome by modifying the equation (Luenberger (1997)).

(a) Binomial Lattice (BL) Method
The most commonly used and widely accepted technique for options valuation is the binomial lattice (BL) method. Its wide application in the literature could 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. Further, unlike the Monte Carlo simulation method, the BL method requires less computational effort and time for the problem formulation. However, the BL method produces an approximate value. This method is based on a no-arbitrage assumption, meaning that the market is efficient, and investments are able to earn the risk free rate of return. The BL method is used to determine the value of an option by first constructing a tree-like structure (Figure 8.2), which starts from the existing value of the asset, S_0.

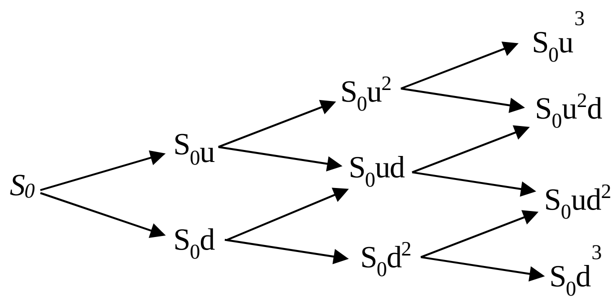


Figure 8.2 Binomial lattice with three time-step

Higher branches of the lattice indicate when the underlying value of the asset of the option is higher. 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 until reaching each node. Backward induction is then applied to determine 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 at a risk-free rate. This weight refers to a risk-neutral probability. Equations (8.3)- (8.5) calculate the up and the down factors and the risk-neutral probability (or, the weight), respectively. Equation (8.6) computes the option value.

$$u = e^{(\sigma\sqrt{T})} \tag{8.3}$$

$$d = 1/u \tag{8.4}$$

$$p = \left(\frac{rf*\triangle t}{u-d}\right) \tag{8.5}$$

$$OptionValue = \left(\frac{(p*\text{Option value at upstage})+[(1-p)*\text{Option value at downstage}]}{e^{(rf*\triangle t)}}\right) \tag{8.6}$$

Where, T = time to maturity: rf = risk-free rate; $\triangle t$ = time step, σ = volatility.

An implicit assumption of path independence is associated with the BL method. This means that the value at any state does not depend on which path is taken to reach that state or how the state is reached.

(b) Monte Carlo Simulation (MCS) Method

Monte Carlo simulation is the most flexible of the three methods for real options valuation. Although MCS involves a large number of computations, this method can be adapted for any option type. For real options, the analysis can be done by tracking the expected trajectory of their underlying value. An approximation technique is used by dividing the option's life into small time steps. As the time step gets smaller, the option value becomes closer to that established using the Black-Scholes formula. The MCS simulation can be carried out using Equation (8.7):

$$S_{t+1} = S_t + S_t\,(r_f\,\Delta t + \sigma\,\varepsilon\,\sqrt{\Delta t}) \tag{8.7}$$

Where: St = value of the underlying asset at time t; St+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 (8.7) 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 using a risk-free rate. The accuracy of this method is influenced by the number of simulation trials and time increments. A major disadvantage of the MCS technique is the enormous computational effort required to produce accurate outputs. The efficiency of this technique is particularly 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 point in time: this is not applicable in for the investment problem context under consideration in this report. In contrast, the American option can be exercised at any point in time before its expiry date: this is the case for the investment problem being analyzed in this report. 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, such computation could be extremely inefficient and tedious. Therefore, for purposes of analyzing AV-related investments, 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 of these methods.

8.3.4 Limitations of ROA and Potential Remedies

ROA assumes a market monopoly. In other words, it postulates that by deferring the proposed investment, the project value does not decline over time but rather increases when the option is exercised. This presumption may not be the case in certain situations particularly in the case of market competition. The integration of Game Theory with ROA, abbreviated as ROG, has been identified by Smit (2003) as a remedy to this restriction. Also, 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 (8.8).

$$\textit{Strategic NPV} = \textit{Direct (passive) NPV} + \textit{Strategic value} + \textit{Value of flexibility} \tag{8.8}$$

The Real Option Games (ROG) approach is useful in identifying optimal investment strategies (Smit, 2003; Smit and Trigeorgie, 2009). Ferreira et al. (2009) developed a payoff matrix before identifying the optimal strategy from game theory. The classic NPV fails to realize the value of flexibility and the strategic value of the investment. The authors noted that, game theory has a major limitation in its inability to incorporate flexibility into the payoff matrix. On the other hand, ROG, can address this limitation because it relaxes the monopoly assumption of ROA and improves the outcome of the game theory incorporation by considering uncertainty and flexibility in the analytic framework.

8.3.5 ROA Parameters

Valuation using 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 could be an indicator of the value of the underlying asset. The risk-free rate is used 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 projects are often unique, and therefore it is often difficult to acquire historical data on real projects for purposes of valuation. From a practical standpoint, the volatility of the project is estimated after simulating the project cash flow using 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 value based on expert opinion (Mun, 2006).

8.3.6 ROA – Discussion

NPV considers a non-dynamic cash flow (using the same discount rate for each period, signifying the same level of risk throughout the entire time horizon of a project investment), which, in reality, 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. 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 could significantly influence the outcome.

On the other hand, the ROA approach offers a structured method for integrating flexibility in the value engineering process. Such flexibility could manifest as the ability to defer, abandon, or proceed with a proposed investment, and more so, to incorporate the value of this flexibility into project evaluation and decision-making. For example, deferring the decision (at the current time or at a future specified time) to another time when conditions are more conducive, for example when new favorable knowledge is available about the project or economic conditions. According to the ROA method, the final solution is that which maximizes the project value both in terms of the project outcomes and the inherent flexibility.

It is important to note that ROA is not a replacement of 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 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 use the ROA method. This is because the value of the option is zero and the project's NPV is the equal to that obtained traditional evaluation approaches.

8.4 Overcoming the Barriers to Effective Evaluation of AV Infrastructure Investments

8.4.1 Political Influences

Often, certain aspects of AV-related investments may not be consistent with prevailing political goals. For example, the need to seek emissions reductions through the proposed investment may be viewed with different priorities by different groups of people. To minimize such influences, it is helpful for the IOO to not only to incorporate the concerns of the general public but also to solicit support of various levels of government (local, state, and federal).

8.4.2 Unstable Goals and Objectives of the IOO

If the AV-related investment is a larger goal sought by the IOO such as increased economic development, enhanced quality of life, increased security and safety, greater mobility, and increased accessibility to raw materials for production or to social centers, improved quity, and so on. The final decision is often a tightrope act that balances these different, often conflicting, goals spawned by the different stakeholders. As society evolves on an issue, changing perceptions lead to a shift in the relative weights of these goals, and a system plan that was once optimal at the time of conception may not be optimal decades later. It is helpful for IOO to predict (and account for) such trends in their long-term investment plans or to add significant flexibility in their infrastructure designs to accommodate any future unforeseen changes in the technological or socio-economic environment.

8.4.3 Difficulty of Achieving Holistic Solutions

The criteria used to evaluate AV investments are often not independent but overlap in ways that lead to synergies among them. The sum of the criteria impacts is often not equal to the impact of the sum of the criteria. AV investments, as much as possible, should be evaluated in the broader context of the effect of other existing or prospective road corridors in the larger system of systems. In certain cases, it may be difficult to achieve such holism do to technical (difficulty of quantifying the interactions among systems) or institutional (difficulty of relating the different sector practices and goals across privately-owned and publicly owned systems). Nevertheless, the IOO should always seek to opportunities that incorporate any synergies from other anthropogenic systems or infrastructure with which the proposed AV-related investment shares a proximal, institutional, or operational relationship.

8.4.4 Multiplicity of Stakeholders and their concerns

It has been shown in practice that in general, solutions that are robust and effective in the long term are those that consider the perspectives of a broad spectrum of stakeholders. However, where the number of stakeholders is rather excessive, this could pose a threat to the integrity of the evaluation. In evaluating AV- related infrastructure investments, all views need to be considered; however, it is often the case that not all these perspectives can be accommodated fully.

8.4.5 Severity of Budgetary Constraints

At the current time when the AV market share is miniscule, autonomous mobility may not be an immediate concern for public IOOs who are already tied up juggling priorities and contending with tight budgets for traditional infrastructure development and operations (Duvall et al., 2019). Nevertheless, some IOOs are already considering providing AV-related infrastructure targeted areas or corridors. This suggests that some IOOs are cognizant of infrastructure challenges in the AV era and are willing and able to start addressing these challenges.

CHAPTER 9. PROJECT-LEVEL AV-RELATED INVESTMENT EVALUATION CONSIDERING UNCERTAINTY: A CASE STUDY

9.1 Introduction

Duvall et al (2019) stated that depending on the extent of AV demand, IOOs will soon begin addressing AV-supporting infrastructure needs in greater detail as part of their capital development plans. As discussed in chapter 8 of this report, AV-related infrastructure investments should be flexible enough to respond to unforeseen and uncertain futures.

Traditional value engineering techniques are generally unable to capture and quantify the monetary value of flexibility and therefore may result in decisions that may be optimal at the inception year only but not over the lifetime of the infrastructure investment. On the other hand, Real options analysis (ROA) identifies the latent value of projects and captures flexibility and can produce more robust long-term investment decisions.

Based on the perspectives of the stakeholders captured directly through survey instruments (Chapter 4) and the needed design changes (Chapter 6), road infrastructure readiness can be evaluated economically for any of at least two scenarios in the specific context of AV lanes:

a) deploying the AVs in the existing lanes in a mixed traffic stream while they share lanes with traditional vehicles; and,
b) providing an exclusive lane for AV operations on freeways.

The IOO and OEM respondents of the survey (see earlier chapters of this report) indicated that freeways are the most likely locations for the initial deployment of AVs. As such, the case study for the investment evaluation involved an Interstate highway corridor from West Lafayette, Indiana to the Indianapolis International Airport, a 4-6 lane, 66-mile section that consists various stretches of Interstate 65, 465, and 70.

9.2 The Binomial Lattice Method for the ROA Analysis

For ROA analysis using the binomial lattice method, Table 9.1 presents the key items used in the computation. The lattice structure for this case study is presented in Figure 9.1. As discussed earlier in Chapter 8 of this report, 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 follows:

$$u = e(\sigma\sqrt{T});\ d = 1/u. \quad (9.1)$$

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 would 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 9.1 Analogies in real and financial options for dedicated AV lane investment

ATTRIBUTE	OPTIONS TYPE	
	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

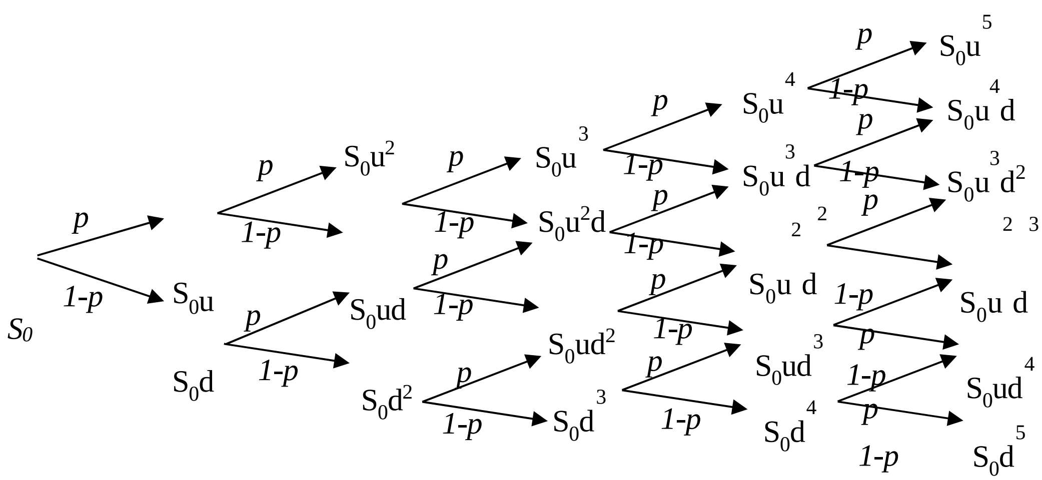


Figure 9.1 Binomial lattice structure for five (5) time steps

Starting with the nodes at the extreme right, the instant cost savings associated with the implementation 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 this, Equations (9.2) and (9.3) were used.

$$\overline{\Omega}_{k,l} = [p * Value_{uppernode} + (1 - p) * Value_{lowernode}] * \exp(-r_f \Delta t) \quad (9.2)$$

$$\begin{Bmatrix} Option\ Value_{k,l} = \max(\Omega_{k,l}, 0)\ if\ l = analysis\ period\ \ and \\ Option\ Value_{k,l} = max(\Omega_{k,l}, \overline{\Omega}_{k,l})if\ l \neq analysis\ period \end{Bmatrix} \quad (9.3)$$

Where:

p, the risk-neutral probability = $(exp[r_f * \Delta t] - d) / (u - d)$

$\overline{\Omega}_{k,l}$ = the expected cost savings at node (k,l); and rf is the risk-free rate. Other symbols are the same as defined earlier. The analysis is based on the American option valuation which allows exercising the option at any point in time before its date of expiration.

9.3 Investment scenario I

9.3.1 Introduction

This scenario assumes that the AVs are deployed at existing lanes in a mixed traffic stream, that is, the AVs share each lane with traditional vehicles. This scenario may be considered generally suitable in cases of low market penetration of AVs. In this scenario, pavement markings can be considered to be an important class of infrastructure to facilitate autonomous driving. A number of studies recommend to not add exclusive lanes for AV operations when market penetration is less than 20% for reasons including equity and possibility of traffic congestion at general-purpose lanes and/or underutilization of the exclusive lanes (NASEM, 2018).

As such, the only item of infrastructure suggested to facilitate AV operations at low market penetration, is high-quality pavement markings (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 from 2 to 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. It has been found to provide reliable visibility and navigation for lane detection and lane guidance systems of AVs under various adverse meteorological conditions (Meeks, 2019; Pike et al., 2019). Past research has shown that 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 resolved.

Currently, for pavement markings, a number of IOOs are 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 annually using waterborne paint (Saeed, 2019). 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 other light-colored roads, and false identification of crack seals, seams, and other marks as lane markings.

It is assumed that an improvement in road safety (a decrease in road crashes) and congestion (a decrease in travel time delay) occurs with the installation of wet reflective pavement markings to support AV operations on the Interstate highway corridor (with an AV market penetration of ≤15%). The analysis period used is 10 years. It is assumed that after AVs are initially deployed, the percentage of AV users traffic stream (which could be considered a proxy for penetrating) not significantly exceed 15% over the 10-yr period.

9.3.2 Quantification of Cost Components

This step involves quantification of key cost components: agency costs and user costs. The agency's cost consists of the cost of wet-reflective pavement marking installation and its annual maintenance cost. The user costs are the travel time cost and the crash cost. The initial capital cost and annual maintenance cost were estimated based on the cost values and service life estimates noted in the previous section. A user cost to agency cost weight ratio of 1:1 was used. In other words, $1 of agency cost was assumed to be equal to $1 of user cost. A conservative estimate of 3 years was used to represent the pavement marking service life.

To estimate the crash cost savings, crash data were acquired from the Center for Road Safety at Purdue University. On average, the study corridor was found to have 43 fatal/incapacitating injury crashes, 95 non-incapacitating/possible injury crashes, and 789 property-damage-only crashes annually. The 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 50,000 vehicles per day (two-way combined) on average. For computing the travel time savings, an average of $17 per hour per vehicle was used (Schrank et al., 2012).

9.3.3 Results and Discussion

Figure 9.2 presents the results of analysis for the first scenario. Sensitivity analysis was carried out using four different discount rates: 3%, 5%, 7%, and 10%. The U.S. Office of Management and Budget (OMB) requires using a discount rate of 7% for federal projects (LaHood, 2011). The base analysis used a discount rate of 7% and 10%. 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. These assumptions appear to be justified by the findings from past research. Several studies have established that with increased AV market penetration, the benefits to both users and agencies will increase significantly(Tientrakool, 2011; Atiyeh, 2012; Shladover et al., 2012; NAE, 2018). For example, Fagnant and Kockelman (2015) assumed: 50% crash reduction and 15% travel time delay reduction at 10% AV market penetration on freeways; 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.

The results of the analysis (Figure 9.2) indicate that the user benefits consistently outweigh the agency costs at all the discount rates considered. 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, IOOs can initiate AV-related freeway retrofitting with this basic investment of deploying wet reflective tape markings across freeways, arterials, and other major streets. Such an investment could be easily made system-wide (across the entire state), which may incentivize greater demand for AVs.

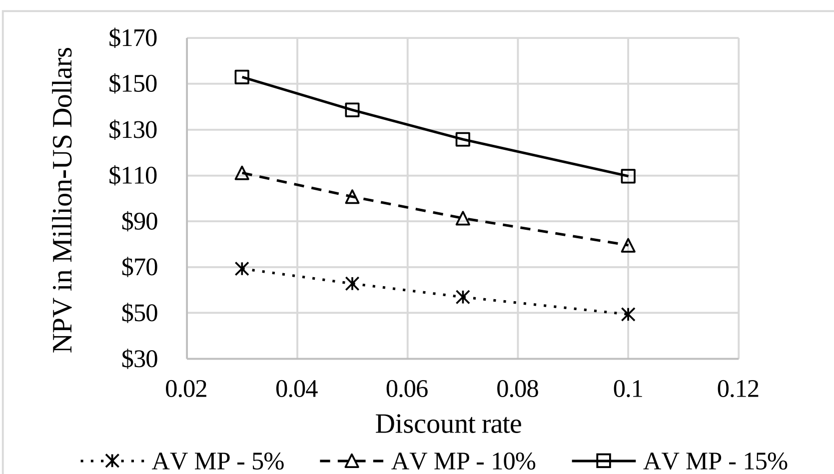


Figure 9.2 NPV outcomes at different levels of AV market penetration

9.4 Investment scenario II

9.4.1 Introduction

From the stakeholder responses to the survey questions presented in Chapter 4, it was recognized that the key stakeholders expect high-speed freeways will be the roadway class to first host AV operations. This could be attributed to their superior pavement and geometric designs, higher number of lanes, limited access and fever traffic conflict compared to the other road classes. In the survey, forty-one percent (41%) of OEM respondents and 44% of IOO respondents suggested allocating a dedicated lane for AV freeway operations at the early stages of AV deployment on the public roads.

The IOO's costs include primarily, the costs of AV-dedicated lane (1 in each direction) construction, and rehabilitation, and maintenance. The user benefits are represented by reductions of crash occurrences and travel time. Further, AV platooning at the dedicated freeway lanes potentially offers an additional benefit (fuel cost savings) to the users. All the costs and benefits can be quantified in monetary values, and the net economic impact calculated. The economic evaluation was carried out using two alternative approaches: NPV and ROA.

Regarding the ROA approach, the binomial lattice (BL) and Monte Carlo simulation methods were used to determine the value of the option. It may be noted that BL method is often recommended in real practice because it facilitates tracking of the project value throughout the period of analysis and has low computational effort.

A user and agency cost weight ratio of 1:1 and an analysis period of 5 years were used. 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 consist of 35% reduction in crashes, a 25% reduction in fuel consumption, and 25% in travel time savings. Some studies suggest the addition of exclusive AV lanes at market penetration rates greater than or equal to 20% (TRB, 2018).

<u>9.4.2 Results and Discussion</u>

This section discusses the methods used to analyze this scenario and the results.

9.4.2.1 NPV Method

Figure 9.3 presents the NPV outcomes for Scenario II (providing a dedicated lane) and Figure 9.3 presents the NPV outcomes for each of the four discount rates. With an increase in the discount rate (that helps offset the effect of 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. Moreover, the analysis was repeated to account for the trade-off between the weights of the agency cost (AC) dollar vs. the user cost (UC) dollar, by using different weight ratios. This influences the feasibility of the proposed investment and the optimal decision. Figure 9.4 suggests that the proposed addition of a dedicated AV lane is no longer viable when the agency cost dollar for outweighs the user benefit dollar (AC/UC weight ratio exceeds 3).

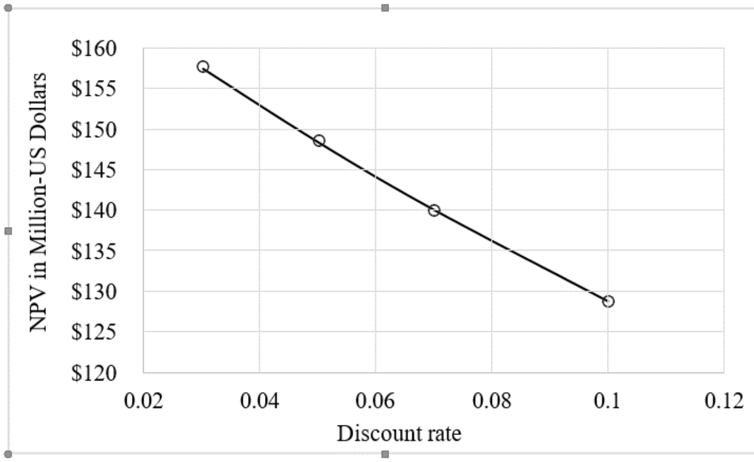


Figure 9.3 NPV outcomes for Scenario II (providing a dedicated lane)

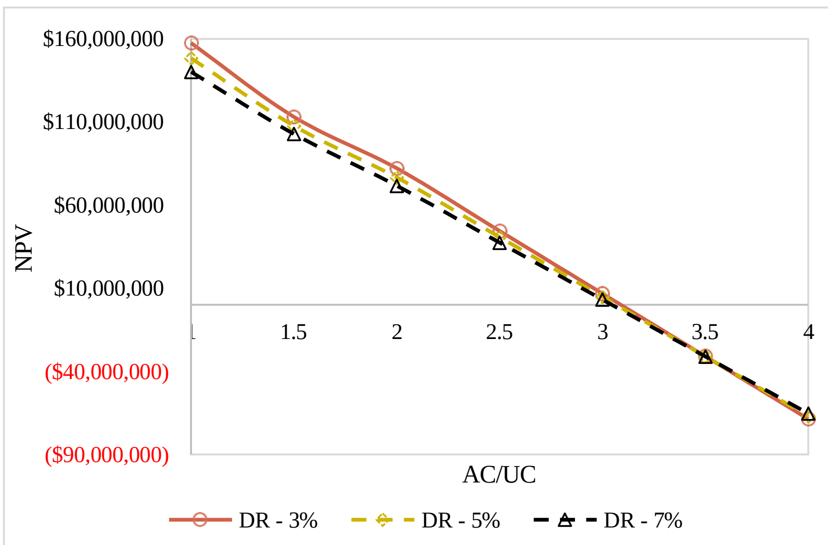


Figure 9.4 Sensitivity analysis of NPV w.r.t agency and user dollar weights

9.4.2.2 The ROA Method

Table 9.2 and 9.3 present the underlying values of the dedicated AV lane (computed forward in time) and the value of the defer option respectively, using Equations (9.2) and (9.3), 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 in year 5, the underlying value is $813M which exceeds the strike price. The option can be rationally exercised (meaning that the proposed addition of a dedicated AV lane can 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 9.3 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 determine the option value at each node. The value of the proposed project if it is implemented at the current time, can be determined as 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.

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 can be calculated as max ($558M, $560M) = $560M. Equations (9.2) and (9.3) were used for these computations. The amounts shown in Tables 9.2 and 9.3 are in the units of million US dollars.

Table 9.2 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 9.3 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 9.3, at year 5 and node *S0u2d3* (the cells highlighted grey in Tables 9.2 and 9.3), the option may be allowed to expire, and the project may be carried out (that is, the AV-dedicated lane may be constructed). As evident in this case, the ROA approach considers and monetizes the flexibility inherent in a project. This flexibility in this case, is the possibility to wait and observe what the level of uncertainty (AV market penetration) is. It is evident from Table 9.3 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 decide 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 9.5 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.

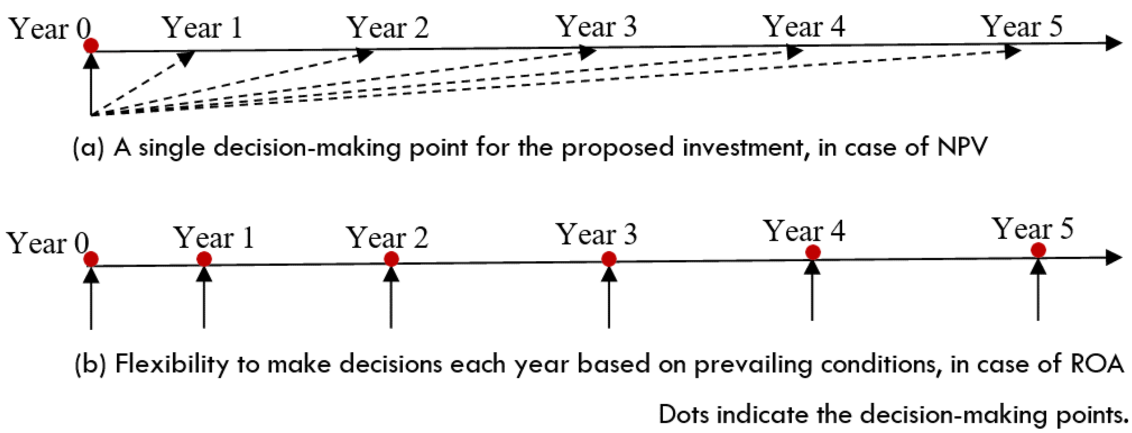


Figure 9.5 Illustration of decision-making points in NPV and ROA methods

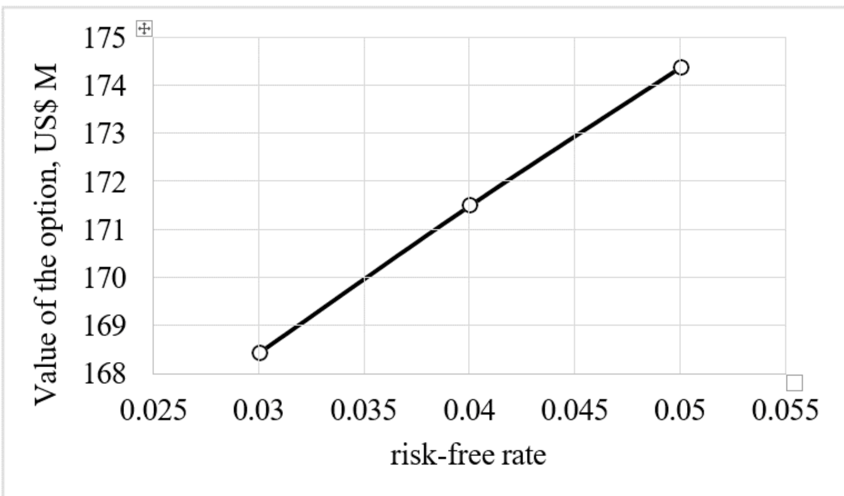


Figure 9.6 Sensitivity of the option value to the risk-free rate Monte Carlo Simulation Method

The analysis was repeated several times to investigate the sensitivity of the option value to the key factors of the evaluation, namely, the volatility and the risk-free rate. Figure 9.6 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.

Table 9.4 presents the results of 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, the table presents only a small subset of the outcomes of these trials. 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 9.4) is 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 9.4 are discounted to determine the present values, for all the simulation trials. These present values are presented in the last column of Table 9.4; the value of the option is equal to the average of these present values. Using the MCS method, it is found that the option can be exercised 96.78% of the times over the lifetime of the option (5 years). The value of the option is determined as $167.49M, which is approximately equal to that determined found using the BL method ($168M). 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, the MCS method involved a significant amount of computational effort.

Table 9.4 Valuation of the option "defer," using the MCS approach.

	Time step increment											**Value of the proposed investment**	**Expanded NPV**
Trials	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**		
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.

9.4.3 Limitations

Currently, there is lack of real-world evidence of the potential benefits of AV operations on existing roads. However, simulation studies to date have shown that AVs will provide several benefits in terms of safety, congestion reduction, travel across, and so on. In this study, the analysis used forecasts from past simulation studies and some assumptions to quantify the user benefits of AV operations. Compared with forecasts from past simulation studies, the assumptions regarding the benefit estimates used in this analysis, were relatively conservative. There is an opportunity to revisit the assumptions in the future era of AV deployment using the actual values of observed benefits (savings in crash cost, travel time, and fuel consumption). Nevertheless, this study presents a framework that can help IOOs account for AV market penetration uncertainty into their AV- infrastructure decision-making. This framework can, be used to analyze possible scenarios of AV infrastructure investments.

9.5 Discussion

This chapter presented an economic evaluation of two scenarios AV-infrastructure investment using a 66-mile (a 4-6 lane highway). This highway corridor runs from West Lafayette to Indianapolis International Airport. The first scenario was based on low AV market penetration (≤ 15%,) and the investment is road pavement marking with AV-friendly material to assist the lane keeping and lane guidance systems of AVs. This scenario assumed traffic mixing that is, AVs share lanes with HDVs. The agency and user cost components were identified and quantified. An agency/user cost weight ratio of 1:1, was used. Using the NPV method, it was found that the user benefits outweighed the agency's costs. The second scenario was based on adding a dedicated lane for AVs at the freeway corridor by converting the inside/left shoulder into a travel lane. This involved conversion of the shoulder into a relatively narrow AV travel lane and remarking the pavement. 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. This scenario was evaluated economically using the NPV and ROA approaches.

The scenario involving a dedicated lane provision was found to be beneficial using both approaches. The ROA approach additionally determined the time (years) by which the agency could delay the implementation of this investment, based on the nature of uncertainty associated with AV market penetration. This 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 Monte Carlo simulation. Using the BL method, the value of the option could be tracked throughout the analysis period with low computational effort. 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 conventional NPV approach helped address the decision-making at the start of the proposed project but is unable to account for the uncertainty associated with the AV market penetration. 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.

Future research could consider a broad range of agency, user, and non-user impacts and revisit the problem formulation 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 consider other evaluation criteria including emissions, cybersecurity, and other social and environmental impacts.

CHAPTER 10. A FRAMEWORK FOR NETWORK-LEVEL AV-RELATED INVESTMENT PLANNING CONSIDERING HOLISTIC EFFECTS

10.1 Introduction

Parking infrastructure plays a vital role in today's urban transportation networks. To address the parking needs of commuters and travelers in such areas, city road agencies provide on-street and off-street parking facilities. However, these consume a rather excessive amount of land space in downtown areas. Further, the management and operations of urban parking continue to pose a serious issue in several cities. This has been attributed to poor location design of parking facilities and inefficiencies in their capacity management. The emerging era of autonomous vehicle (AV) operations presents promising benefits not only from road capacity, safety, and emissions perspectives, but also from perspective of to urban parking. The capability of autonomous vehicles to operate without human input makes it possible for the vehicle occupant to disembark at the trip destination and direct the AV to park anywhere, even outside of the city center. Therefore, AVs can mitigate the lengthy out-of-vehicle travel time typically expended by commuters on getting to/from the parking facility to/from their destination.

With reduced demand for parking downtown as a result of this nature of AV use, some of the parking infrastructure currently at downtown locations will eventually see significantly reduced demand and, ultimately, possible decommissioning and repurposing. Then, new parking infrastructure will be needed at the city's outskirts to serve demand primarily driven by the AVs in an era of high AV market penetration. Such translocation of current parking facilities to the city outskirts could result in the availability of valuable city-center land at the erstwhile parking facility locations. This could be repurposed towards alternative uses that include capacity expansion for road lanes or rail lines, or for facilities that improve urban quality of life, such as, new recreation centers, green areas, commercial areas, and active transportation hubs (Kellett et al., 2019). Therefore, the translocation of parking facility infrastructure to outlying areas could be beneficial overall as it fosters new urban planning paradigms.

The ability of commutes to dispatch their AVs (after being dropped at work) to outlying parking lots where parking is prospectively cheaper compared to city parking, could lower the vehicle operations costs of the AV owner. However, AVs, despite their potential to finally solve the vexing problem of urban parking, could engender unintended consequences. In the short term, AVs may spend significant time in traffic searching for parking, exacerbating road congestion and causing increased travel times for road users, including human-driven vehicles (HDVs). In the long term, HDVs that use the parking infrastructure relocated to the city outskirts may experience additional travel delays as they will have to travel from their origins to these parking locations or from these parking locations to their destinations. Any hastened implementation of such parking location shifts could worsen this potentially inequity. Therefore, developing a modeling framework that integrates both parking supply and demand, and prescribes optimal locations for parking facilities on a city road system can be beneficial for road users and the city road agency. Further, the management framework, ideally, should be capable of addressing issues of traveler inequity.

In the literature, there exists two groups of studies on parking facilities and road networks. The first group evaluates parking facility locations and their corresponding impact on traffic mobility. Zhang et al. (2019a) proposed a model involving an AV fleet to analyze the route and parking preferences of AV travelers simultaneously. Zhang et al. (2020) developed a model that integrated traffic and dynamic equilibrium to consider the parking patterns of AVs and to study their overall societal impacts. These studies generally found travelers, costs could be reduced when AVs are used relative to HDVs but cautioned that the non-occupant cruising of AVs while searching for parking could exacerbate traffic congestion. Zhang et al. (2019b) studied a morning-evening commute problem in a fully automated environment, considering a single work region, residential area, and parking location. The authors assumed that AVs travel from their parking location to pick up their passengers and drive them home. They focused on commuters' trip departure patterns and studied system optimal design of the network under an optimal tolling scheme. In a similar study, Su and Wang (2020) addressed morning commute problems but considered AV parking options. The authors assumed that AV chose their parking locations from a variety of options, including CBD parking spots that are near the workplace or home and shared parking located farther from the workplace locations. They studied the impact of available parking pricing on traffic congestion. Other studies presented parking assignment tools to alleviate the adverse impact associated with AV cruises and parking searches.

Zhao et al. (2021) presented a parking dispatching framework to help AVs identify available parking locations. The authors framework used macroscopic fundamental diagrams to model the flow of mixed traffic on the road network. Zhang et al. (2022) proposed a framework for the real-time assignment of parking to vehicles in a mixed-traffic environment (that is, where both connected and non-connected vehicles share the roadways). Their model incorporated multiple agents and a deep reinforcement method that resolved the issue of partial observations regarding parking demand and long-term road network performance. These studies provided valuable insights on the parking behavior of prospective AV users. However, they did not address the immediate impacts on HDV users' parking and travel behaviors, the long-term impacts of new parking infrastructure translocation and decommissioning of existing parking facilities in downtown areas.

The second group of literature addresses the parking facility location problem. While a large number of studies address the well-known facility location problem (FLP) (Zanjirani and Hekmatfar, 2009; Melo et al., 2009), only a small number of them focused on the parking facility location problem (PFLP). Most of the early PFLP studies did not investigate the effects of new parking infrastructure on network congestion and travel equilibrium conditions (Jelokhani-Niaraki and Malczewski, 2015; Chiu, 2006; Kazazi Darani et al., 2018). These studies implemented multi-criteria decision-making frameworks. For example, Jelokhani-Niaraki and Malczewski (2015), found the ideal locations for constructing new parking infrastructure by using a holistic multi-criteria framework. With GIS and considered population density adjacent to potential locations of parking infrastructure. This line of groundbreaking research on parking facility location problems (PFLPs) introduced practical frameworks that could be deployed by the city road agency. However, there exist challenges in determining the "optimal" parking facility locations using these frameworks. Furthermore, these studies lack consideration of the response of travelers to new parking facility locations.

There exist yet other group of PFLP studies that did not consider traffic congestion in their optimization methods. In one of the early studies in the PFLP literature, the objective was to minimize a battery of costs (maintenance, operations, and construction) related to parking facilities through a multi-objective optimization framework (Chiu et al., 2006). Furthermore, in their research, (Eskandari and Shahandeh, 2018) considered parking demand coverage as a crucial criterion. Du et al. (2019) considered traffic equilibrium conditions and parking search cruising and analyzed the PFLP for morning travelers. Their study sought to minimize the overall delay for travelers. In the case study, a working area within a few blocks was analyzed to find the optimal off-street and on-street parking locations.

Levin et al. (2020) assessed the influence of road traffic congestion on parking facility design in a mixed traffic environment (both AV and HDV travelers). However, by assuming the existence of a parking facility for HDV travelers at their destinations, the need for "last-mile" travel was not considered. In their case study, all nodes were destinations for HDV travelers, therefore it was assumed that there existed parking facilities at every node. Then the extra capacity needed for AV travelers at each parking facility was determined. That study did not address the equity of HDV users, nor was the possibility of decommissioning existing parking facilities considered.

The past studies provided valuable and significant insights and useful frameworks regarding the problem of urban parking in the AV era. Yet still, there exist a few gaps in the literature that could be addressed to shed more light on this problem. First, the planning-horizon schedule for constructing the parking facilities and possible decommissioning of existing parking infrastructure for more effective land use, could be considered. In an attempt to address such lacuna in published literature, the present study addresses the city network parking facility redesign problem by presenting a methodology for determining the corresponding optimal capacities and locations over a given planning horizon. In other words, this study's methodology considers not only the gradual provision of new parking infrastructure at selected locations on the city's outskirts but also the decommissioning of selected existing facilities within the city. This covers the parking management aspect of the existing literature on infrastructure management for emerging technologies (Seilabi et al., 2022). Moreover, the present study considers social equity among AV and HDV travelers by proposing a long-term parking pricing strategy.

There are two main contributions of this study. First, a bi-level, multi-period framework is developed in which the transportation decision-maker seeks to maximize the benefits associated with (a) repurposing land occupied by existing parking facilities, and (b) parking fee revenues. This is done while minimizing the overall cost of road users' travel time. Bi-level modeling is a popular method in transportation network design literature and is implemented in several studies (Chen et al., 2016; He et al., 2018; Chen et al., 2017; Miralinaghi et al., 2020; Madadi et al., 2021; Miralinaghi et al., 2022; Saneii et al., 2022; Pourgholamali et al., 2023(a)). Next, this study uses a novel optimal, differentiated, location-based parking pricing strategy in a mixed fleet traffic environment. In a bid to address equity considerations, the analysis includes a constraint to ensure that the equity related ratio of HDV travel cost to AV travel cost (HATCOR) ratio, is kept within a pre-specified upper bound in any period of the planning horizon.

In the remaining sections of this chapter, we first present the study framework and its components. Then, the solution algorithm is presented. Next, the results of numerical experiments are demonstrated and discussed. Finally, concluding remarks are provided.

10.2 Methodology

The study uses a bi-level framework to model the proposed parking facility location/relocation/ decommissioning and pricing problem (as shown in Figure 10.1). The monetary benefits of parking facility decommissioning, as well as its revenues, are maximized at the upper level. The overall or total system travel cost of network users is minimized at a lower level. The travelers minimize their costs of travel by choosing parking locations and routes based on the upper-level decisions. In the rest of this section, preliminaries of the bi-level framework are presented first, followed by a discussion of the models used at each of the two levels of the overall framework.

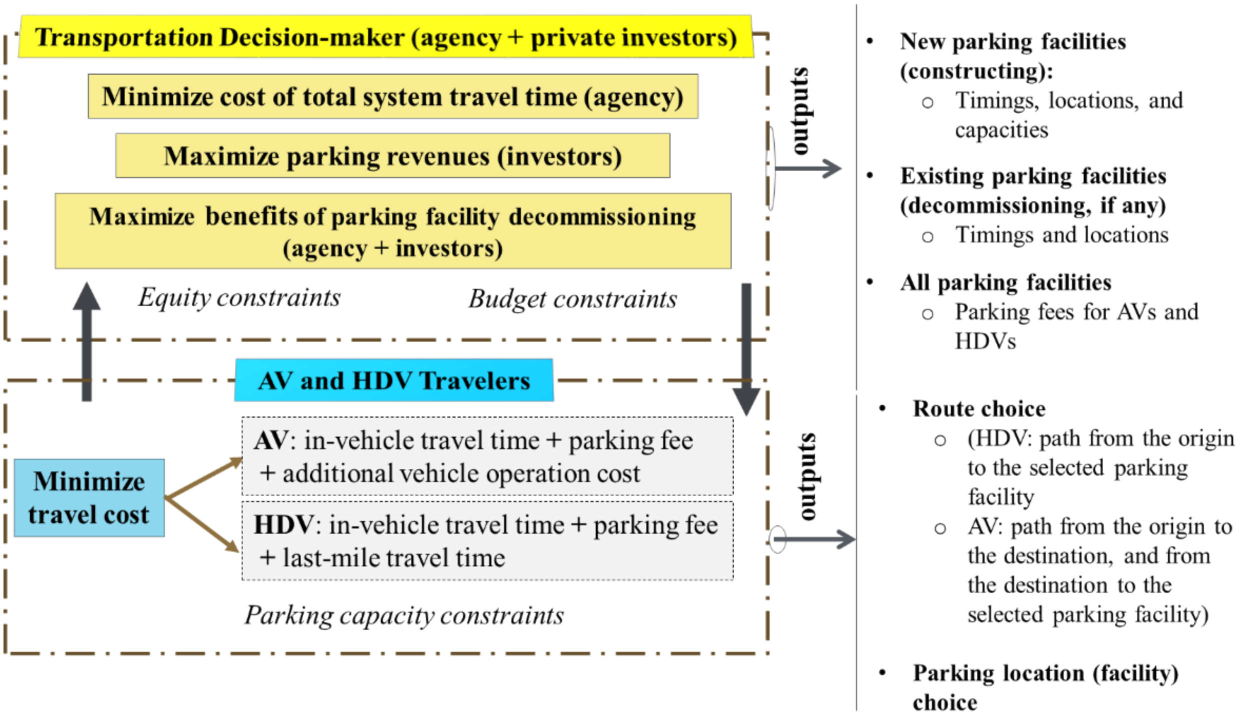


Figure 10.1 The structure of the bi-level optimization framework

10.3 Preliminaries

Let A and N denote the set of links and nodes of a city road network. G=(N,A) represents the city road network. In this research, a number of assumptions were made. The road users are either (i) daily travelers or commuters that need a parking facility to park their vehicle (sub-class 2, $\overset{\frown}{g} = 1$), or (ii) daily travelers or commuters that have parking at their trip destination, which could be their homes or workplaces, (sub-class 2, $\overset{\frown}{g} = 2$), irrespective of their user class (HDV vs. AV). Further, this study assumes AVs are not sent back to their travel origins, which often, the AV owners' residence (for parking or day-to-day purposes such as family use). Third, all AVs in the network are assumed to be privately-owned and personal, and not owned operated by a ridesharing company. In other words, the number of shared AVs is negligible. Fourth, the decision maker (road agency) designs different fee levels for parking (the fee is constant within each planning period). Lastly, it is assumed that parking capacity, once established through facility construction, will not change in the subsequent periods. It is further assumed that users are unable to use an existing parking facility for parking purposes after it is decommissioned. That is, in the entire analysis horizon, each parking facility can go under construction or be decommissioned only once. Table 10.1 presents the summary of notations.

10.3.1 The Upper-Level Model

At this level, the objective of the agency (decision-maker) is to minimize the total system travel cost, parking revenue, and prospective benefits of existing facilities decommissioning by making decisions regarding: (i) decommissioning of existing parking facilities; (ii) the differentiated parking fees (AV vs. HDV); and (iii) the capacity and location of new parking facilities. Let ξ_1, ξ_2, ξ_3 denote the relative weights of overall systemwide travel time, overall revenue from parking fees, and the monetary benefits associated with decommissioning current parking infrastructure, respectively.

In practice, the road agency or decision-maker uses weights that are consistent with the agency's mission, strategic plan, or priorities. Sinha et al. (2009) presented different weighting methods for transportation facility management, which require questionnaire surveys to collate the preferences of different stakeholders, including the road agency and road users. A few examples of these methods are: the direct weighting method (i.e., the direct assignment of numerical values to each stakeholder's goals) and the observer-derived weights method (i.e., using regression analysis to understand the different stakeholders' subjective evaluation). In this study, our model formulation suggests that, in general, for agencies that assign a higher weight to their benefits, parking fee revenue, or prospective benefits of existing parking facilities decommissioning, the optimal decisions are often associated with decommissioning the existing parking facilities in downtown areas and maximizing the parking fees for the new parking facilities. This might lead to the high overall costs of travel incurred by the travelers. On the contrary, for agencies that assign a higher weight to the users' benefit (travel cost reduction), the optimal decision will be generally associated with the construction of more parking facilities at the candidate locations, as this facilitates users' access to parking and reduces their parking fees. However, this reduces the agency's benefits. Therefore, there seems to exist an implicit trade-off between the benefits of travelers (road users) benefits and that of agency.

$$\text{Min } Z^U = \xi_1 \Upsilon_1 - \xi_2 \Upsilon_2 - \xi_3 \Upsilon_3 \qquad 10.1$$

$$\Upsilon_1 = \sum_{t\in T} \sum_{(i,j)\in A} \Delta^t (\theta_t^{HDV} \sigma_{i,j}^t x_{i,j}^t + \theta_t^{AV} \sigma_{i,j}^t y_{i,j}^t) + \sum_{t\in T} \sum_{s\in S} \sum_{k\in K} \Delta^t \theta_t^{HDV} x_{k,d_2^s}^{s,t,1}\, \bar{g}\, g_k^{s,t} \qquad 10.2$$

$$\Upsilon_2 = \sum_{t\in T} \sum_{k\in K} \Gamma_k^t \qquad 10.3$$

$$\Upsilon_3 = \sum_{t\in T} \sum_{k\in K'} (\omega_k^t (1-\delta_k^t) - \bar{\omega}_k^t (\delta_k^t - \delta_k^{t-1})) \qquad 10.4$$

$$\frac{u_{r,s,AV}^{t,1}}{u_{r,s,HDV}^{t,1}} \geq \varphi^t \qquad \forall (r,s) \in W, \forall t \in T \qquad 10.5$$

$$\frac{u_{r,s,AV}^{t,1,pre}}{u_{r,s,HDV}^{t,1}} \geq \upsilon^t \qquad \forall (r,s) \in W, \forall t \in T \qquad 10.6$$

$$\sum_{k\in K} f_k^t (\vartheta(Q_k^t, \delta_k^t) - \vartheta(Q_k^{t-1}, \delta_k^{t-1})) \leq B^t \qquad \forall t \in T \qquad 10.7$$

$$\delta_k^{t+1} \geq \delta_k^t \qquad \forall k \in K \qquad 10.8$$

$$\delta_k^t \leq Q_k^t \leq \varsigma \delta_k^t \qquad \forall k \in K \qquad 10.9$$

$$\delta_k^{t+1} - \delta_k^t \leq Q_k^{t+1} - Q_k^t \leq \varsigma \cdot (\delta_k^{t+1} - \delta_k^t) \qquad \forall k \in K \qquad 10.10$$

$$\delta_{k'}^1 = 1 \qquad \forall k' \in K', \forall t \in T \qquad 10.11$$

$$\delta_k^{t+1} \leq \delta_k^t \qquad \forall k \in K' \qquad 10.12$$

$Q_{k'}^t = \bar{Q}^{k'} \delta_{k'}^t$ $\forall k \in K'$ 10.13

$\sum_{k \in K \cup K'} \gamma_k^t\ Q_k^t \geq \sum_{m \in M} \sum_{(r,s) \in W} q_{r,s,m}^{t,2}$ $\forall t \in T$ 10.14

$\delta_k^t \leq H_{k,m}^t \leq \varrho \delta_k^t$ $\forall m \in M, \forall k \in K, \forall t \in T$ 10.15

$x \in x^{UE}, y \in y^{UE}, v \in v^{UE}, u \in u^{UE}$ 10.16

$\delta_k^t \in \{0,1\},\ Q_k^t \in \{0,1, \dots, \varsigma\},\quad H_{k,m}^t \in \{0,1, \dots, \varrho\}$ $\forall k \in K, \forall t \in T, \forall m \in M$ 10.17

The following mixed-integer nonlinear problem (MINLP) is used to formulate the upper-level model: the objective function (10.1) has three weighted components. The first (Equation 10.2) represents the systemwide travel time incurred by the travelers. This is the sum of the last-mile (where applicable) cost and the in-vehicle costs of travelers. The second component (Equation 10.3) is the parking fee revenue, and the third component (Equation 10.4) is the prospective monetary benefits associated with decommissioning and repurposing a number of existing parking facilities. Equation 10.5 sets a pre-determined threshold for each OD pair in each period to constrain the difference between the travel costs of HDV travelers of sub-class 1 and the travel costs of AV travelers to a pre-determined threshold: Equation 10.5 represents this HATCOR equity constraint. Similarly, Equation 10.6 keeps the travel cost of HDV sub-class 1 travelers in each period from growing considerably compared to their travel cost in the previous period. This is represented by Equation 10.6, the HTCOR equity constraint.

Equations 10.7 – 10.10 reflect the constraints regarding the construction of new parking facilities. The budget constraint is reflected by Equation 10.7 for providing new parking infrastructure within each planning period t. That is, $\delta_k^t = 1$, and $Q_k^t = Q$ for $\forall t \geq t'$ if parking facility k having capacity Q, is provided within the planning period t'. Further, in period t, the term $f_k^t \cdot (\vartheta(Q_k^t, \delta_k^t) - \vartheta(Q_k^{t-1}, \delta_k^{t-1}))$ in constraint 10.7 will be equal to the cost of providing parking facility k of level Q, (that is $f_k^t \cdot \vartheta(Q, 1)$). Equation 10.8 ensures that a parking facility built in a given period will be available in subsequent periods. The capacity limits of each parking facility are expressed using Equation 10.9 based on the availability of that parking facility in each period. Equation 10.10 ensures that the capacity of a parking facility remains unchanged after construction.

Equations 10.11-10.13 are related to the possible decommissioning of existing parking facilities. Equation 10.11 describes the availability of parking facilities in the initial period. Equation 10.12 specifies the possibility of future unavailability in the next period of a currently available parking facility. The equation also states that a decommissioned parking facility cannot provide parking service for the rest of the analysis horizon after it is decommissioned. Equation 10.13 specifies that for a parking facility that is still available in a given period t, its capacity is the same as its initial capacity; that is, its capacity is constant.

Equation 10.14 balances the parking supply and demand of HDV users and does the same for AV users. Equation 10.15 guarantees the non-negativity of the parking fee level at each parking facility for AV or HDV. This equation also limits the fee level to the maximum fee level, ϱ. Equation 10.16 uses the output of the lower level to establish the overall travel cost of each traveler (user) class and sub-class, and O-D and link travel times. Finally, Equation 10.17 indicates the acceptable domains for each upper-level binary or integer decision variable.

10.3.2 The Lower-Level Model

The users' travel costs are minimized considering both the available parking facility and the selected route at the lower level. The parking and travel behavior of sub-class 1 HDV and AV users is presented in Figure 10.2. The HDV user's travel cost in sub-class 1 includes the last-mile time of travel, that is, after parking the vehicle, the walking or shuttle time to the destination, the parking fee, and for the return leg of the trip, the walking or shuttle time from the origin to the parking facility. For sub-class 2, as the parking spots are available at the destination for this subclass, their travel cost includes only the travel time of the HDV users in sub-class 2 from their origins to destinations. The travel costs of travelers in AV sub-class 1 consist of operation fees, parking fees, and their O-D travel time. The travel cost of AV travelers in sub-class 2, similar to HDV travelers, includes only their O-D travel time. Note that no improvement in the travel costs can be obtained by unilaterally changing choices under equilibrium conditions.

Based on the exclusive or mutual behaviors of travelers (which are HDV or AV users), the lower-level model can be divided into three parts: Part I examines the mutual behavior of both AV and HDV travelers; Part II captures AV's travel behavior exclusively; and Part III represents HDV travelers' travel behavior exclusively.

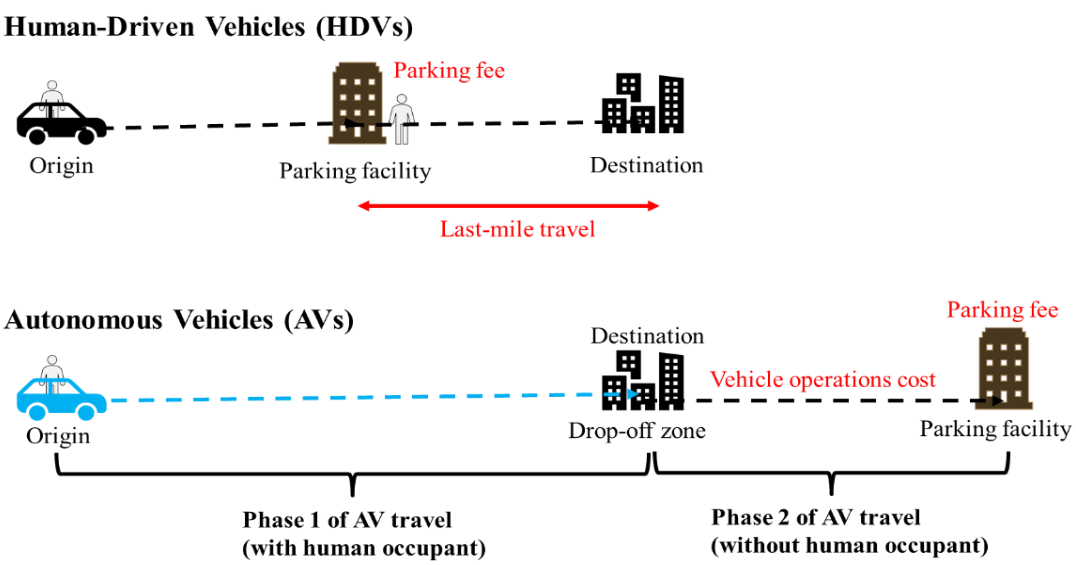


Figure 10.2 Travel and parking behavior modeling of sub-group 1 of AVs and HDV travelers

<u>Lower-level Model Part I: The travel of both AVs and HDVs</u>

The travel behaviors of AV and HDV travelers are formulated as below:

$$\sigma_{ij}^{t}\left(v_{i,j}^{t}\right) = \sigma_{0,i,j}^{t}\left(1 + 0.15\left(\frac{v_{i,j}^{t}}{\chi_{i,j}^{t}}\right)^{4}\right) \qquad \forall (i,j) \in A - A^{D}, \forall t \qquad 10.18$$

$$\sum_{s \in S} x_{k,d_1^s,1}^{s,t} + \frac{1}{\aleph} \cdot \sum_{s \in S} y_{k,d_2^s,1}^{d_2^s,t,2} \leq Q_k^t \cdot \gamma_k^t \qquad \forall k \in K, \forall t \in T \qquad 10.19$$

$$0 \leq \rho_k^t \perp \left(-\sum_{s \in S} x_{k,d_m^s,1}^{s,t} - \frac{1}{\aleph} \cdot \sum_{s \in S} y_{k,d_2^s,1}^{d_2^s,t,2} + Q_k^t \cdot \gamma_k^t\right) \geq 0 \qquad \forall k \in K, \forall t \in T \qquad 10.20$$

$$v_{i,j}^{t} = \sum_{\hat{g}} \sum_{s \in S} x_{i,j,\hat{g}}^{s,t} + \sum_{\hat{g}} \sum_{s \in S} y_{i,j,\hat{g}}^{s,t,1} + \sum_{s \in S} y_{i,j,2}^{d_2^s,t,2} \qquad \forall (i,j) \in A, \forall t \in T \qquad 10.21$$

$$\Gamma_k^t = \sum_{s \in S} x_{k,d_m^s,1}^{s,t} \cdot \bar{\Psi}^t H_{k,HDV}^t + \sum_{s \in S} y_{k,d_2^s,1}^{d_2^s,t,2} \cdot \bar{\Psi}^t H_{k,AV}^t \qquad \forall k \in K, \forall t \in T \qquad 10.22$$

The link travel times are captured by the BPR link-performance function in equation 10.18. Equation 10.19 limits the number of parked vehicles at a parking facility to the parking capacity, in each analysis time step. The smaller parking space requirement of AVs (compared to HDVs) is considered by using the parameter ℵ (ℵ>1) in this equation. Note that that Q_k^t is equal to zero in the case that parking facility k is not available. The travelers' extra cost due to the time delay experienced when a parking facility is not available for parking or when it is full, is captured by the complementarity equation 10.20. For each parking facility in each period, Equations 10.21 and 10.22 specify the total aggregate flow for each link and total parking revenue, respectively.

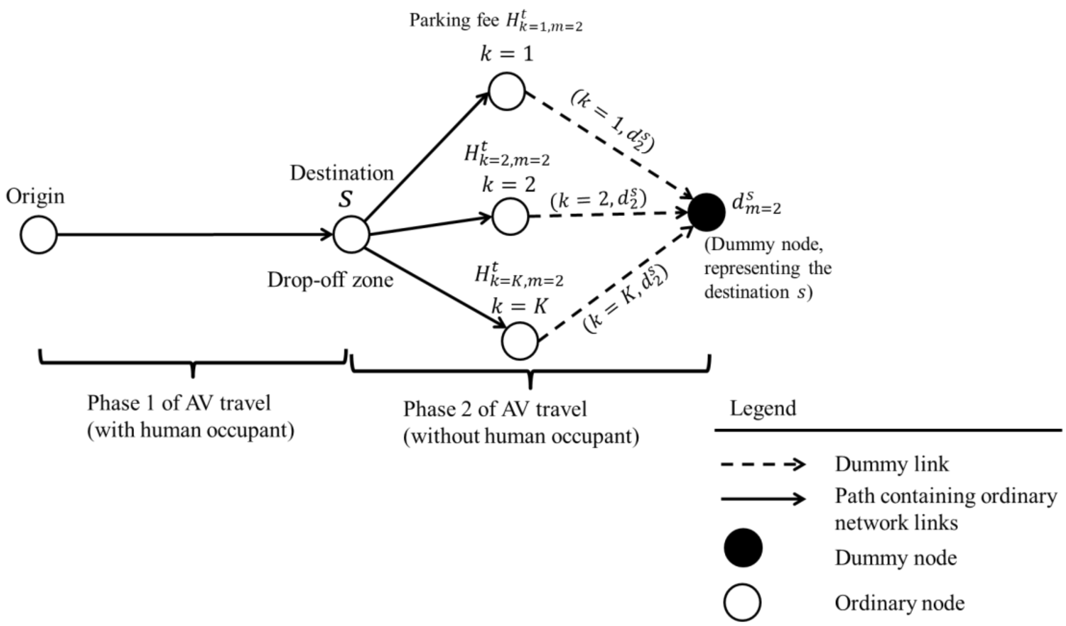
Lower-level Model Part II: The travel of AVs

The AV user may prefer to dispatch their vehicle to a parking facility of their choice after disembarking at their destination. Each AV trip consists of two phases (Figure 10.2). During the first phase, both sub-classes of AV users incur in-vehicle travel costs, irrespective of their parking requirements, as they are physically present in the vehicle. The AVs of the sub-class 1 start another trip, which is phase 2 of AV travel (without the passengers), to park at their desired parking facilities as soon as their users disembark from their vehicles at the drop-off zones. During this phase, the AV user incurs vehicle operations costs associated with their AV's empty trip after the drop-off to the parking location and the parking fee.

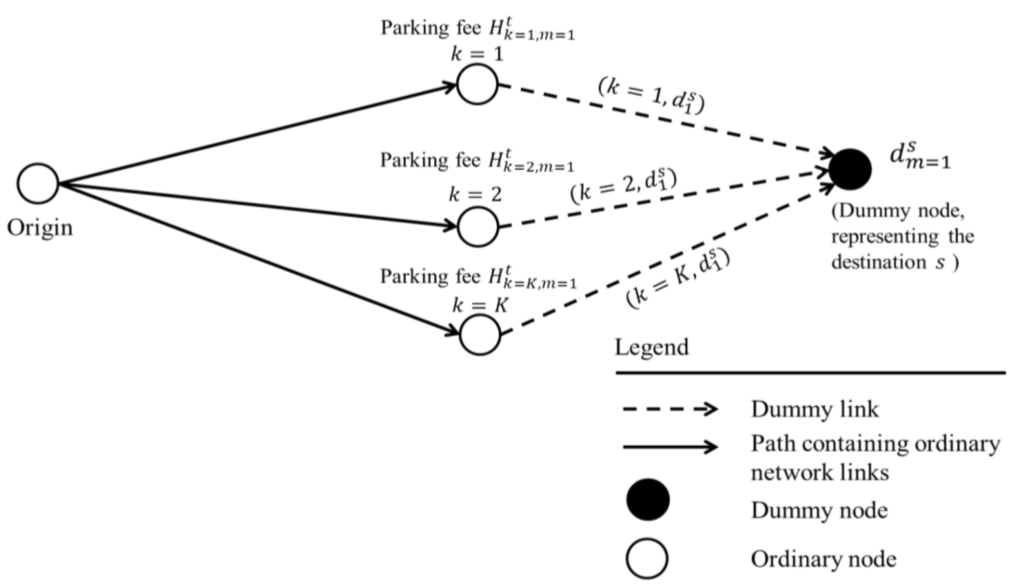
Both sub-classes of AV users seek to minimize their total travel times, and begin and complete their trips at the corresponding origins and destinations, respectively, in phase 1. However, this is not the case in phase 2. In fact, in the second phase, a parking fee as well as a vehicle operation cost (which is proportional to their trip travel time) is incurred by AV users. Therefore, a combined route and parking selection process best describes phase 2 of AV travel. To capture this selection process in this study, dummy links and nodes are established for the road network to represent parking capacities and fees. For each destination s, a dummy node (d_2^s) is defined to represent the AV destination in the second phase of their trip. Moreover, these dummy nodes are connected to each node representing a parking facility using dummy links (k, d_2^s). Equation 10.23 models the fee for AV parking at that parking facility using these dummy links:

$$\sigma_{k,d_2^s}^t = \Psi^t \cdot H_{k,AV}^t \qquad \forall k \in K, \forall s \in S, \forall t \in T \qquad 10.23$$

The above discussion for the case of K parking facilities and one destination is depicted in Figure 10.3 (a). AVs require to use one of the dummy links ($k = 1, d_2^s$), ($k = 2, d_2^s$), …, or ($k = K, d_2^s$) to complete their trips, because they park at one of the facilities $k = 1,\dots, K$. Note that each of the dummy links can be representative of a path consisting of multiple links. This discussion is meant to emphasize that the phase 2 part of the trip starts at the node s.



(a) AV travel -- phase 2 of the trip



(b) HDV sub-class 1-- last-mile travel

Figure 10.3 Network Transformation

The combined behavior of travel and parking selection of the AV users is modeled with constraints 10.24-10.36

$$0 \le y_{i,j,\widehat{g}}^{s,t,1} \perp \left(\sigma_{i,j}^{t}\left(v_{i,j}^{t}\right) - \lambda_{i,\widehat{g}}^{s,t,1} + \lambda_{j,\widehat{g}}^{s,t,1}\right) \ge 0 \quad \forall (i,j) \in (A - A^{D}), \forall \widehat{g} \in \widehat{\widehat{G}}, \forall s \in S, \forall t \in T \qquad 10.24$$

$$0 \le y_{i,j,1}^{d_2^s,t,2} \perp \left(\sigma_{i,j}^{t}\left(v_{i,j}^{t}\right) - \lambda_{i,1}^{d_2^s,t,2} + \lambda_{j,1}^{d_2^s,t,2}\right) \ge 0 \quad \forall (i,j) \in (A - A^{D}), \forall s \in S, \forall t \in T \qquad 10.25$$

$$\lambda_{s,\widehat{g}}^{s,t,1} = 0 \quad \forall \widehat{g} \in \widehat{\widehat{G}}, \forall s \in S, \forall t \in T \qquad 10.26$$

$$\lambda_{d_2^s,1}^{d_2^s,t,2} = 0 \quad \forall s \in S, \forall t \in T \qquad 10.27$$

$$0 \le y_{k,d_2^s,1}^{d_2^s,t,2} \perp \left(\bar{\theta}\frac{1}{\theta}\bar{\Psi}^{t} H_{k,AV}^{t} - \lambda_{k,1}^{d_2^s,t,2} + \lambda_{d_2^s,1}^{d_2^s,t,2} + \frac{1}{\aleph}\cdot \rho_k^t\right) \ge 0 \quad \forall (k, d_2^s) \in A^{D}, \forall t \in T \qquad 10.28$$

$$\sum_{j:(j,i)\in A} y_{j,i,\widehat{g}}^{s,t,1} - \sum_{j:(i,j)\in A} y_{i,j,\widehat{g}}^{s,t,1} = \bar{b}_{i,\widehat{g}}^{s,t} \quad \forall i \in N, \forall s \in S, \forall \widehat{g} \in \widehat{\widehat{G}}, \forall t \in T \qquad 10.29$$

$$\sum_{j:(j,i)\in A} y_{j,i,2}^{d_2^s,t,2} - \sum_{j:(i,j)\in A} y_{i,j,2}^{d_2^s,t,2} = \bar{\bar{b}}_{i}^{d_2^s,t} \quad \forall i \in N, \forall s \in S, \forall t \in T \qquad 10.30$$

$$y_{i,j}^{t} = \sum_{s\in S}\sum_{\widehat{g}} y_{i,j,\widehat{g}}^{s,t,1} \quad \forall (i,j) \in (A - A^{D}), \forall t \in T \qquad 10.31$$

$$u_{r,s,AV}^{t} = \lambda_{r,1}^{s,t,1} + \frac{1}{\bar{\theta}}\lambda_{s,1}^{d_2^s,t,2} \quad \forall r \in R, \forall s \in S, \forall t \in T \qquad 10.32$$

$$y_{i,j,\widehat{g}}^{s,t,1} \ge 0 \quad \forall (i,j) \in A, \forall g \in G, \forall s \in S, \forall t \in T \qquad 10.33$$

$$y_{i,j,1}^{d_2^s,t,2} \ge 0 \quad \forall (i,j) \in A, \forall s \in S, \forall t \in T \qquad 10.34$$

$$\lambda_{i,g}^{s,t,1} \ge 0 \quad \forall i \in N, \forall s \in S, \forall g \in G, \forall t \in T \qquad 10.35$$

$$\lambda_{i,1}^{d_2^s,t,2} \ge 0 \quad \forall i \in N, \forall s \in S, \forall t \in T \qquad 10.36$$

Where

$\bar{b}_{i,\widehat{g}}^{s,t}$ and $\bar{\bar{b}}_{i,2}^{d_2^s,t}$ in equations 10.29 and 10.30 are represented by equations 10.37 and 10.38 as follows:

$$\bar{b}_{i,\widehat{g}}^{s,t} = \begin{cases} -q_{i,s,AV}^{t,\widehat{g}}, \text{if } i \in R \\ 0, \text{if } i \notin R, \text{and } i \ne s \\ \sum_{r\in R} q_{r,s,AV}^{t,\widehat{g}}, \text{if } i = s \end{cases} \quad \forall i \in N, \forall s \in S, \forall t \in T, \forall \widehat{g} \in \widehat{\widehat{G}} \qquad 10.37$$

$$\bar{\bar{b}}_{i,2}^{d_2^s,t} = \begin{cases} -\sum_{r\in R} q_{r,s,AV}^{t,1}, \text{if } i = s \\ 0, \text{if } i \ne s \text{ and } i \ne d_2^s \\ \sum_{r\in R} q_{r,s,AV}^{t,1}, \text{if } i = d_2^s \end{cases} \quad \forall i \in N, \forall s \in S, \forall t \in T \qquad 10.38$$

The complementarity equation 10.24 represents the link- and destination-based conditions of user equilibrium for phase 1 of the trip. This constraint specifies that if link (i,j) in period t is used by sub-class $\hat{\bar{g}}$ of AV travelers that have destination s, then the shortest-path route for that destination includes that link. Equation 10.25 exclusively describes the same constraint for the second phase of trips of sub-class 1 AV travelers. For both AV user sub-classes in the first phase, the fact that each destination node s has zero travel time to itself is reflected in equation 10.26. Similarly, equation 10.27 indicates that sub-class 1 of AV travelers in phase 2 experience zero travel time in traveling from the dummy node, d_2^s, to itself. While constraint 10.28 is almost identical to constraints 10.24 and 10.25, it only includes the dummy links in sub-class 1 AVs' second phase of their trip. Note that these constraints reflect the AV travel costs in phase 2. The flow conservation of AV travel in phase 1 is considered by constraints 10.29 and 10.37 for both sub-classes. For AV traveler sub-class 1, phase 2 of travel is represented by constraints 10.30 and 10.38. Next, the total flow of AV users at each network link is computed by aggregating the traffic flow of AV users in phase 1 over each user sub-class and destination, which is represented via constraint 10.31.

It may be noted that $y_{i,j}^t$ just reflects the AV users in phase 1 of their travels using link (i,j) AV users sub-class 1's travel cost in period t for the OD pair (r,s) is represented by constraint 10.32. Finally, constraints 10.33-10.36 ensure that the travel costs are non-negative.

Lower-level Model Part III: The travel of HDVs

HDV users (travelers) can be further divided into two sub-classes depending on their parking requirements. Each sub-class seeks to minimize their in-vehicle travel costs. In addition, sub-class 1 users incur the last-mile travel cost and a parking fee. Similar to Part 2 for AV travel, the last part of the trip of the HDV travelers is considered by implementing dummy links and nodes on the network. A dummy node (d_1^s) for each destination s is defined to capture the last part of these HDV trips. Then, each of these dummy nodes is connected to the parking facility nodes by dummy links.

This concept is illustrated in Figure 10.3(b) for 1 destination and K parking facilities by incorporating K dummy links and a dummy node. One of the dummy links ($k = 1, d_1^s$), or ($k = K, d_1^s$) is used for parking purposes by HDV users' sub-class 1 having a given destination s. The parameter $\bar{g}$ represents the disutility of walking compared to driving. This disutility is a function of the attributes of the traveler and the travel environment (weather, etc.) and illustrates that a $\bar{g}$-minute walk (associated with the last-mile leg of their trip) tends to have a similar level of disutility as a 1-minute drive. The cost value of last-mile travel time can be converted to $\theta_1^t \cdot \bar{g} \cdot g_k^{s,t}$. This converted cost, and the parking facility k fee (i.e., $\bar{\Psi}^t \cdot H_{k,1}^t$) are expressed as the link travel cost (k, d_1^s) in period t. It can be noted that the converted cost value of last-mile travel time accounts for the last-mile ravel discomfort relative to driving ($\bar{g}$) and the value of time for HDV travelers in the planning period t (θ_1^t). Therefore, it can be expressed as follows:

$$\sigma_{k,d_1^s}^t = \bar{\Psi}^t \cdot H_{k,HDV}^t + \theta_1^t \cdot \bar{g} \cdot g_k^{s,t} \qquad \forall k \in K, \forall s \in S, \forall t \in T \qquad 10.39$$

On this basis, the HDV travel equilibrium conditions can be modeled as follows:

$$0 \le x_{i,j,\hat{\bar{g}}}^{s,t} \perp \left(\sigma_{i,j}^t\left(v_{i,j}^t\right) - \pi_{i,\hat{\bar{g}}}^{s,t} + \pi_{j,\hat{\bar{g}}}^{s,t}\right) \ge 0 \qquad \forall (i,j) \in (A - A^D), \forall \hat{\bar{g}} \in \hat{\bar{G}}, \forall s \in S, \forall t \in T \qquad 10.40$$

$$\pi_{s,2}^{s,t} = 0 \qquad \forall s \in S, \forall t \in T \qquad 10.41$$

$$\pi^{s,t}_{d_1^s,1} = 0 \qquad \forall s \in S, \forall t \in T \qquad (10.42)$$

$$0 \le x^{s,t}_{k,d_1^s,1} \perp \left(\frac{1}{\theta_1^t} \bar{\Psi}^t H^t_{k,HDV} + \bar{g} \cdot g_k^{s,t} - \pi^{s,t}_{k,1} + \pi^{s,t}_{d_1^s,1} + \rho_k^t \right) \ge 0 \qquad \forall (k, d_1^s) \in A^D, \forall t \in T \qquad (10.43)$$

$$\sum_{j:(j,i)\in A} x^{s,t}_{j,i,\overset{\frown}{g}} - \sum_{j:(i,j)\in A} x^{s,t}_{i,j,\overset{\frown}{g}} = b^{s,t}_{i,\overset{\frown}{g}} \qquad \forall i \in N, \forall s \in S, \forall t \in T \qquad (10.44)$$

$$x^t_{i,j} = \sum_{s\in S} \sum_{\overset{\frown}{g}} x^{s,t}_{i,j,\overset{\frown}{g}} \qquad \forall (i,j) \in (A - A^D), \forall t \in T \qquad (10.45)$$

$$u^t_{r,s,1} = \pi^{s,t}_{r,1} \qquad \forall r \in R, \forall s \in S, \forall t \in T \qquad (10.46)$$

$$x^{s,t}_{i,j,\overset{\frown}{g}} \ge 0 \qquad \forall (i,j) \in A,, \forall \overset{\frown}{g} \in \overset{\frown}{G}, \forall s \in S, \forall t \in T \qquad (10.47)$$

$$\pi^{s,t}_{i,\overset{\frown}{g}} \ge 0 \qquad \forall i \in N, \forall \overset{\frown}{g} \in \overset{\frown}{G}, \forall s \in S, \forall t \in T \qquad (10.48)$$

$$b^{s,t}_{i,\overset{\frown}{g}} = \begin{cases} -q^{t,\overset{\frown}{g}}_{i,s,HDV}, \text{ if } i \in R \\ 0, \text{ if } i \notin R, i \ne d_1^s \text{ for } \overset{\frown}{g} = 1, \text{and} \\ \text{if } i \notin R, i \ne s \text{ for } \overset{\frown}{g} = 2 \\ \sum_{r\in R} q^{t,\overset{\frown}{g}}_{r,s,HDV}, \text{ if } i = d_1^s \text{ for } \overset{\frown}{g} = 1, \text{and} \\ \text{if } i = s \text{ for } \overset{\frown}{g} = 2 \end{cases} \qquad \forall i \in N, \forall s \in S, \forall t \in T, \forall \overset{\frown}{g} \in \overset{\frown}{G} \qquad (10.49)$$

Similar to the model formulation for AV users (see Part 2), the UE conditions for HDV travelers are captured using Equations 10.40-10.43. In particular, Equation 10.40 ensures the shortest path route for destination s includes link (*i*,*j*) in case this link is used by HDV travelers in period t with specific destination s. Moreover, for HDV users' sub-class 1, the destination node s is represented via the dummy node d_1^s. Thus, equations 10.41 and 10.42 keep the travel time from destination *s* or dummy node d_1^s to destination *s*, respectively, at zero. Similar to equation 10.40, the extra cost experienced by users when a chosen parking facility is full or not available, is described using equation 10.43.

The flow conservation constraints are represented in Equations 10.44, 10.47, and 10.49. They ensure that traffic flow into origin node i ($i \in R$) is equal to sum of HDV travel demand (of sub-class $\overset{\frown}{g}$ of O-D (r, s)) in period t and that node's outflow. Regarding dummy node d_1^s for destination *s* in period *t*, the outflow is equal to sum of the total travel demand of HDV users sub-class 1 traveling to that destination in that period and its inflow (note that HDV travelers of sub-class 1 complete their trips at dummy nodes (d_1^s)).

In a similar fashion, HDV users' sub-class 2 complete their trips at destination node s. Next, for each of the other nodes, the outflow and inflow must be equal. To obtain the total flow of HDV users in each link, the flow of HDV users for each user sub-class and each destination is aggregated using Equation 10.45. Equation 10.46 ensures that the HDV users sub-class 1's travel cost for OD pair (*r*,*s*) in period t is equal to their travel cost from node r to destination s in that period. Finally, equations 10.47-10.48 ensure decision variables remain non-negative.

<u>Lower-level: Reformulation</u>

The nature of presented mathematical program makes its solution rather challenging, particularly due to its several complementarity constraints. To overcome this challenge, we use 1st-order optimality conditions to reformulate the model. In the Appendix of this chapter (Section 10.8), it is shown that both the original model and its reformulation yield the same solution. The equation below presents the reformulated model for the lower level. The reformulated model is a non-linear convex minimization problem.

$$\text{Min } Z_L = \sum_{t\in T}\sum_{(i,j)\in A}\int_0^{v_{i,j}^t}\sigma_{i,j}^t(\omega)d\omega \qquad 10.50$$

Subject to 10.18, 10.19, 10.21, 10.22, 10.26-10.27, 10.29-10.38, 10.39, 10.41-10.42, 10.44-10.49 where the objective function 10.50 represents a minimization form of the traffic assignment function. Further, the presented reformulation is solved sequentially for each planning period. This sequential approach relieves the computational challenges considerably. The presented bi-level optimization problem is a nonlinear program with mixed integers at the upper level and the user equilibrium at the lower level and is NP-hard (non-deterministic polynomial-time hard). Generally, any bi-level program, even with linear programs in the upper and lower levels, is NP-hard (Ayed (1990)). The following section presents the solution algorithm implemented to develop a solution to the bi-level program in this study.

10.4 Solution Algorithm

A hybrid method consisting of machine learning (with linear regression) and the Frank-Wolfe method (Algorithm 1) is used to solve the bi-level framework iteratively (Bagloee et al., 2018; Patriksson, 1994).

Algorithm 1 Implemented Frank-Wolfe algorithm

Initiate feasible values for $x_{i,j,\hat{g}}^{s,t}, y_{i,j,\hat{g}}^{s,t,1}, y_{i,j,2}^{d_2^s,t,2}$, $\epsilon \leftarrow +\infty$

$v_{i,j}^t \leftarrow \sum_{\hat{g}}\sum_{s\in S} x_{i,j,\hat{g}}^{s,t} + \sum_{\hat{g}}\sum_{s\in S} y_{i,j,\hat{g}}^{s,t,1} + \sum_{s\in S} y_{i,j,2}^{d_2^s,t,2}$

$z_1 \leftarrow \sum_{t\in T}\sum_{(i,j)\in A}\int_0^{v_{i,j}^t}\sigma_{i,j}^t(\omega)d\omega$

While $\epsilon > \epsilon_{max}$ ***do:***

Update travelers' travel costs ($\sigma_{i,j}^t$) through equations 10.18, 10.32, and 10.39

Solve 10.50 by keeping the $\sigma_{i,j}^t$ constant.

Update $x_{i,j,\hat{g}}^{s,t}, y_{i,j,\hat{g}}^{s,t,1}, y_{i,j,2}^{d_2^s,t,2}$ according to the solutions of 10.50

$v_{i,j}^t \leftarrow \sum_{\hat{g}}\sum_{s\in S} x_{i,j,\hat{g}}^{s,t} + \sum_{\hat{g}}\sum_{s\in S} y_{i,j,\hat{g}}^{s,t,1} + \sum_{s\in S} y_{i,j,2}^{d_2^s,t,2}$

$z_2 \leftarrow \sum_{t\in T}\sum_{(i,j)\in A}\int_0^{v_{i,j}^t}\sigma_{i,j}^t(\omega)d\omega$, $\epsilon \leftarrow \frac{|z_1 - z_2|}{z_1}$, $z_1 \leftarrow z_2$

End

Return $x_{i,j,\hat{g}}^{s,t}, y_{i,j,\hat{g}}^{s,t,1}, y_{i,j,2}^{d_2^s,t,2}$

The motivation for using this solution algorithm is that it solves a modified form of the upper-level model rather than its original version. In this regard, the solution algorithm uses adaptive multi-variate regression ($\overline{Z}^U$) that approximates the original version of the objective function of the upper-level model, Z^U. The adaptive multi-variate regression function is updated based on the observation newly gathered from the original upper-level objective function (Z^U) of the previous iteration. Each observation is a vector in the form of (X, Y), where the X component represents the corresponding values to the decision variables at the upper level that serve as inputs to the problem.

The Y components represent the values of the objective function at the upper level, corresponding to decision variables values (X components). In other words, the original upper-level model, given inputs (X), solves the model at the lower level to calculate the values of the objective function and outputs Y. Further, the constraints presented in the original model at the upper level are kept, ensuring the feasibility of the solutions. Therefore, as the solution algorithm identifies additional observations, the modified upper-level model ($\overline{Z}^{U}$) is enhanced further. The modified model at the upper level (MUL) can be rewritten as:

$$\text{Min } \overline{Z}^{U} = \sum_{t\in T}\sum_{k\in K\cup K'}\sum_{m\in M} \ddot{b}_{k,m}^{t}\cdot H_{k,m}^{t} + \sum_{t\in T}\sum_{k\in K\cup K'} \dot{b}_{k}^{t}\cdot Q_{k}^{t} + b_0 \qquad 10.51$$

$$Q_k^t = \sum_{\bar{\varsigma}=1}^{\varsigma} \bar{\varsigma}\times \dot{Q}_{k,\bar{\varsigma}}^{t} \qquad \forall k\in(K\cup K'),\forall t\in T \qquad 10.52$$

$$\sum_{\bar{\varsigma}=0}^{\varsigma} \dot{Q}_{k,\bar{\varsigma}}^{t} = 1 \qquad \forall k\in(K\cup K'),\forall t\in T \qquad 10.53$$

$$H_{k,m}^t = \sum_{\bar{\varrho}=1}^{\varrho} \bar{\varrho}\times \dot{H}_{k,m,\bar{\varrho}}^{t} \qquad \forall k\in(K\cup K'), \forall m\in M,\forall t\in T \qquad 10.54$$

$$\sum_{\bar{\varrho}=0}^{\varrho} \dot{H}_{k,m,\bar{\varrho}}^{t} = 1 \qquad \forall k\in(K\cup K'), \forall m\in M,\forall t\in T \qquad 10.55$$

$$\sum_{\dot{Q}_{k,\bar{\varsigma}}^{t}\in Y1^{iter}} \dot{Q}_{k,\bar{\varsigma}}^{t} - \sum_{\dot{Q}_{k,\bar{\varsigma}}^{t}\in Y0^{iter}} \dot{Q}_{k,\bar{\varsigma}}^{t} + \sum_{\dot{H}_{k,m,\bar{\varrho}}^{t}\in \ddot{\tilde{Y}}1^{iter}} \dot{H}_{k,m,\bar{\varrho}}^{t} - \sum_{\dot{H}_{k,m,\bar{\varrho}}^{t}\in \ddot{\tilde{Y}}0^{iter}} \dot{H}_{k,m,\bar{\varrho}}^{t} \le \left|Y1^{iter}\right| - 1, \qquad \forall\, iter \qquad 10.56$$

$$\dot{Q}_{k,\bar{\varsigma}}^{t}\in\{0,1\} \qquad \forall\bar{\varsigma}\in\{0,1,\dots,\varsigma\}, \forall k\in(K\cup K'),\forall t\in T \qquad 10.57$$

$$\dot{H}_{k,m,\bar{\varrho}}^{t}\in\{0,1\} \qquad \forall\bar{\varrho}\in\{0,1,\dots,\varrho\}, \forall k\in(K\cup K'), \forall m\in M,\forall t\in T \qquad 10.58$$

Where $\ddot{b}_{k,m}^{t}$, $\dot{b}_{k}^{t}$, and b_0 represent the user class-specific parking price, parking capacity coefficients, and intercept coefficients. In addition, $Y1^{iter} = \{\dot{Q}_{k,\bar{\varsigma}}^{t} | \dot{Q}_{k,\bar{\varsigma}}^{t,iter} = 1\}$, $Y0^{iter} = \{\dot{Q}_{k,\bar{\varsigma}}^{t} | \dot{Q}_{k,\bar{\varsigma}}^{t,iter} = 0\}$, $\ddot{\tilde{Y}}\,1^{iter} = \{\dot{H}_{k,m,\bar{\varrho}}^{t} | \dot{H}_{k,m,\bar{\varrho}}^{t,iter} = 1\}$, and $\ddot{\tilde{Y}}\,0^{iter} = \{\dot{H}_{k,m,\bar{\varrho}}^{t} | \dot{H}_{k,m,\bar{\varrho}}^{t,iter} = 0\}$.

Equation 10.51 represents the minimization multi-variate regression function, which has an objective function $\overline{Z}^{U}$. In the developed approximation function, a modified form of the decision variables is used. In this regard, decision variables Q_k^t and $H_{k,m}^t$ are converted to binary variables $\dot{Q}_{k,\bar{\varsigma}}^{t}$ ($\bar{\varsigma} = 0,1,\dots,\varsigma$) and $\dot{H}_{k,m,\bar{\varrho}}^{t}$ ($\bar{\varrho} = 0,1,\dots,\varrho$), respectively. Equations 10.52 and 10.53 conduct the conversion of Q_k^t (as integer variables) to binary variables ($\dot{Q}_{k,\bar{\varsigma}}^{t}$). More specifically, if $\dot{Q}_{k,\overline{\varsigma_1}}^{t} = 1$, Q_k^t will be equal to $\overline{\varsigma_1}$.

Besides, $\dot{Q}_{k,\overline{\varsigma_1}}^{t} = 0$ for $\forall\bar{\varrho} \neq \overline{\varsigma_1}$. Similarly, equations (54) and (55) convert ($H_{k,m}^t$) to binary variables ($\dot{H}_{k,m,\bar{\varrho}}^{t}$). To prevent the development of repetitive solutions, we include equation 10.56

based on the converted forms of the decision variable. Last, equations 10.57 and 10.58 ensure that $\dot{Q}^t_{k,\bar{\varsigma}}$ and $\dot{H}^t_{k,m,\bar{\varrho}}$ are binary.

One of the main constraints included in the upper-level model is the equity constraint equation 10.5-10.6. In the reformulated form of the upper-level model, this constraint is not considered explicitly. To capture this constraint in the reformulated form of upper-level, the violation of the equity constraint by each resulting solution is evaluated. The violation level of the equity constraint is added to the corresponding objective function value of the resulting solution after scaling up by a large $\bar{M}$ value $(\bar{M} \cdot \sum_t \sum_{(r,s)} \max(0, u^t_{r,s,1} - \varphi^t \cdot u^t_{r,s,2}))$. This way, a violating solution does not get considered as a potential feasible solution to the bi-level problem.

Figure 10.4 represents the solution algorithm flowchart. In the first step, the iteration counter and the maximum number of iterations are set. Next, a feasible solution is generated and then evaluated on the basis of the objective function at the upper level and the penalty for an equity constraint violation. In the next step, a multi-variate regression function is calibrated if there are enough observations (feasible solutions and their corresponding objective function values). If not, a set of random coefficients ($\ddot{b}^t_{k,m}$, $\dot{b}^t_k$, and b_0) are generated to produce a regression function.

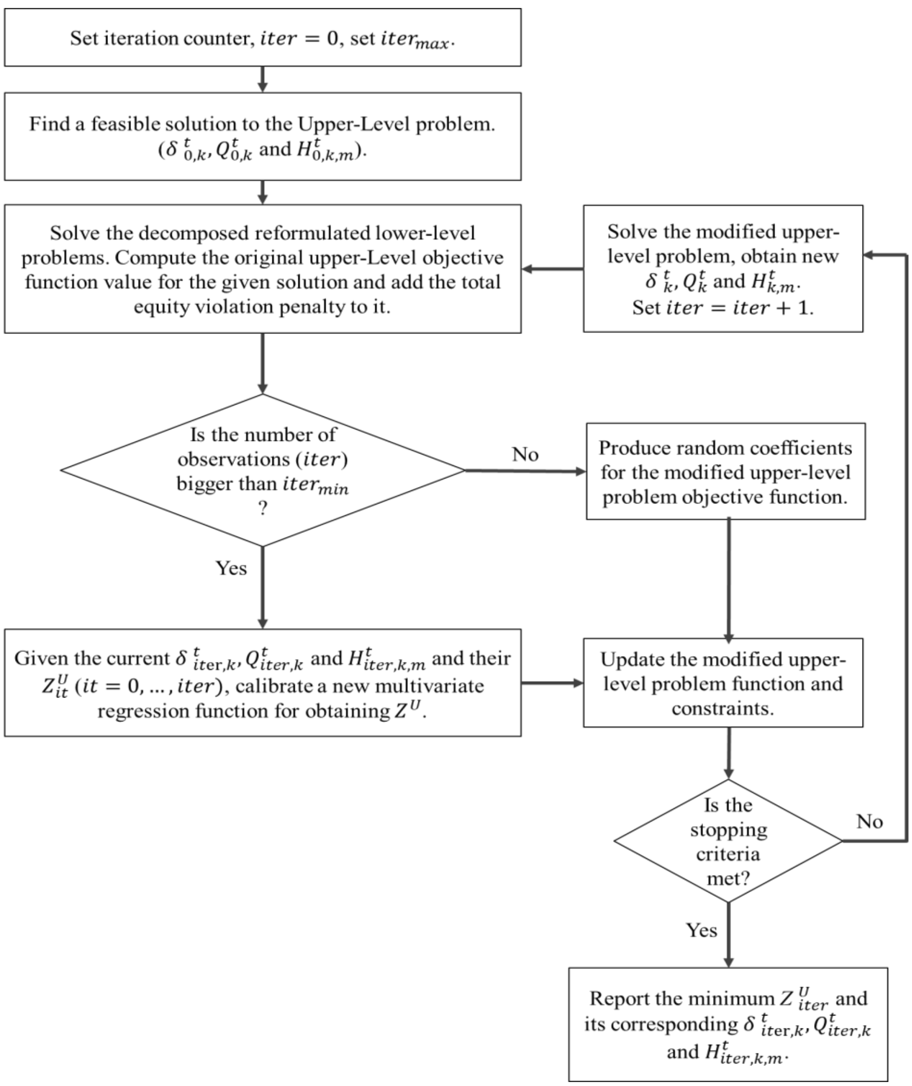


Figure 10.4 Solution algorithm

The a set of random coefficients ($\ddot{b}_{k,m}^{t}$, $\dot{b}_{k}^{t}$, and b_0) are generated to produce a regression function. This serves as the feasible observations (i.e., decision variables and their corresponding objective values) generator stage to provide a sufficient number of observations to calibrate the multi-variate regression function. This process is done only in the initial iterations. After generating enough observations, an updated regression function is calibrated and then solved to generate a new solution. This iterative process keeps going until the difference between the modified upper-level objective value ($\overline{Z}_{iter}^{U}$) in two iterations is less than 1% or the algorithm reaches the maximum number of iterations.

10.5 Numerical Experiment

10.5.1 Problem Setting

The Sioux-Falls city network of (Figure 10.5) with 76 links and 24 nodes (Leblanc et al. (1975)), is used as the case study road network for demonstrating the proposed bi-level framework. GAMS and MATLAB 2018 are used as the coding platforms for implementing the solution algorithm. More specifically, two main solvers, CONOPT 4 and CPLEX, are used to solve the problems in GAMS. The planning horizon is assumed to comprise 6 planning periods, each with a duration of 5 years. Also, the planning horizon has two planning phases: construction and evaluation. The construction phase is periods 1-4 where the road agency conducts the planning of parking facilities.

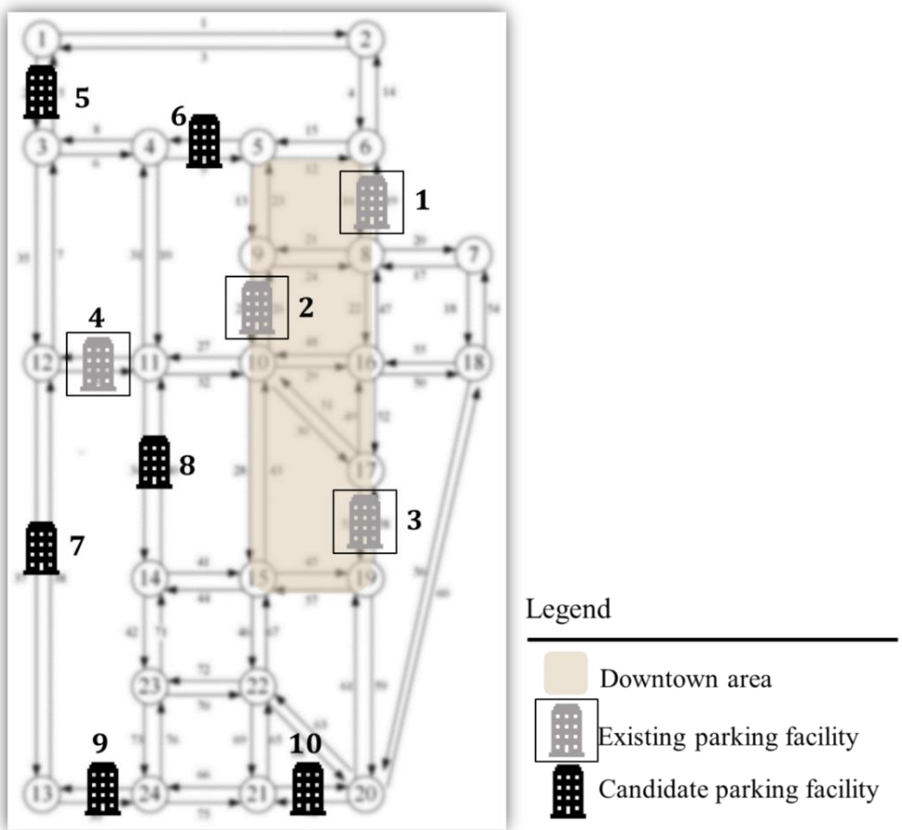


Figure 10.5 locations of available and potential parking facilities on Sioux-Falls network

Next, the evaluation phase refers to periods 5-6, in which there is no change in the parking facility configuration and the city road agency evaluates the implemented changes during the periods 1-4. In the test-bed network (Sioux-Falls), there exist 4 parking facilities (#1 to 4). These parking facilities have the same operation capacity of level 3. Parking facilities #1-3 are located in the CBD area, while parking facility #4 is outside the CBD area. Figure 10.5 presents the approximate locations of the available parking facilities. The locations of the available parking facilities approximately represent their corresponding locations on the real network. Besides, the city road agency has 6 potential locations for constructing new parking facilities (# 5-10).

At the construction phase, the road agency considers three levels of operational capacities for the new facilities (ς=3). The cost of construction and the capacity of a level 1 parking facility in the first period are $20 million and 1,000 vehicles, respectively (Rowland (2019)). Also, a level 2 parking facility has a $30 million construction cost and a 2,000-vehicle capacity in the first period. Parking facility level 3 has a $40 million construction cost and a capacity of 3,000 vehicles. Moreover, it is shown in the literature that the required parking space for AVs is 65% less than that of HDVs (Nourinejad et al. (2018)). Therefore, this study assumes the required space for AVs drops by ($\aleph$=3), relative to the required space for HDVs. Each parking facility is capable of operating at different fee levels. Also, the parking fees are assumed to increase with each planning period. In this regard, this study assumes three levels of parking fees that increase by $1 per period. The possible parking fees at the first planning period are assumed as $10, $20, and $30.

As discussed in the Methodology section, two classes of travelers exist in the network: travelers of subclass ($\tilde{\bar{g}} = 1$) who do not have access to any parking spots at their destinations, which are inside the CBD area, and travelers of subclass ($\tilde{\bar{g}} = 2$) who have available parking spots at their destinations, which are outside of CBD. In this study, it is assumed that 80% of travelers belong to the sub-class ($\tilde{\bar{g}} = 1$) and the rest of the travelers, 20% of total travelers, belong to the sub-class ($\tilde{\bar{g}} = 2$). The travel demand assumed for this study inherits the same pattern as that reported in Leblanc et al. (1975). However, it is scaled up by a factor 2 as the travel demand has grown during the last almost 50 years. The scaled-up travel demand is considered for the first planning period. This travel demand growths by 5% every period.

It is assumed that the values of time for AV and HDV travelers are different. More specifically, a lower value of time is assumed for AV travelers. This is due to the fact that AV users can use their in-vehicle time to do some other activities (e.g., working, reading, etc.) as they do not need to drive any more during the trips (van den Berg & Verhoef, 2016; Tian et al., 2019; Correia et al., 2019; Zhong et al., 2020). In the first planning period, AV and HDV travelers' values of time are $10 and $20, respectively. The value of time increases by $1 per period. A 5% discount rate is also applied to the captured monetary costs and benefits of the presented bi-level framework. Last, it is assumed that walking is three times more uncomfortable compared to driving ($\bar{g} = 3$), for HDV travelers.

10.6 Assumptions, Analysis, and Discussion

To have a benchmark for evaluating the performance of the solution algorithm and comparing different parking planning scenarios with each other, a base parking planning scenario is defined. In such base scenario, the city road agency has a $40 million budget ($B^t$) for parking facility construction in each of the planning periods 1 to 4. A set of sensitivity analyses is conducted on the available parking facility construction budget. Further, if the city road agency repurposes or decommissions an existing parking facility, it will receive prospective monetary benefits. The prospective monetary benefits are equal to $54 million in Period 1. This value is calculated based on the revenue gained from a parking facility of level 3 (which has a $20 parking fee and a 3,000-vehicle capacity) in each period if half of its capacity is utilized. Also, the market penetration rate of AVs starts at 10% in the first planning period and increases by 10% every period.

Figure 10.6 presents, for each iteration, the objective function's best values, for the base planning scenario. As shown in Figure 10.6, the improvements in the objective function values are not considerable during the first 150 iterations. This is because the algorithm is still identifying sufficient initial solutions to develop a multi-variate regression function. On the other hand, considerable improvements happen after iteration 150 until iteration 200.

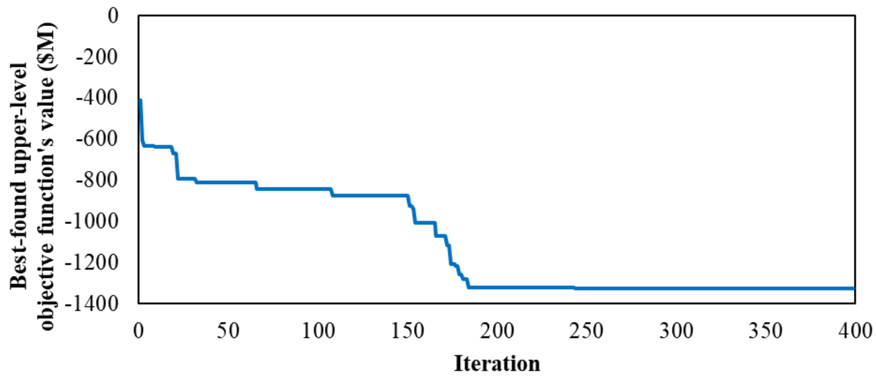


Figure 10.6 Best objective values over iterations

First, the effects of parking fee levels on parking facility planning are analyzed. Figure 10.7 presents the optimal configuration for the parking facilities (construction year, location, and capacity) for the base planning scenario. According to this optimal parking plan, two level 1 parking facilities, #6 and #8, are constructed in the first planning period. In the next period, parking facility #9 with a level 1 capacity is constructed. Besides, the city road agency should repurpose and decommission parking facility #4 during this planning period. In the next two planning periods, 3 and 4, level 1 parking facilities #5 and #10 are constructed, respectively. Next, parking facility #2 should be repurposed in period 5.

Table 10.2 presents the parking fee at each parking facility at each planning period. According to the results reported in Table 10.2, the determined parking fees follow different patterns for HDVs and AVs. For example, parking facilities #1-3 at the CBD operate at the maximum fee levels for both AVs and HDVs. However, the parking fee at these parking facilities for HDVs starts to decrease in periods 5 and 6. These fee decreases are due to the repurposing/decommissioning of parking facility #4. By repurposing parking facility #2 in planning period 5, HDV travelers chose parking facilities #1 and #3 for parking their vehicles. As these locations are not preferable for HDV travelers, the bi-level framework decreased the parking fees at parking facilities #1 and #3 to satisfy the equity constraints. Moreover, the suggested parking fee at facility #8 is higher for AVs, relative to HDVs. This motivates AVs to use facilities #5, #9, and #10, which have lower parking fees and are located at areas distant-from the city center.

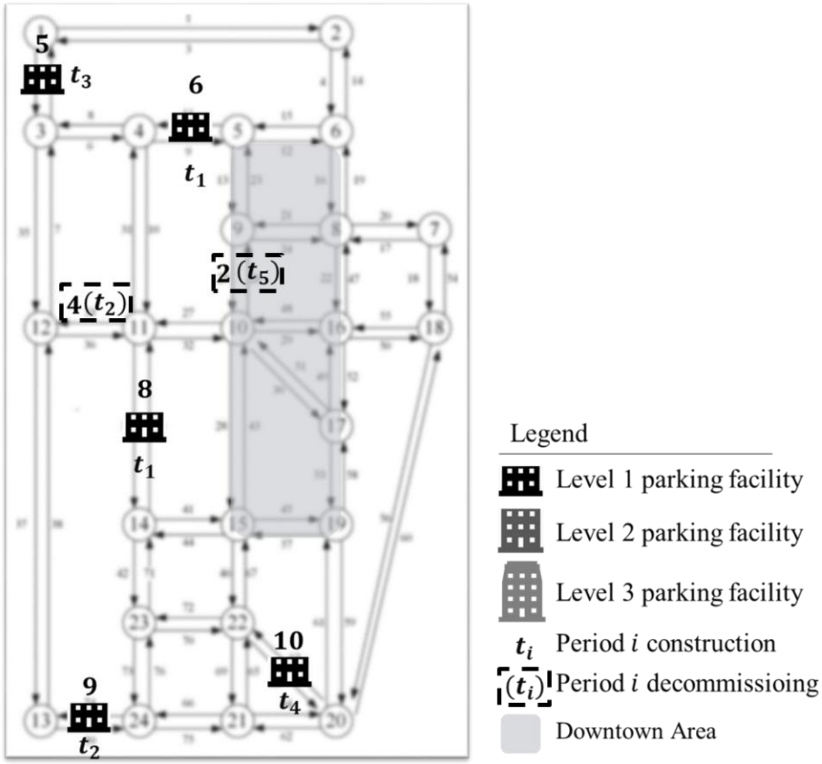
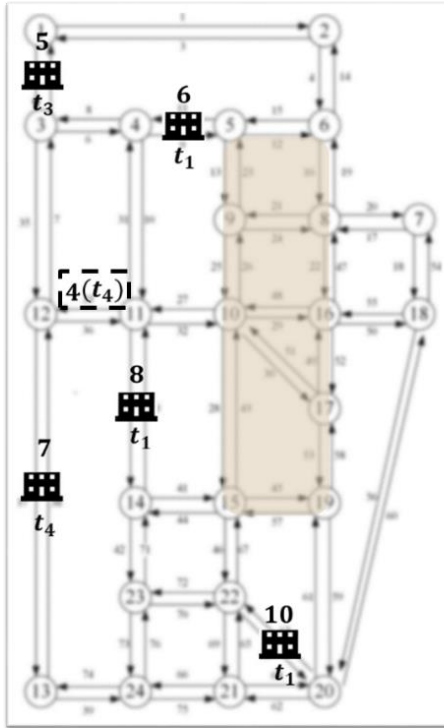


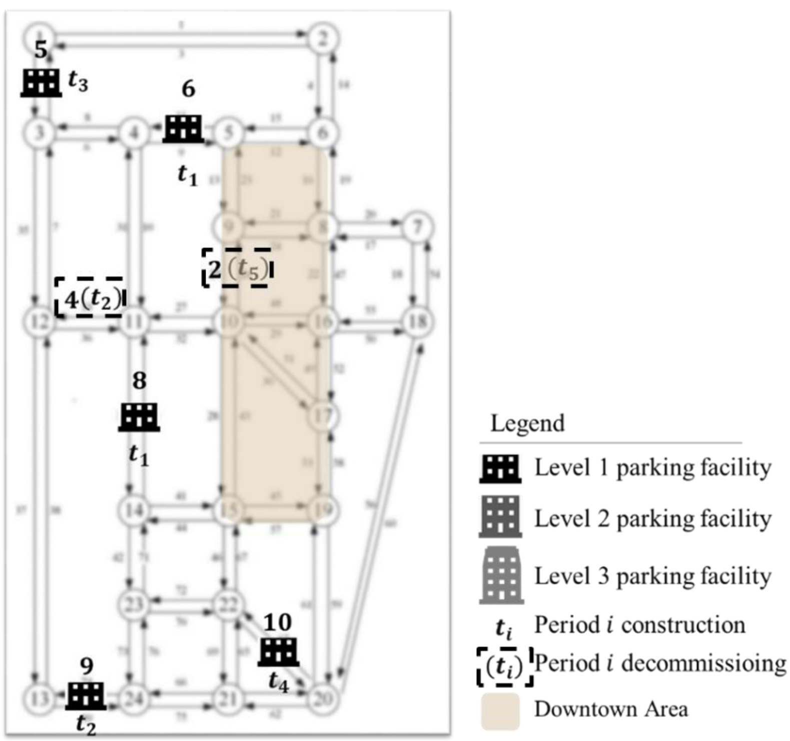
Figure 10.7 Optimal parking configuration under the base planning scenario

The effects of the prospective benefits of parking facility decommissioning are also investigated. To do this, three prospective decommissioning benefit levels—$5 million, $10 million, and $100 million—are considered besides the benchmark value of $54 million. The construction budget at each period is considered to be $40 million dollars in this set of analyses. Also, the initial penetration rate of AVs is 5%, and growth occurs periodically at 10% until it reaches 55% in the last planning period.

Table 10.3 summarizes the results of different prospective decommissioning benefit values. Increasing the prospective decommissioning benefit values has positive effects on the total decommissioning benefits and improves them. For example, by increasing the prospective decommissioning benefit from $10 million to $100 million, the total decommissioning benefit increases from $58.02 to $829.37 million dollars. This effect is not significant on overall system travel cost and overall parking revenue. More specifically, the overall travel costs and parking revenues increase by increasing the prospective decommissioning benefit from $5 million to $10 million. However, the overall system travel costs and parking revenues of $10 million, $54 million, and $100 million remain the same, despite the different prospective decommissioning benefits. This is due to the same configurations of constructed or decommissioned parking facilities in the $10 million, $54 million, and $100 million cases (figure 10.8). The solution algorithm was run on a computer system with a RAM of 8 GB and CPU of 2.6 GHz (Core i7). The mean time of computation was 140 minutes.



(a) \$5 Million



(b) ≥ \$10 Million

Figure 10.8 Configuration of parking facility planning under different budgets

10.7 Final Remarks

This chapter provides a comprehensive bi-level framework to design an optimal configuration (locations, schedules, and capacities) of new parking infrastructure and the repurposing or decommissioning of existing parking infrastructure in a mixed (HDV and AV) environment. At the upper level, the city road agency has two main goals: (1) minimize the overall system travel cost; and (2) maximize the overall revenues from parking fees and the monetary benefits of repurposing or decommissioning existing parking infrastructures in the city. At the lower level, AV and HDV travelers seek to minimize their overall costs of travel.

It is worth mentioning that at the current time, some parking lots are underground and parking garages are designed in ways that shield out communication signals such as GPS. Therefore, these garages may not provide full support to AVs operations. It has been suggested in the literature to use Bluetooth and near field communications to support AV operations at parking lots and garages (Othman, 2021; UK Autodrive, 2021).

Numerical experiments yielded results that suggest the feasibility of the proposed bi-level framework and the efficiency of the solution algorithm. The numerical experiments generated an optimal schedule of parking facility locations at various parts of the city network over the analysis period, with parking fees differentiated by vehicle mode (HDV and AV). The study results also shed light on the impacts of parking fee levels on the configuration (locations, timings, and capacities) associated with the optimal solution. The numerical results showed the parking facilities in the CBD area have the highest parking fees for both HDVs and AVs in the first 4 periods of the planning horizon. The HDVs' parking fees at these locations decreased in the last period due to the decommissioning of parking facilities; these decreases are designed to compensate for the HDV's the increase in travel costs, thereby satisfying the equity constraint. The results also shed light on the sensitivity of the total system travel costs, decommissioning benefits, and parking revenues to the prospective decommissioning benefit levels.The overall system travel costs and parking revenue, on the other hand, do not increase considerably due to the similar configurations of constructed and decommissioned parking facilities.

There exist several directions for extending this research further. The first is to address the uncertainty associated with AV market penetration in the long term and travel demand by using a robust framework. The second is the inclusion of on-street parking in the planning framework to capture the potential benefits of repurposing on-street parking land to other uses (such as capacity expansion of road lanes or transit lines). Third, parking construction costs and decommissioning benefits should be considered spatially variable over a city network: in practice, the purchase of spaces near downtown and the decommissioning benefits of downtown parking facilities are higher than those in the suburbs. If spatially-variable purchase costs and benefits are considered the economic impact predictions of parking infrastructure management becomes more realistic. Finally, there is a need for a solution algorithm that is capable of solving this problem for large city road networks.

10.8 Appending Information Part 1

This section presents the proof of equivalency of the original lower-level model and its reformulated form. Note that $\lambda_{i,\widehat{g}}^{s,t,1}$, $\lambda_{i,1}^{d_2^s,t,2}$, $\pi_{i,\widehat{g}}^{s,t}$, ρ_k^t, $\psi_{i,j,\widehat{g}}^{s,t}$, $\dot{\psi}_{i,j}^{s,t}$, and $\ddot{\psi}_{i,j,\widehat{g}}^{s,t}$ are the dual variables associated with constraints 10.60-10.67, respectively.

$$\text{Min } Z_L = \sum_{t\in T} \sum_{(i,j)\in A} \int_0^{v_{i,j}^t} \sigma_{i,j}^t(\omega)d\omega \tag{10.59}$$

$$\sum_{j:(j,i)\in A} y_{j,i,\widehat{g}}^{s,t,1} - \sum_{j:(i,j)\in A} y_{i,j,\widehat{g}}^{s,t,1} - \bar{b}_{i,\widehat{g}}^{s,t} = 0 \qquad \forall i, \forall s, \forall \widehat{g}, \forall t \qquad \lambda_{i,\widehat{g}}^{s,t,1} \tag{10.60}$$

$$\sum_{j:(j,i)\in A} y_{j,i,2}^{d_2^s,t,2} - \sum_{j:(i,j)\in A} y_{i,j,2}^{d_2^s,t,2} - \bar{\bar{b}}_i^{d_2^s,t} = 0 \qquad \forall i, \forall s, \forall t \qquad \lambda_{i,1}^{d_2^s,t,2} \tag{10.61}$$

$$\sum_{j:(j,i)\in A} x_{j,i,\widehat{g}}^{s,t} - \sum_{j:(i,j)\in A} x_{i,j,\widehat{g}}^{s,t} - b_{i,\widehat{g}}^{s,t} = 0 \qquad \forall i, \forall s, \forall \widehat{g}, \forall t \qquad \pi_{i,\widehat{g}}^{s,t} \tag{10.62}$$

$$Q_k^t \cdot \gamma_k^t - \sum_{s\in S} x_{k,d_1^s,1}^{s,t} - \frac{1}{\aleph} \cdot \sum_{s\in S} y_{k,d_2^s,1}^{d_2^s,t,2} \geq 0 \qquad \forall k, \forall t \qquad \rho_k^t \tag{10.63}$$

$$x_{i,j}^t - \sum_{\widehat{g}\in\widehat{G}} \sum_{s\in S} x_{i,j,\widehat{g}}^{s,t} - \sum_{\widehat{g}\in\widehat{G}} \sum_{s\in S} y_{i,j,\widehat{g}}^{s,t,1} - \sum_{s\in S} y_{i,j,2}^{d_2^s,t,2} = 0 \qquad \forall (i,j) \in A, \forall t \tag{10.64}$$

$$y_{i,j,\widehat{g}}^{s,t,1} \geq 0 \qquad \forall (i,j) \in A, \forall \widehat{g}, \forall s, \forall t \qquad \psi_{i,j,\widehat{g}}^{s,t} \tag{10.65}$$

$$y_{i,j,1}^{d_2^s,t,2} \geq 0 \qquad \forall (i,j) \in A, \forall s, \forall t \qquad \dot{\psi}_{i,j}^{s,t} \tag{10.66}$$

$$x_{i,j,\widehat{g}}^{s,t} \geq 0 \qquad \forall (i,j) \in A, \forall \widehat{g}, \forall s, \forall t \qquad \ddot{\psi}_{i,j,\widehat{g}}^{s,t} \tag{10.67}$$

The KKT conditions, or the first-order conditions, of this problem are used to prove the equivalency. Since Z_L is a function of $x_{i,j,\widehat{g}}^{s,t}$, $y_{i,j,\widehat{g}}^{s,t,1}$, and $y_{i,j,1}^{d_2^s,t,2}$, the KKT conditions are thus represented based on each of these variables.

1. $\boldsymbol{x_{i,j,\widehat{g}}^{s,t}}$

Based on $x_{i,j,\widehat{g}}^{s,t}$, the existing links of the network $(i,j) \in A$ are categorized either as regular links $(\forall (i,j) \in (A - A^D))$ or dummy links $(\forall (k, d_1^s) \in A^D)$:

- $\forall(\boldsymbol{i},\boldsymbol{j}) \in (\boldsymbol{A}-\boldsymbol{A^D}), \forall \overset{\frown}{g}, \forall \boldsymbol{s}, \forall \boldsymbol{t}$**:**

$$\frac{\partial\left(\sum_{t\in T}\sum_{(i,j)\in A}\int_0^{v_{i,j}^t}\sigma_{i,j}^t(\omega)d\omega\right)}{\partial x_{i,j,\overset{\frown}{g}}^{s,t}} - \pi_{i,\overset{\frown}{g}}^{s,t}\cdot\left(\frac{\partial\left(\sum_{j:(j,i)\in A}x_{j,i,\overset{\frown}{g}}^{s,t}-\sum_{j:(i,j)\in A}x_{i,j,\overset{\frown}{g}}^{s,t}-b_{i,\overset{\frown}{g}}^{s,t}\right)}{\partial x_{i,j,\overset{\frown}{g}}^{s,t}}\right)$$

$$-\pi_{j,\overset{\frown}{g}}^{s,t}\cdot\left(\frac{\partial\left(\sum_{j':(j',j)\in A}x_{j',j,\overset{\frown}{g}}^{s,t}-\sum_{j':(j,j')\in A}x_{j,j',\overset{\frown}{g}}^{s,t}-b_{j,\overset{\frown}{g}}^{s,t}\right)}{\partial x_{i,j,\overset{\frown}{g}}^{s,t}}\right)-\ddot{\psi}_{i,j,\overset{\frown}{g}}^{s,t}=0$$

$$=>\ \sigma_{i,j}^t\left(v_{i,j}^t\right)-\pi_{i,\overset{\frown}{g}}^{s,t}+\pi_{j,\overset{\frown}{g}}^{s,t}-\ddot{\psi}_{i,j,\overset{\frown}{g}}^{s,t}=0$$

We also have $x_{i,j,\overset{\frown}{g}}^{s,t}\cdot\ddot{\psi}_{i,j,\overset{\frown}{g}}^{s,t}=0$. This results in:

$$x_{i,j,\overset{\frown}{g}}^{s,t}\cdot\left(\sigma_{i,j}^t\left(v_{i,j}^t\right)-\pi_{i,\overset{\frown}{g}}^{s,t}+\pi_{j,\overset{\frown}{g}}^{s,t}\right)=0 \qquad \forall(i,j)\in(A-A^D),\forall\overset{\frown}{g},\forall s,\forall t \qquad 10.68$$

- $\forall(\boldsymbol{k},\boldsymbol{d_1^s}) \in \boldsymbol{A^D}, \forall \boldsymbol{t}$**:**

$$\frac{\partial\left(\sum_{t\in T}\sum_{(i,j)\in A}\int_0^{v_{i,j}^t}\sigma_{i,j}^t(\omega)d\omega\right)}{\partial x_{k,d_1^s,1}^{s,t}} - \pi_{i,\overset{\frown}{g}}^{s,t}\cdot\left(\frac{\partial\left(\sum_{j:(j,i)\in A}x_{j,i,\overset{\frown}{g}}^{s,t}-\sum_{j:(i,j)\in A}x_{i,j,\overset{\frown}{g}}^{s,t}-b_{i,\overset{\frown}{g}}^{s,t}\right)}{\partial x_{k,d_1^s,1}^{s,t}}\right)$$

$$-\pi_{j,\overset{\frown}{g}}^{s,t}\cdot\left(\frac{\partial\left(\sum_{j':(j',j)\in A}x_{j',j,\overset{\frown}{g}}^{s,t}-\sum_{j':(j,j')\in A}x_{j,j',\overset{\frown}{g}}^{s,t}-b_{j,\overset{\frown}{g}}^{s,t}\right)}{\partial x_{k,d_1^s,1}^{s,t}}\right)$$

$$-\rho_k^t\cdot\left(\frac{Q\,{}_k^t\cdot\gamma_k^t-\sum_{s\in S}x_{k,d_1^s,1}^{s,t}-\frac{1}{\aleph}\cdot\sum_{s\in S}y_{k,d_2^s,1}^{d_2^s,t,2}}{\partial x_{k,d_1^s,1}^{s,t}}\right)-\ddot{\psi}_{k,d_1^s,1}^{s,t}=0$$

- $\sigma_{k,d_1^s}^t\left(x_{k,d_1^s,1}^{s,t}\right)-\pi_{k,1}^{s,t}+\pi_{d_1^s,1}^{s,t}+\rho_k^t-\ddot{\psi}_{k,d_1^s,1}^{s,t}=0$

Since $x_{k,d_1^s,1}^{s,t}\cdot\ddot{\psi}_{k,d_1^s,1}^{s,t}=0$, it results in:

$$x_{k,d_1^s,1}^{s,t}\cdot\left(\sigma_{k,d_1^s}^t\left(x_{k,d_1^s,1}^{s,t}\right)-\pi_{k,1}^{s,t}+\pi_{d_1^s,1}^{s,t}+\rho_k^t\right)=0.$$

We also know that $\sigma_{k,d_1^s}^t\left(x_{k,d_1^s,1}^{s,t}\right)=\frac{1}{\theta_1^t}\Psi^t H_{k,1}^t+g_k^{s,t}$. Therefore,

$$x_{k,d_1^s,1}^{s,t}\cdot\left(\frac{1}{\theta_1^t}\Psi^t H_{k,1}^t+g_k^{s,t}-\pi_{k,1}^{s,t}+\pi_{d_1^s,1}^{s,t}+\rho_k^t\right)=0 \qquad \forall(k,d_1^s)\in A^D,\forall t \qquad 10.69$$

2. $\boldsymbol{y_{i,j,\widehat{g}}^{s,t,1}}$

$y_{i,j,\widehat{g}}^{s,t,1}$ represents the traffic volume of AVs in the first phase of their travels.

$$\frac{\partial\left(\sum_{t\in T}\sum_{(i,j)\in A}\int_0^{v_{i,j}^t}\sigma_{i,j}^t(\omega)d\omega\right)}{\partial y_{i,j,\widehat{g}}^{s,t,1}}-\lambda_{i,\widehat{g}}^{s,t,1}\cdot\left(\frac{\partial\left(\sum_{j:(j,i)\in A}y_{j,i,\widehat{g}}^{s,t,1}-\sum_{j:(i,j)\in A}y_{i,j,\widehat{g}}^{s,t,1}-\bar{b}_{i,\widehat{g}}^{s,t}\right)}{\partial y_{i,j,\widehat{g}}^{s,t,1}}\right)$$

$$-\lambda_{j,\widehat{g}}^{s,t,1}\cdot\left(\frac{\partial\left(\sum_{j':(j',j)\in A}y_{j',j,\widehat{g}}^{s,t,1}-\sum_{j':(j,j')\in A}y_{j,j',\widehat{g}}^{s,t,1}-\bar{b}_{j,\widehat{g}}^{s,t}\right)}{\partial y_{j,j',\widehat{g}}^{s,t,1}}\right)-\psi_{i,j,\widehat{g}}^{s,t}=0$$

- $\sigma_{i,j}^t\left(v_{i,j}^t\right)-\lambda_{i,\widehat{g}}^{s,t,1}+\lambda_{j,\widehat{g}}^{s,t,1}-\psi_{i,j,\widehat{g}}^{s,t}=0$

Since $y_{i,j,\widehat{g}}^{s,t,1}\cdot\psi_{i,j,\widehat{g}}^{s,t}=0$, we will have:

$$y_{i,j,\widehat{g}}^{s,t,1}\cdot(\sigma_{i,j}^t\left(v_{i,j}^t\right)-\lambda_{i,\widehat{g}}^{s,t,1}+\lambda_{j,\widehat{g}}^{s,t,1})=0 \qquad \forall(i,j)\in(A-A^D),\forall\widehat{g},\forall s,\forall t \qquad 10.70$$

3. $\boldsymbol{y_{i,j,1}^{d_2^s,t,2}}$

Last, the first-order conditions with regard to $y_{i,j,1}^{d_2^s,t,2}$, which is the traffic flow of AVs in the second phase of their travel, is required. Similar to $x_{i,j,\widehat{g}}^{s,t}$, each link of the network $(i,j)\in A$ is classified as either regular links ($\forall(i,j)\in(A-A^D)$) or dummy links ($\forall(k,d_2^s)\in A^D$):

- $\boldsymbol{\forall(i,j)\in(A-A^D),\forall s,\forall t}$**:**

$$\frac{\partial\left(\sum_{t\in T}\sum_{(i,j)\in A}\int_0^{v_{i,j}^t}\sigma_{i,j}^t(\omega)d\omega\right)}{\partial y_{i,j,1}^{d_2^s,t,2}}-\lambda_{i,1}^{d_2^s,t,2}\cdot\left(\frac{\partial\left(\sum_{j:(j,i)\in A}y_{j,i,1}^{d_2^s,t,2}-\sum_{j:(i,j)\in A}y_{i,j,1}^{d_2^s,t,2}-\bar{\bar{b}}_i^{d_2^s,t}\right)}{\partial y_{i,j,1}^{d_2^s,t,2}}\right)$$

$$-\lambda_{j,1}^{d_2^s,t,2}\cdot\left(\frac{\partial\left(\sum_{j':(j',j)\in A}y_{j',j,1}^{d_2^s,t,2}-\sum_{j':(j,j')\in A}y_{j,j',1}^{d_2^s,t,2}-\bar{\bar{b}}_i^{d_2^s,t}\right)}{\partial y_{i,j,1}^{d_2^s,t,2}}\right)-\dot{\psi}_{i,j}^{d_2^s,t}=0$$

⇨ $\quad \sigma_{i,j}^t\left(v_{i,j}^t\right)-\lambda_{i,1}^{d_2^s,t,2}+\lambda_{j,1}^{d_2^s,t,2}-\dot{\psi}_{i,j}^{d_2^s,t}=0$

Since $y_{i,j,1}^{d_2^s,t,2}\cdot\dot{\psi}_{i,j}^{d_2^s,t}=0$, we will have:

$$y_{i,j,1}^{d_2^s,t,2}\cdot(\sigma_{i,j}^t\left(v_{i,j}^t\right)-\lambda_{i,1}^{d_2^s,t,2}+\lambda_{j,1}^{d_2^s,t,2})=0 \qquad \forall(i,j)\in(A-A^D),\forall s,\forall t \qquad 10.71$$

- $\forall(\boldsymbol{k}, \boldsymbol{d_2^s}) \in \boldsymbol{A^D}, \forall \boldsymbol{t}$:

$$\frac{\partial\left(\sum_{t\in T}\sum_{(i,j)\in A}\int_0^{v_{i,j}^t}\sigma_{i,j}^t(\omega)d\omega\right)}{\partial y_{k,d_2^s,1}^{d_2^s,t,2}} - \lambda_{k,1}^{d_2^s,t,2}\cdot\left(\frac{\partial\left(\sum_{j:(j,i)\in A} y_{j,i,1}^{d_2^s,t,2} - \sum_{j:(i,j)\in A} y_{i,j,1}^{d_2^s,t,2} - \bar{\bar{b}}_i^{d_2^s,t}\right)}{\partial y_{k,d_2^s,1}^{d_2^s,t,2}}\right)$$

$$-\lambda_{d_2^s,1}^{d_2^s,t,2}\cdot\left(\frac{\partial\left(\sum_{j':(j',j)\in A} y_{j',j,1}^{d_2^s,t,2} - \sum_{j':(j,j')\in A} y_{j,j',1}^{d_2^s,t,2} - \bar{\bar{b}}_i^{d_2^s,t}\right)}{\partial y_{k,d_2^s,1}^{d_2^s,t,2}}\right)$$

$$-\rho_k^t\cdot\left(\frac{Q\,_k^t\cdot\gamma_k^t - \sum_{s\in S} x_{k,d_1^s,1}^{s,t} - \frac{1}{\aleph}\cdot\sum_{s\in S} y_{k,d_2^s,1}^{d_2^s,t,2}}{\partial y_{k,d_2^s,1}^{d_2^s,t,2}}\right) - \dot{\psi}_{k,d_2^s}^{d_2^s,t} = 0$$

- $\sigma_{k,d_2^s}^t\left(y_{k,d_2^s,1}^{d_2^s,t,2}\right) - \lambda_{k,1}^{d_2^s,t,2} + \lambda_{d_2^s,1}^{d_2^s,t,2} + \frac{1}{\aleph}\cdot\rho_k^t - \dot{\psi}_{k,d_2^s}^{d_2^s,t} = 0$

Since $y_{k,d_2^s,1}^{d_2^s,t,2}\cdot\dot{\psi}_{k,d_2^s}^{d_2^s,t} = 0$, hence, we will have:

$$y_{k,d_2^s,1}^{d_2^s,t,2}\cdot(\sigma_{k,d_2^s}^t\left(y_{k,d_2^s,1}^{d_2^s,t,2}\right) - \lambda_{k,1}^{d_2^s,t,2} + \lambda_{d_2^s,1}^{d_2^s,t,2} + \frac{1}{\aleph}\cdot\rho_k^t) = 0.$$

We also know that $\sigma_{k,d_2^s}^t\left(y_{k,d_2^s,1}^{d_2^s,t,2}\right) = \bar{\theta}\frac{1}{\theta_2^t}\Psi^t H_{k,2}^t$. Therefore,

$$y_{k,d_2^s,1}^{d_2^s,t,2}\cdot(\bar{\theta}\frac{1}{\theta_2^t}\Psi^t H_{k,2}^t - \lambda_{k,1}^{d_2^s,t,2} + \lambda_{d_2^s,1}^{d_2^s,t,2} + \frac{1}{\aleph}\cdot\rho_k^t) = 0 \qquad \forall(k, d_2^s) \in A^D, \forall t \qquad 10.72$$

Also, the equity constraints should be presented as complementarity constraints, as follows:

$$\left(Q\,_k^t\cdot\gamma_k^t - \sum_{s\in S} x_{k,d_1^s,1}^{s,t} - \frac{1}{\aleph}\cdot\sum_{s\in S} y_{k,d_2^s,1}^{d_2^s,t,2}\right)\cdot\rho_k^t = 0 \qquad \forall k, \forall t \qquad 10.73$$

This set of model (equations (60)-(73)) is the same as the lower-level model presented in the main part of this chapter.

10.9 Appending Information Part 2

Table 10.1 presents a summary of the notations used in the Chapter.

Table 10.1 - Summary of Notations

Sets	
$\boldsymbol{N}$	Set of network nodes
$\boldsymbol{A}$	Set of network links ($(i,j) \in A$)
$\boldsymbol{S}$	Destination set ($s \in S$)
$\boldsymbol{T}$	Time periods set ($t \in T$)
$\boldsymbol{R}$	Set of origins of the network ($r \in R$)
$\boldsymbol{N^D}$	Dummy nodes set
$\boldsymbol{A^D}$	Dummy links set
$\boldsymbol{M}$	Set of user class $\boldsymbol{M} = \{HDV, AV\}$
$\boldsymbol{K}$	Set of candidate locations for provision of parking facilities
$\boldsymbol{\widetilde{G}}$	Set of user sub-class ($\widetilde{g} = 2$ if user do not require parking, $\widetilde{g} = 1$ otherwise)
$\boldsymbol{W}$	Set of origin-destinations (O-D) of the network ($w = (r,s) \in W$)
$\boldsymbol{K'}$	Existing parking facility set
Parameters	
$\boldsymbol{\xi_1}$	Weight of system travel time cost
$\boldsymbol{\xi_2}$	Weight of parking fee revenue
$\boldsymbol{\xi_3}$	Weight of monetary benefits of decommissioning the current parking facilities
$\Delta^{\boldsymbol{t}}$	Factor of present value of a cost considering the period duration t
$\boldsymbol{\chi^t_{i,j}}$	Capacity of link (i,j) in a given period t
$\boldsymbol{\sigma^t_{0,i,j}}$	Free-flow travel time of link (i,j) in period t
$\boldsymbol{\varphi^t}$	Maximum acceptable ratio for HDV-AV travel cost
$\boldsymbol{\upsilon^t}$	Maximum acceptable ratio for HDV travel cost
$\boldsymbol{\theta^t_m}$	User class m value of time in a given period t
$\boldsymbol{\overline{\theta}}$	Relative value of AV in-vehicle cost of travel in comparison to operation cost
$\boldsymbol{\varrho}$	Maximum parking facility fee level
$\boldsymbol{\Psi^t}$	Fee for parking level 1 in a given period t ($)
$\boldsymbol{\varsigma}$	Parking facility maximum capacity level
$\boldsymbol{q^{t,\widetilde{g}}_{r,s,m}}$	Travel demand of user sub-class g (of user class m) of O-D pair (r,s) in a given period t
$\boldsymbol{\theta^t_m}$	Value of time for user class m, in a given period t ($/hr).
$\boldsymbol{g^{s,t}_k}$	Parking facility k to destination s last-mile travel time in a given period t
$\boldsymbol{f^t_k}$	Level 1 parking facility k construction cost in a given period t
$\boldsymbol{\overline{\omega}^t_k}$	Parking facility k decommissioning cost in a given period t
$\boldsymbol{\omega^t_k}$	Decommissioning monetary gain associated with parking facility k, in a given period t
$\boldsymbol{\gamma^t_k}$	Level 1 capacity of parking facility k in a given period t
$\boldsymbol{\iota_1}$	Factor representing Construction-capacity
$\boldsymbol{B^t}$	Construction budget in a given period t
$\boldsymbol{d^s_2}$	Dummy node for destination s, for sub-class 1 of AV travelers
$\boldsymbol{d^s_1}$	Dummy node for destination s, for sub-class 1 of HDV travelers
$\aleph$	AV Parking space requirement factor compared to HDV

Variables	
Z^U	Objective function of the upper-level problem
Υ_1	System travel cost
Υ_2	Parking fee revenues
Υ_3	Decommissioning monetary benefits for parking facilities
$\sigma_{i,j}^t$	Link (i,j) travel time in period t
$x_{i,j}^t$	Link (i,j) HDV traffic flow in period t
$v_{i,j}^t$	Link (i,j) traffic flow in period t
$y_{i,j}^t$	Link (i,j) AV traffic flow, period t, phase 1
$y_{i,j,g}^{s,t,1}$	User sub-class g AV travelers flow on link (i,j) that have destination s in phase 1 travel, in period t
$y_{i,j,1}^{d_2^s,t,2}$	AV traffic flow of link (i,j) which dropped off occupants, for destination s, in phase 2, period t
$x_{i,j,\hat{g}}^{s,t}$	User sub-class g HDV traffic flow of link (i,j) having destination s in period t
Z_L	Reformulated lower-level problem objective function
Γ_k^t	Revenues of parking facility k in period t
$u_{r,s,m}^{t,\hat{g}}$	Sub-class g of travel class m cost for O-D pair (r,s) in a given period t
$\lambda_{i,g}^{s,t,1}$	Node i to destination s travel time in period t for a sub-class g AV traveler
$\lambda_{i,1}^{d_2^s,t,2}$	Node i to the dummy node d_2^s travel time for AVs in period t which dropped off their travelers at destination s
$\pi_{i,\hat{g}}^{s,t}$	Node i to destination s travel time in period t for sub-class g HDV travelers
δ_k^t	= 0 if traveler cannot patronize parking facility k in a given period t; = 1 otherwise.
Q_k^t	Capacity level of parking facility k in a given period t
$H_{k,m}^t$	Fee level at parking facility k, in a given period t, user class m
$b_{i,m}^{s,t}$	Flow conservation constraint auxiliary variable for HDVs
$\bar{b}_{i,g}^{s,t}$	Flow conservation constraint auxiliary variable for of AVs (phase 1)
$\bar{\bar{b}}_{i,2}^{d_2^s,t}$	Flow conservation constraint auxiliary variable for of AVs (phase 2)
ρ_k^t	Extra perceived cost that prevents users in period t from parking facility k

Table 10.2 – Parking fee levels under the base planning scenario

Parking facility	Period											
	1		2		3		4		5		6	
	HDV	AV	HDV	AV	HDV	AV	HDV	AV	HDV	AV	HDV	AV
1	3	3	3	3	3	3	3	3	2	3	2	3
2	3	3	3	3	3	3	3	3	-	-	-	-
3	3	3	3	3	3	3	3	3	2	3	2	3
4	3	1	-	-	-	-	-	-	-	-	-	
5	-	-	-	-	2	1	2	1	2	1	2	1
6	2	3	2	3	2	3	2	3	2	3	2	3
7	-	-	-	-	-	-	-	-	-	-	-	-
8	2	3	1	3	1	3	1	3	1	3	1	3
9	-	-	2	1	2	1	2	1	2	1	2	1
10	-	-	-	-	-	-	2	1	2	1	2	1

Table 10.3 – Performance of different prospective parking facility decommissioning benefit levels (in $M)

Prospective benefit of parking facility decommissioning	System travel time cost	Decommissioning benefits	Parking revenues
5	265.02	18.25	1,173.84
10	301.98	58.02	1,179.13
54	301.98	447.86	1,179.13
100	301.98	829.37	1,179.13

CHAPTER 11. SUMMARY AND CONCLUSIONS

11.1 Prelude

This chapter presents a summary of the conclusions, policy recommendations regarding AV-related infrastructure investments, the main contributions of the report, and recommendations for future work.

11.2 A Synopsis of the Research

The report started with a presentation of the study background, problem statement, study objectives, the key elements of the study. The starting chapter recognized the limited nature of current research regarding preparations of the road infrastructure to accommodate AV operations, and the need to examine feedback relationships (and the need for collaboration) among AV stakeholders (road users, IOOs, OEMs, and government regulations and policy makers) including infrastructure providers, and the types of infrastructure readiness required for transitioning to the prospective era of autonomous mobility.

The report then discusses some background information that is critical in efforts towards road infrastructure adequacy and needs to support AV operations. This information includes AV issues and concepts in the context of roadway infrastructure. The report also identifies specific infrastructure-related roles of the key stakeholders. The study also presents the results of a nationwide questionnaire survey of highway agencies, which helped identify the types of infrastructure readiness that may be needed to support AV operations. Through the survey, AV technology developers provided information on the timing of AV technology deployments for public use.

Infrastructure preparations hinge on demand forecasts, and therefore, the study also touched on AV demand forecasts. These forecasts are those that were made by past researchers and are published in the literature. The study carried out a nationwide questionnaire survey of stakeholders regarding AV demand. The survey was diagnostic in nature and therefore threw more light on the factors that are expected to influence AV demand. 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. In addition, the results of an interview that provided aggregate levels of AV market penetration for each level of autonomy, was provided.

No discussion on infrastructure readiness can be made without explicit identification of the issue at the phases of infrastructure planning, design, traffic operations. The report identifies elements of road planning, roadway design, traffic operations, infrastructure maintenance, and monitoring of infrastructure usage and condition, which will be impacted in the AV era. Most of this discussion focuses on the different classes of infrastructure that will be impacted: new infrastructure classes, modification of existing infrastructure (design elements), and infrastructure that will gradually become obsolete.

Highway agencies continue to seek guidance on evaluation of their prospective investments in infrastructure to enhance their readiness for AVs. The report presents a framework on how agencies could do this and demonstrates these frameworks using case studies. The first framework is project level and addresses uncertainty using a flexibility-based real options approach (ROA). Volatility was expressed in terms of the AV market penetration. The framework was implemented for a case study involving an Indiana Interstate corridor. The case study results showed how ROA captures the latent value of proposed AV-related infrastructure investment and therefore is superior to the traditional net present value (NPV) approach. The second framework is for network level AV-related infrastructure project evaluations and addresses holistic effects of the planned investments. Such holism was studied in terms of user equilibrium on a traffic network where driver route choices are influenced by investments. The bi-level parking infrastructure locational design and management framework was implemented for a case study involving parking garages in a city road system. The numerical experiment yielded results that demonstrate the feasibility of the framework and the efficiency of the solution algorithm. The numerical experiments generated an optimal schedule of parking facility locations at various parts of the network over the analysis period, with parking fees differentiated by vehicle mode. The study results also shed light on the impacts of parking fee levels on the configuration (locations, timings, and capacities) associated with the optimal solution. Finally, the report provides a number of guidelines that could be helpful to road agencies seeking to further enhance their infrastructure preparations for the AV era.

11.3 Discussion and Policy Recommendations

In the United States, federal, state, and local agencies mostly constitute the IOOs that are responsible for the oversight or implementation of construction and maintenance projects for the road infrastructure. 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 jurisdictions. To help achieve this, this report recommends that IOOs should make explicit efforts to (a) document and disseminate evaluation results of their AV-related infrastructure, (b) promote design standardization with neighboring states and ultimately all states, thereby, fostering consistency and uniformity in road design and operational standards, and (c) support the establishment of supporting policies and regulations, as discussed below.

11.3.1 Considerations for infrastructure evaluation

The existing road infrastructure was designed and constructed to accommodate human driver capabilities (or lack thereof) and their information needs. For example, road signs are located, installed, and sized based on human perception capabilities relative to the traffic environment. AVs, on the other hand, have sensors that provide sensing accuracy and range far in excess of those of the human driver. In addition, unlike human drivers that have limited exchange of roadway environment information with other human drivers, AVs are capable of acquiring such information from thousands of vehicles via V2V communication and thereby carry out more efficient and accurate navigation and planning (Harrington et al., 2018). On the flip side, prospective AV design is predicated on the need for the AV to be able to operate with little or no support from the infrastructure, and it has been postulated that AVs will ultimately be capable of operating in the same road infrastructure environment used by HDVs currently. As such, in line with Harrington et al. (2018), this report argues that to keep abreast with AV technological advancements, IOOs should continually carry out AV-related road audits, and update their design policies are retrofitting projects to enable their infrastructure to evolve in ways that:

- reflect prevailing technological trends,
- account for AV sensing capabilities,
- supplement the AVs sensing capabilities, and
- adapt to the needs of emerging modes of transport that are enabled by AVs.

Deeper integration of vehicles and infrastructure will decrease AV vulnerability to adverse infrastructure conditions and inconsistencies, and can help build greater robustness, making AVs safer in anomalous infrastructure conditions.

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, IOO's should lay out a clear plan for infrastructure readiness in both the short and long term 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 ensure that the roadway environment is 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 important to clearly discern the short- and long-term infrastructure needs. The short-term needs may include punctual maintenance of lane markings, quick-response and enhanced repairs of road pavements, and improvements to road signs to increase their visibility in all weather conditions. Moreover, increased vehicle electrification in the AV era may also necessitate the promotion of an extensive trans-jurisdictional network of electric vehicle charging infrastructure.

It is also important for IOOs to recognize that the path to full market penetration of AVs will be gradual and fraught with uncertainty. As stated in the literature, autonomous mobility may not be an immediate concern for IOOs and other public officials who are already straining under severe budgetary constraints, and AV market penetration is miniscule at the current time. Nevertheless, it is important for IOOs to realize that investing in certain types of AV-related infrastructure at the current time, could be less costly than acting later to respond to an exigency or emerging need. Therefore, the limitations and needs of the current technology should reflect in I00's 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, as such, planning paradigms including Flexibility in Design, and Designing and Planning for Changeability, are proposed for consideration by the IOOs. 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, the IOOs need to continue collaboration with the OEMs to ensure the former's cognizance of the emerging needs of latter.

11.3.2 Infrastructure design and policy standardization

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 others do not, this inconsistency will 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, IOOs, OEMs, and all other stakeholders collaborate to standardize AV related infrastructure 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.

11.3.3 Coordination among road infrastructure agencies

There exists a need for coordination among IOOs 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, IOOs could be encouraged to depart from their silos 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. Also, this would require rigorous supervision and stronger leadership from national bodies, such as the FHWA (inside the U.S.), and close coordination among the IOOs to promote infrastructure design consistency and uniformity. This will be key to the successful implementation of AV operations and the full realization of its associated safety and efficiency benefits.

11.3.4 Formal and regular coordination between stakeholders

This report 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 (IOOs, OEMs, interest groups) to discuss issues including:

- 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

As such, 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.

11.3.5 Develop mechanisms for information sharing between IOOs and other stakeholders.

A clearly defined mechanism is needed for regular information sharing and the formation of new strategic partnerships among stakeholders. For example, OEMs and IOOs could together 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. Infrastructure agencies need to enhance their processes for data management including sharing among infrastructure, vehicles, and other entities, due to the huge quantity of traffic data that will accompany AV deployment. Also, road corridors with the AV deployment, roadways with smart infrastructure installations are expected to generate massive information transferred between the 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, IOOs 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). IOOs will place themselves in a good position if they start considering strategies for the wider integration of sensing, communications, analytics, and decision support technologies and systems into their operations.

11.3.6 Recognition of the role of infrastructure as a holistic issue not standalone

As discussed in Chapter 1, road infrastructure needs for AVs will influence (and also will be influenced by) three other major forces: AV technology level (OEMs), AV customer demand (travelers and the general public) and supporting legislation and policy (governments). Harrington et al (2018) aptly recognized the quadripartite nature of these relationships and argued that the current infrastructure decisions will impact and define AV operation for decades to come, and therefore communication and coordination among the automotive, technology development, and infrastructure communities will be essential. As such, consistent with their recommendations, this report argues that to develop solutions that are robust and holistic, infrastructure agencies must:

- be aware of advancements in AV technology to identify and measure the extent to which their current infrastructure may foster or inhibit the efficacy of AV sensors and the safety of AV operations.
- need to track AV customer demand over time in order to make timely provisions for new or retrofitted infrastructure (such as AV-dedicated lanes (Ramzi Rad et al., 2020) and PUDOs) to serve AVs.
- encourage, through regular dialogue, the OEMs to duly consider to some extent, the existing (and possibly, the prospective) road plans, funding, designs, and maintenance in the design of their automated systems.
- recognize that AVs will evolve not independently but together with other sibling technologies – electric vehicles, ride-sharing, and connected vehicles, and therefore, it is important to plan for new infrastructure for not only AVs but also these other elements of next generation transportation.

11.4 Contributions of the Report

The main contributions of this report are as follows:

a) Documented stakeholder roles. The study documented the existing and prospective relationships among the key AV stakeholders (road users, IOOs, OEMs, and government policy makers). These include the direct and feedback relationships among the stakeholders and how these relationships could help foster infrastructure readiness for the imminent era of autonomous mobility.
b) Presented insights into AV market penetration forecasts (combined, and for each level of automation) over the next few decades, and the factors that will potentially drive market penetration.
c) Identified the types of infrastructure preparedness (from perspectives of planning, design, and operations) that will be needed to support AV operations. This was done using a literature review, examination of the AASHTO design policies, and a questionnaire survey. The elements of preparedness include identification of new infrastructure classes, existing infrastructure (design elements) that will need to be modified, and infrastructure that will gradually become obsolete.
d) Provided guidance to IOOs for planning and evaluating their prospective investments in infrastructure to enhance AV readiness. The first guidance was a corridor-level framework that addresses uncertainty. The second is network-level framework that considered holistic effects associated with drivers' route choices in response to the investments at various parts of the network. To demonstrate the framework, the study used parking garages as the infrastructure type. However, with slight medication to the problem setting, the framework could be applied to most types of infrastructure.
e) Provided AV-related road infrastructure policy guidelines to guide road agencies that seek to further enhance their infrastructure preparation for AVs.

11.5 Recommendations for Future Work

a) The results of the survey of road users presented in this report 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 new technolog 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 IOOs (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 from road users.
b) OEM's forecasts of AV market penetration, presented in this report, will need periodic updates due to the continuous evolution and maturation of AV technology. The market penetration trends presented in this report may change as the state of the AV technology and the deployment schedules and models become clearer and more certain with time.
c) For quantifying user benefits in Chapter, 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.

d) This report addressed the economic evaluation of AV-related 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.

e) Regarding the network level case study, future research could address the uncertainty associated with AV market penetration in the long term and travel demand by using a robust framework. The second is the inclusion of on-street parking in the planning framework to capture the potential benefits of repurposing on-street parking land to other uses (such as capacity expansion of road lanes or transit lines). Third, parking construction costs and decommissioning benefits should be considered spatially variable over a city network. In practice, the purchase of spaces near downtown and the decommissioning benefits of parking facilities are higher than those in the suburbs. Considering the spatially variable purchase costs and benefits, the economic aspect of parking infrastructure management becomes more realistic. Finally, there is a need for a solution algorithm that is capable of solving this problem for large city road networks.

CHAPTER 12 SYNOPSIS OF PERFORMANCE INDICATORS

12.1 USDOT Performance Indicators Part I

Seven (7) transportation-related courses were offered during the 2018-2019 study period and were taught by the PIs:

- Smart mobility (taught a module), CE 299
- Civil engineering systems design, CE 398
- Highway asset management systems, CE 568
- Transportation systems evaluation, CE 561
- Congestion pricing and its application in the era of smart mobility, CE 597

Five of these were newly developed graduate courses inspired and directly associated with CCAT research. Two graduate students and three post-doctoral researchers (one was subsequently designated a Visiting Assistant Professor) participated in the research project during the study period. Two (2) transportation-related advanced degree programs (masters and doctoral) utilized the CCAT grant funds from this research project, during the study period to support graduate students. This research project was leveraged to obtain the following:

- $210,000 in additional funding from the Indiana DOT on project titled "Integrating Transformative Technologies in Indiana's Transportation Operations" (with: PI's Ananth Iyer and Steve Dunlop).
- $100,000 in additional funding from the Indiana DOT on project titled "Cost and benefit analysis of installing fiber optics on INDOT projects". (with: PI's Kumares Sinha, Jon Fricker, Nadia Gkritza).

12.2 USDOT Performance Indicators Part II

Research Performance Indicators: Seven (7) journal articles and twenty-four (24) conference presentations were produced from this project. The research from this research project was disseminated to over 740 people from industry, government, and academia, through the 24 conference presentations. These include the 2020 Purdue Road School, the 2019 and 2020 Next Generation Transportation Systems Conference (NGTS), the 2019 ITE (Purdue Chapter) Annual Dinner, the 2019-2022 TRB annual meetings, the 2020-2021 INFORMS Annual Meeting, and the 2022 ASCE International Conference on Transportation and Development. Two (2) other related research projects were funded by a source other than UTC and matching fund sources. At the time of writing, there are no new technologies, procedures/policies, and standards/design practices that were produced by this research project.

Leadership Development Performance Indicators: This research project generated 5 academic engagements and 2 industry engagements. The PI held positions in 2 national organizations that address issues related to this research project. One of the CCAT students who worked on this project held a leadership position. The project motivated the PI to establish a series of student-run and student-organized annual conferences “Next Generation Transportation Systems” which has been held in 2019 (West Lafayette), 2020 (online), and 2023 (West Lafayette) that has had international participation and a growing audience. This series has gained adequate momentum and will continue even after the expiry of the USDOT grant.

Education and Workforce Development Performance Indicators: The methods, data and/or results from this study were incorporated in the course syllabi for the following courses at Purdue University: (a) CE 561: Transportation Systems Evaluation, a mandatory graduate level course at Purdue’s transportation engineering M.S. and Ph.D. programs, (b) CE 568: Highway Infrastructure Management Systems, an elective graduate level course at Purdue’s transportation engineering M.S. and Ph.D. programs, (c) CE 299: Smart Mobility, an elective undergraduate level course at Purdue’ civil engineering B.S. program, (d) CE 398: Introduction to Civil Engineering Systems, a mandatory undergraduate level course at Purdue University’s civil engineering program. Most of these students have entered the workforce. Thereby, the research helped enlarge the pool of people trained to develop knowledge and utilize at least a part of the technologies developed in this research, and to put them to use when they enter the workforce.

Collaboration Performance Indicators: There was collaboration with other agencies, and one agency provided matching funds.

The outputs, outcomes, and impacts are described in Chapter 13 below.

CHAPTER 13 STUDY OUTCOMES AND OUTPUTS

13.1 Outputs

13.1.1 Publications, conference papers, and presentations

(a) Journal Publications

i. Seilabi, S., Tabesh, M., Davatgari, A., Miralinaghi, M., Labi, S. (2020). Promoting autonomous vehicles using travel demand and lane management strategies, *Frontiers in the Built Environment*, doi.org/10.3389/fbuil.2020.560116 (**awarded the Joe Sussman best paper prize, by the Journal, 2020**]

ii. Saeed, T.U., Burris, M., Labi, S., Sinha, K.C. (2020). An empirical discourse on forecasting the use of autonomous vehicles using consumers' preferences, *Technological Forecasting and Social Change*, Volume 158, 120130.

iii. Labi, S. (2021). Measuring the benefits of civil systems connectivity and automation–a discussion in the context of highway transport, *Civil Engineering & Environmental Systems*, 1-21,

iv. Saeed, T.U., Alabi, B.N.T., Labi, S., Sinha, K.C. (2021). Preparing road infrastructure to accommodate connected and automated vehicles: System-level perspective, *Journal of Infrastructure Systems*, Volume 27, Issue 1, doi/full/10.1061/%28ASCE%29IS.1943-555X.0000593. **[Recognized as the Editor's Choice Collection, 2021]**

v. Feng, J., Chen, S., Ye, Z., Miralinaghi, M., Labi, S., Chai, J. (2021). Repositioning shared urban personal transport units: considerations of travel cost and demand uncertainty, *Journal of Infrastructure Systems 27* (3), 04021011

vi. Labi, S., Sinha, K.C. (2022). Emerging transportation innovations: Promises and pitfalls, *Innovation and Emerging Technologies*, 1-9, 2240001-1 – 2240001-9.

vii. Labi, S., Saneii, M., Tabesh, M.T., Pourgholamali, M., Miralinaghi, M. (2023). Parking infrastructure location design and user pricing in the prospective era of autonomous vehicle operations, *Journal of Infrastructure Systems* 29(4). 04023025.

viii. Chen, S., Zong, S., Chen, T., Huang, Z., Chen, Y., Labi, S. (2023). A taxonomy for autonomous vehicles considering ambient road infrastructure, Sustainability 15 (14), 11258.

(b) Conference Presentations

i. Saeed, T., Alabi, B., Alinizzi, M., Labi, S., Sinha, K. (2018). Preparing our highways to accommodate CAVs: Research Progress Update, 2018 Global Symposium on Connected & Automated Transportation, Ann Arbor, MI, March 7–8, 2018.

ii. Ghahari, S., Labi, S., Ghotbi, S., Alinizzi, M. (2018). Leveraging advanced technologies for fighting corruption in infrastructure project delivery, ASCE International Conference on Transportation & Development (ICTD), Pittsburgh, PA, July 15–18, 2018.

iii. Ha, Y.J., Ghahari, S., Marfo, A., Labi, S. (2018). Evaluation of automated transit systems: Assessment criteria, Lectern presentation, ASCE International Conference on Automated People Movers and Automated Transit Systems, Tampa, FL, April 29 – May 2, 2018.

iv. Ha, Y.J., Ghahari, S., Marfo, A., Labi, S. (2018). Evaluation of automated transit systems: Assessment criteria, Poster presentation, ASCE International Conference on Automated People Movers and Automated Transit Systems, Tampa, FL, April 29 – May 2, 2018.

v. Ha, Y. J., Ghahari, S., Marfo, A., Labi, S. (2018). Hyperloop systems: An ex ante evaluation, ASCE International Conference on Automated People Movers and Automated Transit Systems, Tampa, FL, April 29 – May 2, 2018.

vi. Nafakh, A., Chen, S., Saeed, T., Labi, S., Ha, Y.J., (2018). Evaluation of an automated people mover in downtown Indianapolis, ASCE International Conference on Automated People Movers and Automated Transit Systems, Tampa, FL, April 29 – May 2, 2018.

vii. Saeed, T., Labi, S., Sinha, K.C. (2018). Roadway infrastructure preparedness for autonomous vehicle operations, 2018 Automated Vehicles Symposium, San Francisco, CA.

viii. Sinha, K.C. (2019). Road Infrastructure Preparedness for Autonomous Mobility, 2019 Global Symposium on Connected & Automated Transportation, Washtenaw Community College, Ann Arbor, MI, February 27, 2019.

ix. Chen, Y., Saeed, T., Volovski, M., Labi, S. (2019), Emergence of big data in smart transportation: big reasons, big challenges, and bigger opportunities, 1st Next Generation Transportation Systems (NGTS-1) Conference, W. Lafayette, IN, May 31, 2019.

x. Li., Y., Saeed, T., Alinizzi, M., Chen, S., Labi, S. (2019). Sustainability-related performance measures – Relevance in an era of smart transportation, 2nd Next Generation Transportation Systems (NGTS-1) Conference, W. Lafayette, IN, May 31, 2019.

xi. Ghahari, S., Queiroz, C., Ghotbi, S., Alinizzi, M., Labi, S. (2019). Anti-corruption activities in infrastructure project delivery using advanced technology, ASCE International Conference on Transportation & Development (ICTD), Alexandria VA, June 9–12, 2019.

xii. Saeed, T.U., Alabi, B.N.T., Labi, S., Miralinaghi, M., Sinha, K.C. (2019). Preparing highway infrastructure for the emerging era of CAVs, ASCE International Conference on Transportation & Development (ICTD), Alexandria VA, June 9–12, 2019.

xiii. Ha, Y.J., Miralinaghi, M., Chen, S., Labi, S. (2019). Sustainability considerations in AV-exclusive lane deployment, ASCE International Conference on Transportation & Development (ICTD), Alexandria VA, June 9–12, 2019.

xiv. Tabesh, M., Miralinaghi, M., Labi, S. (2019). Parking facility location in the era of autonomous vehicles, ASCE International Conference on Transportation & Development (ICTD), Alexandria VA, June 9–12, 2019.

xv. Ha, Y.J., Miralinaghi, M., Labi, S. (2019). Sustainability Considerations in AV Exclusive Lane Deployment, 2019 INFORMS Annual Meeting, Seattle, WA, Oct 20–23, 2019.

xvi. Tabesh, M., Miralinaghi, M., Labi, S. (2020). Parking facility location and user pricing in the era of autonomous vehicles, ITE Seminar, West Lafayette, IN, Oct 13, 2020.

xvii. Tabesh, M., Miralinaghi, M., Labi, S. (2020). Design of parking facility locations and equitable parking fee structures in the era of autonomous vehicles, 2020 INFORMS Annual Meeting, Virtual. Nov 7–13, 2020.

xviii. Pourgholamali, M., Ha, P. Miralinaghi, M., Seilabi, S.E., Labi, S. (2022). Sustainability considerations in AV-exclusive lane deployment. Transportation Research Board 101st Annual Meeting, Washington, DC.

13.1.2 Other products

Other products of this research are as follows:

(a) Course Material

Evaluation methods that can be incorporated in the course syllabi for courses at various universities nationwide that address the subject of CAVs in general and road infrastructure readiness for CAV in particular. Such courses (which may have different titles at the other universities), include:

- Evaluation of transportation systems, projects, programs, and policies
- Highway infrastructure management systems
- Smart mobility or Next-generation transport systems

(b) Editorials co-authored with research partners

Labi, S., Anastasopoulos, P., Miralinaghi, M., Ong, G.P., Zhu, F. (2021). Advances in Planning for Emerging Transportation Technologies: Towards Automation, Connectivity, and Electric Propulsion, Editorial, Frontiers in the Built Environment, Transportation and Transit Systems Volume 7, https://doi.org/10.3389/fbuil.2021.666246

Labi, S. (2021). An influential journal elevating the civil engineering profession and raising its image in the engineering league, Editorial, Computer-Aided Civil and Infrastructure Engineering Volume 36, Issue 10, https://dl.acm.org/doi/abs/10.1111/mice.12751

Labi, S., Lee, H., Derrible, S. (2022). Smart Cities: Infrastructure, Air Quality, Disaster Response, and Data Management, Journal of Infrastructure Systems, Volume 28, Issue 4, DOI: 10.1061/(ASCE)IS.1943-555X.0000723

(c) Student Dissertations and Theses

Tariq U. Saeed, Road infrastructure readiness for autonomous vehicles, PhD Dissertation, Purdue University, 2019, https://doi.org/10.25394/PGS.8949011.v1

Mohammadhosein Pourgholamali, Robust design of electric charging infrastructure locations under travel demand, M.S. Thesis, Purdue University, 2023, https://hammer.purdue.edu/authors/Mohammadhosein_Pourgholamali_Davarani/17683734

Mahmood Tarighati Tabesh, parking facility location and user pricing in the era of autonomous vehicle operations, M.S. Thesis, Purdue University, 2021. https://docs.lib.purdue.edu/dissertations/AAI30504256/

13.2 Outcomes

The outcomes of this project are the prospective changes that can be made to the transportation system, or its regulatory, legislative, or policy framework, resulting from research and development outputs. These are:

- Increased understanding and awareness of the need for the four key AV stakeholders to collaborate towards a smooth path to an autonomous future.
- Greater understanding of AV issues and concepts in the context of roadway infrastructure, and awareness of the infrastructure-related roles of the key stakeholders
- More reliable prognostications of AV demand and better understanding of the factors that will influence AV demand.
- Enhanced understanding of road agencies of the ways to consider AV issues at the various phases of their road infrastructure development – road planning, roadway design, and operations-maintenance-monitoring.
- Awareness of how agencies could address AV-related infrastructure investment evaluation at a project level (considering uncertainty) and at a network level (considering network traffic holistic effects)
- Policy guidelines for road agencies to enhance infrastructure preparation for AVs.

The various frameworks and guidelines presented in this report could serve as planning roadmaps that transportation agencies may use as a point of reference for initiating or promoting AV-related infrastructure investments.

13.3 Impacts

The impacts of this project are the effects of outcomes on the transportation system, or society in general, such as reduced fatalities, decreased capital or operating costs, community impacts, or environmental benefits. This includes how the research outcomes can potentially improves the operation and safety of the transportation system, increase the body of knowledge and technologies, enlarges the pool of people trained to develop knowledge and utilize new technologies and put them to use, and improve the physical, institutional, and information resources that enable people to have access to training and new technologies. A list of specific impacts from this research project, are as follows:

a) Impact on stakeholders: each of the key AV stakeholders (road users, IOOs, OEMs, and government policy makers) will gain further awareness of not only their roles and the impact of their functions on the actions of other stakeholders, and ultimately, AV demand and deployment.
b) Greater awareness of AV market penetration forecasts for each level of automation over the next few decades, and appreciation of the factors that will potentially drive AV market penetration. This will help guide policy development geared toward enhancing AV demand.
c) Impact of road agencies: Road agencies will gain greater awareness of the needed changes in agency planning, design, and operational functions to support autonomous mobility and its sibling technologies (ride sharing and electric propulsion). This includes changes in the design elements of existing infrastructure, new infrastructure classes spawned by AV operations, and obsolescence and retirement of certain classes of infrastructure. Also, agencies will be better positioned to carry out project-level or network-level evaluation of their prospective investments to support traffic operations that includes AV.

REFERENCES

3M. (2018). Products for automated driving: The next evolution of intelligent infrastructure, Retrieved from www.3m.com/3M/en_US/transportation-infrastructure-us/solutions/automated-driving#

AAA (2018), Advanced driver assistance systems (ADAS) repair costs, fact sheet, AAA News Room, newsroom.aaa.com, accessed December 15, 2018.

AAA (annual reports), Your driving costs, American Automobile Association, newsroom.aaa.com and publicaffairsresources.aaa.biz/YDC/html5/index.html, , accessed December 15, 2018.

AAMVA (2022). Safe testing and deployment of vehicles equipped with automated driving systems guidelines 3rd Edition, American Association of Motor Vehicle Administrators, Arlington, VA.

AASHTO (2017). Infrastructure needs for autonomous vehicles. www.tam-portal.com/project/infrastructure-needs-for-autonomous-vehicles/, accessed December 15, 2018.

AASHTO (2018). A policy on geometric design of highways and streets. 7th Edition. Association of American State Highway and Transportation Officials, Washington, DC.

AASHTO (2014). National connected vehicle field infrastructure footprint analysis. Retrieved from http://stsmo.transportation.org/Documents/Exec Summary Final.pdf%0AAmerican

Abraham, H., Lee, C., Brady, S., Fitzgerald, C., Mehler, B., Reimer, B., and Coughlin, J. F. (2017). Autonomous vehicles, trust, and driving alternatives: A survey of consumer preferences. Massachusetts Institute of Technology, AgeLab, Cambridge, 1-16.

Abraham, S. A. (2018). The history of options contracts. www.investopedia.com/articles/optioninvestor/10/history-options-futures.asp, accessed December 15, 2018.

Abuelsamid, S. (2018). Transition to autonomous cars will take longer than you think, Waymo CEO tells Governors. www.forbes.com/sites/samabuelsamid/2018/07/20/waymo-ceo-tells-governors-av-time-will-be-longer-than-you-think/#507b82d6d7da, accessed December 15, 2018.

Ackerman, E. (2017). Toyota's Gill Pratt on self-driving cars and the reality of full autonomy. Spectrum, International Institute of Electrical Engineers. spectrum.ieee.org/cars-that-think/transportation/self-driving/toyota-gill-pratt-on-the-reality-of-full-autonomy, accessed December 15, 2018.

Adam, A. (2005). Roads: Geometric design and layout planning, in Guidelines for Human Settlement Planning and Design: The Red Book, CSIR, Pretoria, South Africa.

Advocates for Highway and Auto Safety (2017). CARAVAN public opinion poll: Driverless cars. saferoads.org/2018/01/12/new-poll-finds-overwhelming-support-for-driverless-car-safety-standards/, accessed December 15, 2018.

Agarwal, R., Prasad, J. (1999). Are individual differences germane to the acceptance of new information technologies? Decision Sciences, 30(2), 361-391.

Ahmed, A., Saeed, T. U., Murillo-Hoyos, J., and Labi, S. (2017). Pavement repair marginal costs: accounting for heterogeneity using random-parameters regression. Journal of Infrastructure Systems, 23(4), 04017012.

Ahmed, S.S., Sonduru Pantangi, S., Eker, U., Fountas, G., Still, S.E., Anastasopoulos, P.C., (2020). Analysis of safety benefits and security concerns from the use of autonomous vehicles: A grouped random parameters bivariate probit approach with heterogeneity in means. Anal. Methods Accid. Res. https://doi.org/10.1016/j.amar.2020.100134
Air Quality Expert Group (2020). Non-exhaust emissions from road traffic, UK Department for Environment, Food and Rural Affairs (https://uk-air.defra.gov.uk); at https://bit.ly/2Ufin64.
Al Alam, A., Gattami, A., Johansson, K.H. (2010). An experimental study on the fuel reduction potential of heavy duty vehicle platooning, in: IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC. https://doi.org/10.1109/ITSC.2010.5625054
Al-Qadi, I.L., Okte, E., Ramakrishnan, A., Zhou, Q., Sayeh, W. (2021). Truck Platooning on Flexible Pavements in Illinois, Illinois Center for Transportation, University of Illinois at Urbana-Champaign, Research Report No. FHWA-ICT-21-010, Urbana-Champaign, IL.
Amelink, M., Kulmala, R., Jaaskelainen, J., Sacs, I., Narroway, S., Niculescu, M., Rey, L., Alkim, T. (2020). EU EIP SA4.2: Road map and action plan to facilitate automated driving on TEN road network – version 2020. European ITS Platform.
American Automobile Association, AAA. (2018). Americans feel unsafe sharing the road with fully self-driving cars. Retrieved from https://newsroom.aaa.com/2017/03/americans-feel-unsafe-sharing-road-fully-self-driving-cars/
Amoozadeh, M., Deng, H., Chuah, C.N., Zhang, H.M., Ghosal, D. (2015). Platoon management with cooperative adaptive cruise control enabled by VANET. Veh. Commun. https://doi.org/10.1016/j.vehcom.2015.03.004
Amram, M., and Kulatilaka, N. (1999). Real options: Managing strategic investment in an uncertain world. Harvard Business School Press, Boston, MA.
Anderson, J. M., Kalra, N., Stanley, K. D., Sorensen, P., Samaras, C., Oluwatola, O. A. (2014). Autonomous vehicle technology a guide for policymakers. RAND Corporation, Santa Monica, CA.
APA (2016). Autonomous vehicles: Knowledge-base collection, American Planning Association (www.planning.org); at www.planning.org/knowledgebase/autonomousvehicles, accessed December 15, 2018.
APA (2016). Planning for the autonomous vehicle revolution. American Planning Association Blog. www.planning.org/blog/blogpost/9105024, accessed December 15, 2018.
Appleyard, B., and Riggs, W. (2018). 10 principles toward more sharing and less sprawl: A manifesto for street livability, health, and humanity in the era of driverless cars, Planetizen (www.planetizen.com); at www.planetizen.com/features/96769-10-principles-toward-more-sharing-and-less-sprawl.
Archambault, P., Delaney, M., Yuzawa, K., Burgstaller, S., Tamberrino, D., Duval, A. (2015). Monetizing the rise of autonomous vehicles. Goldman Sachs-Cars, 2025(3), 81. http://pg.jrj.com.cn/acc/Res/CN_RES/INVEST/2015/9/17/f70472c6-f4ad-4942-8eab-3c01f3c717a7.pdf, accessed December 15, 2018.
Arizona DOT (2023). Autonomous vehicles testing and operating in the state of Arizona, https://azdot.gov/mvd/services/professional-services/autonomous-vehicles-testing-and-operating-state-Arizona
Arrow, K., R. Solow, P. R. Portney, E. E. Leamer, R. Radner, and H. Schuman. (1993). Report of the NOAA panel on contingent valuation, Federal Register, Washington, DC.

Aryal, P. (2020). Optimization of geometric road design for autonomous vehicle. M.S. Thesis, KTH Royal Institute of Technology, Stockholm, Sweden.
Athigakunagorn, N. (2015). Using real options theory to enhance highway asset intervention scheduling. Ph.D. Dissertation, Purdue University.
Atiyeh, C. (2012). Predicting traffic patterns, one Honda at a time. MSN Auto.
Auld, J., Karbowski, D., Sokolov, V. (2017). Assessing the regional energy impact of connected vehicle deployment. Transp. Res. Procedia.
Autonomous Vehicles Laboratory (WAVELab), University of Waterloo, Waterloo, Canada.
AVS (2018). Automated Vehicles Symposium 2018. July 09-12, 2018. San Francisco, CA. www.automatedvehiclessymposium.org/avs2018/home, accessed December 15, 2018.
Ayre, J. (2017). Caltrans is already modifying California's roads for self-driving cars. Clean Technica. cleantechnica.com/2017/07/25/caltrans-already-modifying-californias-roads-self-driving-cars, accessed December 15, 2018.
Bagloee, S.A., Asadi, M., Sarvi, M., Patriksson, M. (2018) A hybrid machine-learning and optimization method to solve bi-level problems. Expert Systems with Applications, 95(1), 142–152.
Bala, H., Anowar, S., Chng, S., Cheah, L. (2023). Review of studies on public acceptability and acceptance of shared autonomous mobility services: past, present and future, Transport Reviews, 43:5, 970-996, DOI: 10.1080/01441647.2023.2188619
Bamberg, S., Ajzen, I., Schmidt, P. (2003). Choice of travel mode in the theory of planned behavior: The roles of past behavior, habit, and reasoned action. Basic and Applied Social Psychology, 25(3), 175-187.
Bamonte, T. J. (2013). Drivers of change. Autonomous vehicles. https://sgcweb.s3.wasabisys.com/roadsbridges/s3fs-public/05_autonomous%20vehicles.pdf, accessed December 15, 2022.
Banerjee, T., Baer, W.C. (1984). Beyond the neighborhood unit: Residential environment and public policy, Plenum Press, New York.
Bansal, P., and Kockelman, K. M. (2018). Are we ready to embrace connected and self-driving vehicles? A case study of Texans. Transportation, 45(2), 641-675.
Bansal, P., Kockelman, K. M., and Singh, A. (2016). Assessing public opinions of and interest in new vehicle technologies: An Austin perspective. Transportation Research Part C: Emerging Technologies, 67, 1-14.
Barbour, N., Menon, N., Zhang, Y., and Mannering, F. (2019). Shared automated vehicles: A statistical analysis of consumer use likelihoods and concerns. Transport Policy, 80(1), 86-93.
Barff, R., Mackay, D., and Olshavsky, R. W. (1982). A selective review of travel-mode choice models. Journal of Consumer Research, 8(4), 370-380.
Barnes, P. (2017). Autonomous vehicles in Delaware: Analyzing the impact and readiness for the first state, Published by University of Delaware's Institute for Public Administration In collaboration with The Delaware Department of Transportation, Delaware. https://deldot.gov/Programs/autonomous-vehicles/pdfs/autonomous-vehicles-2017.pdf
Berechman, J. (2014). Taylor & Francis Routledge Advances in Management and Business Studies.
Bergenhem, C., Hedin, E., Skarin, D. (2012). Vehicle-to-vehicle communication for a platooning system. Procedia - Soc. Behav. Sci. https://doi.org/10.1016/j.sbspro.2012.06.1098
Berman, B. (2011). History of hybrid vehicles, Hybrid Cars (www.hybridcars.com); at

https://bit.ly/2z9aSEg.
Berrada, J., and Leurent, F. (2017). Modeling transportation systems involving autonomous vehicles: State of the art, Transportation Research Procedia, Vol. 27, pp. 215-221 (https://bit.ly/2IK9iwO).
Bhuiyan, J. (2017, September 12) A federal agency says an overreliance on Tesla's Autopilot contributed to a fatal crash. Vox. www.vox.com/2017/9/12/16294510/fatal-tesla-crash-self-driving-elon-musk-autopilot, accessed December 15, 2022.
Bierstedt, J., Gooze, A., Gray, C., Peterman, J., Raykin, L., Walters, J. (2014, January). Effects of next-generation vehicles on travel demand and highway capacity. Technical Report. Fehr and Peers Transportation Consultants, orfe.princeton.edu/~alaink/Papers/FP_NextGenVehicleWhitePaper012414.pdf, accessed December 15, 2022.
Bischoff, J., and Maciejewski, M. (2016). Simulation of city-wide replacement of private cars with autonomous taxis in Berlin. Procedia Computer Science, 83, 237-244.
Black, F., and M. Scholes. (1973). The pricing of options and corporate liabilities. Journal of Political Economy, 81(3), 637–654.
Booz Allen Hamilton and WSP (2020). Impacts of connected and automated vehicle technologies on the highway infrastructure, NCHRP 20-102(15) Task 5 Final Project Report, Prepared for National Cooperative Highway Research Program (NCHRP) Transportation Research Board of The National Academies, https://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-102-15FinalProjectReport.pdf
Bösch, P., Becker, F., Becker, H., Axhausen, K. (2018). Cost-based analysis of autonomous mobility services, Transport Policy 64, 76-91.
Broussard, M. (2018). The dirty truth coming for self-driving cars: Trash. odors, bodily fluids. will autonomous rideshares be ready for our mess? Slate (https://slate.com); at https://slate.me/2Ls9IrI.
BSI (2020). Connected and automated vehicles – Vocabulary v3.0. London: The British Standards Institution.
Burghout, W. Rigole, P.J., and Andreasson, I. (2015). Impacts of shared autonomous taxis in a metropolitan area. Proceedings of the 94th Annual Meeting of the Transportation Research Board, Washington, D.C., USA, 11–15 January 2015.
Burns, L.D. (2013). Sustainable mobility: A vision of our transport future. Nature, 497, 181–182.
Business Insider Intelligence (2018) By the end of 2019, Waymo, Uber, and GM all plan to have fleets of autonomous cars providing on-demand rides — here's how automakers can compete www.businessinsider.com/the-autonomous-mobility-ecosystem-report-2018-3, accessed December 15, 2022.
California Energy Commission. (2017). 2015-2017 California vehicle survey. www.Energy.Ca.Gov/Assessments/Vehiclesurvey/, accessed December 15, 2022.
Campbell, M., Egerstedt, M., How, J.P., Murray, R.M. (2010). Autonomous driving in urban environments: approaches, lessons and challenges, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci., 368 (2010), pp. 4649-4672, https://doi.org/10.1098/rsta.2010.0110
Canisius, T. D. G., Diamantidis, D., Holicky, M, Markova, J., and Vogel, T. (2011). Philosophy and principles of robustness. In Structural robustness design for practicing engineers—COST Action TU0601 Robustness of structures, edited by T. Canisius, 13–30. Brussels,

Belgium: European Cooperation in Science and Technology.
Cardin, M. A. and de Neufville, R. (2009). A direct interaction approach to identify real options "in" large-scale infrastructure systems. Real Options Conference, Braga, Portugal and Santiago, Spain.
Cardin, M. A., Ranjbar-Bourani, M., and de Neufville, R. (2015). Improving the lifecycle performance of engineering projects with flexible strategies: example of on-shore LNG production design. Systems Engineering, 18(3), 253-268.
Capoot, A., Piazza, J. (2023). Uber begins offering rides in self-driving Waymo cars. CNBC-Tech., https://www.cnbc.com/2023/10/26/uber-begins-offering-rides-in-self-driving-waymo-cars.html
Casley, S.V., Jardim, A.S., and Quartulli, A.M. (2013). A study of public acceptance of autonomous cars. Worcester Polytechnic Institute, New York.
CAVita (2017). State DOT CEO Leadership forum on connected & autonomous vehicles and transportation infrastructure readiness in conjunction with 2017 ITSWC, Montreal, Canada. Final Report, Project 20-24(111), NCHRP, TRB, Washington, DC.
CEN (1994). Eurocode 1: Actions on structures: Part 1 basis of design: Committee European de Normalization. CEN-250. Brussels, Belgium: (European Committee for Standardization). CEN.
Center for Autonomous Vehicles (2020). Operational Design Domain (ODD) taxonomy for an automated driving system (ADS) – Specification, British Standards Institution, BSI Standards Limited, London UK.
Chan, C. Y., and Wang, P. (2021). Caltrans Autonomous Vehicles Industry Survey of Transportation Infrastructure Needs. CA21-3650. California Department of Transportation, Sacramento, CA,
Chapin, T., Stevens, L., Crute, J., Crandall, J., Rokyta, A., Washington, A. (2016). Envisioning Florida's future: Transportation and land use in an automated vehicle world. Prepared for the Florida Department of Transportation.
Charness, G., Gneezy, U. (2012). Strong evidence for gender differences in risk taking, Journal of Economic Behavior & Organization, 83(1), 50–58.
Chen, F., Song, M., Ma, X., & Zhu, X. (2019a). Assess the impacts of different autonomous trucks' lateral control modes on asphalt pavement performance. Transportation Research Part C: Emerging Technologies, 103(September 2018), 17–29.
Chen, J. (2018). Rainbow option. Retrieved from https://www.investopedia.com/terms/r/rainbowoption.asp
Chen, S. (2019) Safety implications of roadway design and management: new evidence and insights in the traditional and emerging (autonomous vehicle) operating environments. Ph.D. Dissertation, Purdue University, West Lafayette, IN 47907, USA.
Chen, S., Leng, Y., Labi, S. 2020. A deep learning algorithm for simulating autonomous driving considering prior knowledge and temporal information. Computer-Aided Civil and Infrastructure Engineering, 35(4), 305-321.
Chen, S., Saeed, T. U., Alqadhi, S. D., and Labi, S. (2019a). Safety impacts of pavement surface roughness at two-lane and multi-lane highways: accounting for heterogeneity and seemingly unrelated correlation across crash severities. Transportmetrica A: Transport Science, 15(1), 18-33.
Chen, S., Saeed, T. U., and Labi, S. (2017). Impact of road-surface condition on rural highway safety: A multivariate random parameters negative binomial approach. Analytic methods

in Accident Research, 16, 75-89.
Chen, S., Zong, S., Chen, T., Huang, Z., Chen, Y., Labi, S. (2023). A taxonomy for autonomous vehicles considering ambient road infrastructure, Sustainability 15(14),11258.
Chen, T.D., Kockelman, K.M., and Hanna J.P. (2016). Operations of a shared, autonomous, electric vehicle fleet: Implications of vehicle & charging infrastructure decisions, Transportation Research Part A: Policy and Practice, 94, 243-254.
Chen, Z., He, F., & Yin, Y. (2016). Optimal deployment of charging lanes for electric vehicles in transportation networks. Transportation Research Part B: Methodological, 91, 344-365.
Chen, Z., He, F., Yin, Y., & Du, Y. (2017). Optimal design of autonomous vehicle zones in transportation networks. Transportation Research Part B: Methodological, 99, 44-61.
Chiu, H.-M.A. Location model for the allocation of the off-street parking facilities. (2006) Journal of the Eastern Asia Society for Transportation Studies, 6(1), 1344–1353.
Chuen, T.H. et al. (2013), Autonomous vehicles, MT5009; at https://bit.ly/2RTGdS7.
Circella, G., and Hardman, S. (2022). Driverless cars won’t be good for the environment if they lead to more auto use, The Conversation (https://theconversation.com); at https://bit.ly/3gkmrgO.
City of Sioux Falls, Public parking - City of Sioux Falls. https://www.siouxfalls.org/police/public-parking. Accessed Dec. 2, 2020.
Clausing, D. (1994). Total quality development, ASME Press, New York.
Colonna, P. Intini, P. Berloco, N. Ranieri V. (2018). Connecting rural road design to automated vehicles: The concept of safe speed to overcome human errors, in Advances in Human Aspects of Transportation N.A. Stanton (Ed.), 571-582. https://doi.org/10.1007/978-3-319-60441-1_56
Connecticut DOT (2021). Preparing for connected and automated vehicles strategic plan, https://portal.ct.gov/-/media/DOT/PLNG_STUDIES/CT-CAV-Report-Final.pdf
Copeland, T. and Antikarov, V. (2001). Real options: A practitioner’s guide. New York, NY: Texere Publishing.
Correia, G.H. de A., Looff, E., van Cranenburgh, S., Snelder, M., van Arem, B. (2019). On the impact of vehicle automation on the value of travel time while performing work and leisure activities in a car: Theoretical insights and results from a stated preference survey. Transportation Research Part A: Policy and Practice, 119, 359–382.
Cottam, B. (2017). Public acceptance of autonomous and connected cars, Journal of Unmanned Vehicle Systems, 5(2), 35-36.
Cox, J. C., Ross, S. A., and Rubinstein, M. (1979). Option pricing: A simplified approach. Journal of Financial Economics 7(3), 229-263.
CPUC (2020), Autonomous Vehicle pilot permits issued, California Public Utilities Commission (www.cpuc.ca.gov/avcissued).
Crawley, E. and deWeck, O. (2003, October 21) Extensibility in space transportation, presentation at NASA Headquarters, Washington, D.C.
Crawley, E., deWeck, O., Eppinger, S., Magee, C., Moses, J., Seering, W., Schindall, J., Wallace, D., and Whitney, D. (2004) The influence of architecture on engineering systems, MIT Engineering Systems Symposium, March 29–31, Cambridge, MA.
Creger, H., Espino, J., Sanchez, A.S. (2019), Autonomous vehicle heaven or hell? Creating a Transportation Revolution that Benefits All, Greenlining (http://greenlining.org); at https://bit.ly/2W710ab.
Cruz Rambaud, S. and Sánchez Pérez, A.M. (2016). Assessing the option to abandon an

investment project by the binomial options pricing model. Advances in Decision Sciences, 2016. http://dx.doi.org/10.1155/2016/7605909
Czarnecki, K. (2018). Operational world model ontology for automated driving systems. Parts I and II. Waterloo Intelligent Systems Engineering Laboratory (WISELab), Waterloo Autonomous Vehicles Laboratory (WAVELab), University of Waterloo, Waterloo, Canada.
Dagan, E., Mano, O., Stein, G.P., Shashua, A. (2004). Forward collision warning with a single camera, in: IEEE Intelligent Vehicles Symposium, Proceedings. https://doi.org/10.1109/ivs.2004.1336352
Davies, C. (2016). Pavement markings guiding autonomous vehicles – A real world study. 68. Retrieved from https://higherlogicdownload.s3.amazonaws.com/AUVSI/14c12c18-fde1-4c1d-8548-035ad166c766/UploadedImages/documents/Breakouts/20-2 Physical Infrastructure.pdf
Dawn Project (2022), Tesla full self-driving safety analysis, The Dawn Project: Making Computers Safe for Humanity (https://dawnproject.com); at https://bit.ly/3rlvh4q.
Daziano, R. A., Sarrias, M., and Leard, B. (2017). Are consumers willing to pay to let cars drive for them? Analyzing response to autonomous vehicles. Transportation Research Part C: Emerging Technologies, 78, 150-164.
de Neufville, R. (1990) Applied systems analysis: Engineering planning and technology, Management, McGraw-Hill College, New York, NY.
de Neufville, R. (2016) Engineering systems analysis. Class Notes. Massachusetts Institute of Technology.
de Neufville, R., and S. Scholtes. (2011). Flexibility in engineering design. Cambridge, MA. MIT Press.
de Neufville, R., Scholtes, S., and Wang, T. (2006). Real options by spreadsheet: parking garage case example. Journal of Infrastructure Systems, 12(2), 107-111.
De Souza, A.M., Yokoyama, R.S., Maia, G., Loureiro, A., Villas, L., 2016. Real-time path planning to prevent traffic jam through an intelligent transportation system, in: Proceedings - IEEE Symposium on Computers and Communications. https://doi.org/10.1109/ISCC.2016.7543822
DeCorla-Souza, P., and Verdouw, W. (2019, January 13-17). Evaluation of a potential strategy to transition to infrastructure that accommodates emerging technologies. 98th TRB Annual Meeting, Washington D.C.
Delcan Technologies (2022). Michigan DOT Intelligent Snow Plow System. Delcan Technologies, http://delcantechnologies.com/michigan-dot-intelligent-snow-plow-system/
DeLuca, A. (2018). Ending the search for parking, Urbanism Next (https://urbanismnext.uoregon.edu); at https://bit.ly/2q6uTWD.
Dennehy, K. (2018). Autonomous vehicle industry needs to foster public acceptance - Inside unmanned systems. Retrieved from http://insideunmannedsystems.com/autonomous-vehicle-industry-needs-foster-public-acceptance/
Deshmukh, A. (2012). Valuing flexibility Phase II. Final Technical Rep. SERC-2012-TR-10-2. Purdue, IL: Stevens Institute of technology and Systems Engineering Research Center.
Dirksen, S. (1997). Air bags: History of American technology, Bryant University Community Web (http://web.bryant.edu/~ehu/h364proj/sprg_97/dirksen/airbags.html).
Dixit, V.V., Chand, S., and Nair, D.J. (2016). Autonomous vehicles: disengagements, accidents

and reaction times. PLoS ONE,11(12): e0168054.
Dong, J., Chen, S., Li, Y., Du, R., Steinfeld, A., Labi, S. (2020a). Spatio-weighted information fusion and DRL-based control for connected autonomous vehicles, IEEE ITS Conference, September 20–23, 2020. Rhodes, Greece.
Dong, J., Chen, S., Li, Y., Du, R., Steinfeld, A., Labi, S. (2020b). Facilitating connected autonomous vehicle operations using space-weighted information fusion and deep reinforcement learning based control. arXiv preprint arXiv:2009.14665.
Dong, J., Chen, S., Ha, P., Du, R., Li, Y., Labi, S. (2020c). A DRL-based multiagent cooperative control framework for CAV networks: A graphic convolution Q network. arXiv preprint arXiv:2010.05437.
Dowling, R., Nevers, B., Jia, A., Skabardonis, A., Krause, C., Vasudevan, M. (2016). Performance benefits of connected vehicles for implementing speed harmonization, in: Transportation Research Procedia. https://doi.org/10.1016/j.trpro.2016.06.039
Du, R., Chen, S., Li, Y., Dong, J., Ha, P., Labi, S. (2020). A cooperative control framework for CAV lane change in a mixed traffic environment. arXiv preprint arXiv:2010.05439.
Du, Y., Yu, S., Meng, Q., Jiang, S. (2019). Allocation of street parking facilities in a capacitated network with equilibrium constraints on drivers' traveling and cruising for parking. Transportation Research Part C: Emerging Technologies, 101(1), 181–207.
Duarte, F., & Ratti, C. (2018). The impact of autonomous vehicles on cities: A review. Journal of Urban Technology, 25(4), 3–18. https://doi.org/10.1080/10630732.2018.1493883
Duell, M., Levin, M.W., Boyles, S.D., Waller, S.T. (2016). Impact of autonomous vehicles on traffic management. Transp. Res. Rec. J. Transp. Res. Board. https://doi.org/10.3141/2567-10
Duval, T., Hannon, E., Katseff, J., Safran, B., Wallace, T. (2019). A new look at autonomous-vehicle infrastructure, McKinsey and Company, Washington, DC.
Ebert, J. (2016). Reinventing the human brain: how A.I. will revolutionize driverless cars. Retrieved from https://www.2025ad.com/latest/driverless-cars-and-artificial-intelligence/
Eddy, J., and Falconer, R. (2017). A civil debate: are driverless cars good for cities?, Doggerel (http://doggerel.arup.com); at https://bit.ly/3Hl2sdX.
Eimler, S.C., Geisler, S. (2015). On the Acceptance of autonomous driving–An a-priori study. Mensch & Computer Workshopband; Walter de Gruyter GmbH: Berlin, 533–540.
Eker, U., Fountas, G., Anastasopoulos, P.C. (2020). An exploratory empirical analysis of willingness to pay for and use flying cars. Aerosp. Sci. Technol. https://doi.org/10.1016/j.ast.2020.105993
Elshazli, M.T., Ibrahim, A., Abdel-Rahim, A. (2023). Truck platooning impact on existing bridge load ratings, Structures 51, 1706-1721
Eskandari, M., Nookabadi, A.S. (2018). Off-street parking facility location on urban transportation network considering multiple objectives: A Case Study of Isfahan (Iran). Transport, 33(4), 1067–1078.
Erhart, J., Harrer, M., Rührup, S., Seebacher, S., Wimmer, Y. (2020). Infrastructure support for automated driving: Further enhancements on the ISAD classes in Austria. Proc. 8th Transp. Res. Arena TRA 2020, April 27-30, 2020, Helsinki, Finland. https://www.inframix.eu/wp-content/uploads/TRA2020 31102019_Erhart_submitted.pdf
ERTRAC (2019). ERTRAC Connected automated driving roadmap. European Road Transport, Research Advisory Council, Brussels, Belgium.

ETSI (2011). Intelligent transport systems (ITS); vehicular communications; basic set of applications; part 2: Specification of cooperative awareness basic service. Draft ETSI TS 20: 448-451.
Eykholt, K., Evtimov, I., Fernandes, E., Li, B., Rahmati, A., Xiao, C., Prakash, A., Kohno, T., Song, D. (2018). Cryptography and security, arxiv.org/abs/1707.08945).
Fagnant, D. J., and Kockelman, K. (2015). Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. Transportation Research Part A: Policy and Practice, 77, 167-181.
Fagnant, D. J., Kockelman, K. M. (2018). Dynamic ride-sharing and fleet sizing for a system of shared autonomous vehicles in Austin, Texas. Transportation, 45, 143–158. https://doi.org/10.1007/s11116-016-9729-z
Fagnant, D. J., Kockelman, K. M., and Bansal, P. (2015). Operations of a shared autonomous vehicle fleet for the Austin, Texas market. Transportation Research Board. 2536. 98–106 http://www.trb.org/Main/Blurbs/173204.aspx
Fagnant, D.J., and Kockelman, K.M., 2014. The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. Transp. Res. Part C: Emerg. Technol. 40, 1–13. http://dx.doi.org/10.1016/j.trc.2013.12.001.
Farah, H., Erkens, S.M., Alkim, T., Van Arem, B. (2016). Infrastructure for automated and connected driving: State of the art and future research directions. In: Advanced Microsystems for Automotive Applications 2016; Springer: Berlin/Heidelberg, Germany, 2017; 187–197
Farris, P. W., Bendle, N., Pfeifer, P., Reibstein, D. (2010). Marketing metrics: The definitive guide to measuring marketing performance. Pearson Education. ISBN 0-13-705829-2.
FCC (2019). Notice of proposed rulemaking – ET Docket No. 19-138.
Fehr & Peers (2014). Effects of next-generation vehicles on travel demand & highway capacity, Fehr and Peers (www.fehrandpeers.com); at www.fehrandpeers.com/fpthink/nextgenerationvehicles.
Feng, J., Chen, S., Ye, Z., Miralinaghi, M., Labi, S., Chai, J. (2021). Repositioning shared urban personal transport units: considerations of travel cost and demand uncertainty, Journal of Infrastructure Systems 27 (3), 04021011
Feng, Y., Head, K.L., Khoshmagham, S., Zamanipour, M. (2015). A real-time adaptive signal control in a connected vehicle environment. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2015.01.007
Ferguson, S., Siddiqi, A., Lewis, K., de Weck, O. L. (2007, January). Flexible and reconfigurable systems: Nomenclature and review. In ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (pp. 249-263), Paper No. DETC2007-35745. American Society of Mechanical Engineers, New York: ASME.
Ferreira, N., Kar, J., and Trigeorgis, L. (2009). Option games: The key to competing in capital-intensive industries. Harvard Business Review 87(3).
FHWA (1999). Asset management primer, Federal Highway Administration, Washington, DC.
FHWA (2018) FHWA national dialogue on highway Automation. Federal Highway Administration. May 08, 2018. Available at https://ops.fhwa.dot.gov/automationdialogue/
FHWA (Annual reports), Highway statistics, Federal Highway Administration (www.fhwa.dot.gov); at www.fhwa.dot.gov/policyinformation/statistics.cfm.
Filipovska, M., Mahmassani, H.S., Mittal, A. (2019). Prediction and mitigation of flow

breakdown occurrence for weather affected networks: Case study of Chicago, Illinois. Transp. Res. Rec. 0361198119851730.
Filippin, A. (2022). Gender differences in risk attitudes, IZA World of Labor Newsletter. Institute of Labor Economics, University of Bonn, Bonn, Germany.
Fleming, K., and Singer, M. (2019), Energy implications of current travel and the adoption of automated vehicles, National Renewable Energy Laboratory; at www.nrel.gov/docs/fy19osti/72675.pdf.
Ford, D. N., Lander, D. M., and Voyer, J. J. (2002). A real options approach to valuing strategic flexibility in uncertain construction projects. Construction Management and Economics 20(4), 343-351.
Forni, A. (2017). 4 areas driving autonomous vehicle adoption. Retrieved from: https://www.gartner.com/smarterwithgartner/4-areas-driving-autonomous-vehicle-adoption/
Fouque, J. and Han, C. (2005). Evaluation of compound options using perturbation approximation. Journal of Computational Finance, 9(1) 41.
Fricke, E. (2006). Der Änderungsprozeß als Grundlage einer nutzerzentrierten Systementwicklung, 1-200, Technical University of Munich, Germany.
Fricke, E., and A. P. Schulz. (2005). Design for changeability (DfC): Principles to enable changes in systems throughout their entire lifecycle. Systems Engineering. 8(4), 342–359.
Fulton, L., Compostella, J., and Kothawala, A. (2020). Estimating the costs of new mobility travel options: Monetary and non-monetary factors, National Center for Sustainable Transportation (https://escholarship.org/uc/itsdavis_ncst); at (https://doi.org/10.7922/G20R9MN8).
Fulton, L., Mason, J., and Meroux, D. (2017). Three revolutions in urban transportation, UC Davis and ITDP (www.itdp.org); at www.itdp.org/publication/3rs-in-urban-transport.
FTIA (2021). Automated Driving on Motorways (AUTOMOTO): Study of infrastructure support and classification for automated driving on Finnish motorways. Finnish Transport Infrastructure Agency, Helsinki.
Gandia, R. M., Antonialli, F., Cavazza, B. H., Neto, A. M., Lima, D. A. D., Sugano, J. Y., Nicolai, I. and Zambalde, A. L. (2019). Autonomous vehicles: Scientometric and bibliometric review. Transport reviews, 39(1), 9-28.
GAO (2016), Vehicle cybersecurity: DOT and industry have efforts under way, but DOT Needs to Define Its Role in Responding to a Real-world Attack, GAO (www.gao.gov); at https://bit.ly/1ruZi09.
García, A., Camacho-Torregrosa, F. J., and Padovani Baez, P. V. (2020a). Examining the effect of road horizontal alignment on the speed of semi-automated vehicles. Accid. Analysis Prev. 146, 105732. doi:10.1016/j.aap.2020.105732
Garcia, A., Llopis-Castello, D., Camacho-Torregrosa, F. (2019). Influence of the design of crest vertical curves on automated driving experience. In Proceedings of the Transportation Research Board 98th Annual Meeting, Washington, DC, USA, 13–17 January, 2019.
Geske, R. and Johnson, H.E. (1984). The American put option valued analytically. Journal of Finance. 39(5), 1511-1524.
Ghahari, S., Labi, S., Ghotbi, S., Alinizzi, M. (2018). Leveraging advanced technologies for fighting corruption in infrastructure project delivery, ASCE International Conference on Transportation & Development (ICTD), Pittsburgh, PA, July 15–18, 2018.
Ghahari, S., Queiroz, C., Ghotbi, S., Alinizzi, M., Labi, S. (2019). Anti-corruption activities in

infrastructure project delivery using advanced technology, ASCE International Conference on Transportation & Development (ICTD), Alexandria VA, June 9–12, 2019.

Ghiasi, A., Ma, J., Zhou, F., Li, X. (2017). Speed harmonization algorithm using connected autonomous vehicles, in: 96th Annual Meeting of the Transportation Research Board, Washington, DC.

GHSA. (2018). Preparing for automated vehicles: Traffic safety issues for states. Governors Highway Safety Association, Washington, DC. Retrieved from https://www.ghsa.org/sites/default/files/2018-08/Final_AVs2018.pdf%0Ahttps://trid.trb.org/view/1532106

Gkartzonikas, C. and Gkritza, K. (2019). What have we learned? A review of stated preference and choice studies on autonomous vehicles. Transportation Research Part C: Emerging Technologies (98), 323-337.

Gkartzonikas, C., Ke, Y., and Gkritza, K. (2022). A tale of two modes: Who will use single-user and shared autonomous vehicles. Case Studies on Transport Policy, 10(3), 1566–1580.

Gkartzonikas, C., Losada-Rojas, L. L., Christ, S., Pyrialakou, V. D., and Gkritza, K. (2022). A multi-group analysis of the behavioral intention to ride in autonomous vehicles: Evidence from three U.S. metropolitan areas. Transportation.

Gkritza, K., Chahine, R. (2023). The Impact of COVID-19 on User Perceptions of Public Transit, Shared Mobility/Micro-Mobility Services, and Emerging Vehicle Types, CCAT Report Nr. 60, The Center for Connected and Automated Transportation, Purdue University, West Lafayette, IN.

GM (2020), OnStar Services (www.onstar.com).

González-González, E., Nogués, S., and Stead, D. (2020). Parking futures: Preparing European cities for the advent of automated vehicles, Land Use Policy, Vo. 90 (doi.org/10.1016/j.landusepol.2019.05.029).

Goodall, N., Smith, B., Park, B. (2013). Traffic signal control with connected vehicles. Transp. Res. Rec. https://doi.org/10.3141/2381-08

Gopalakrishna, D.; Carlson, P.; Sweatman, P.; Raghunathan, D.; Brown, L.; Serulle, N. (2015). Impacts of Automated Vehicles on Highway Infrastructure. Federal Highway Administration (FHWA)-HRT-21-015, Washington, DC.

Gouda, M., Chowdhury, I., Weiß, J., Epp, A., El-Basyouny, K. (2021). Automated assessment of infrastructure preparedness for autonomous vehicles, Autom. Constr., 129, 103820 https://doi.org/10.1016/j.autcon.2021.103820

Greene, W. (1997). Econometric analysis (3rd ed.). New York, NY: Macmillan.

Groves, D.G., and Kalra, N. (2017). Enemy of good: Autonomous vehicle safety scenario explorer, Rand Corporation www.rand.org); at www.rand.org/pubs/tools/TL279.html.

Grush, B. (2016). Driverless cars ahead: Ontario must prepare for vehicle automation, Residential and Civil Construction Alliance of Ontario (RCCAO). Retrieved from http://rccao.com/research/files/RCCAO_Vehicle-Automation_OCT2016_WEB.pdf

Grush, B., and Niles, J. (2018). The end of driving: Transportation systems and public policy Planning for Autonomous Vehicles, Elsevier (www.elsevier.com/books/the-end-of-driving/niles/978-0-12-815451-9).

Guerra, E. (2015). Planning for cars that drive themselves: Metropolitan planning organizations, regional transportation plans, and autonomous vehicles. Journal of Planning Education and Research, 36(2), 210-224.

Guhathakurta, S., and Kumar, A. (2019). When and where are dedicated lanes needed under

mixed traffic of automated and non-automated vehicles for optimal system level benefits? Center for Transportation, Equity, Decisions and Dollars (https://ctedd.uta.edu); at https://bit.ly/3lgxA6l.
Gyergyay, B., Gomari, S., Friedrich, M., Sonnleitner, J., Olstam, J., Johansson, F. (2019). Automation-ready framework for urban transport and road infrastructure planning, Transp. Res. Procedia, 41 (2019), pp. 88-97, https://doi.org/10.1016/j.trpro.2019.09.018
Ha, Y.J, Chen, S., Du, R., Dong, J., Li, Y., Labi, S. (2020). Leveraging the capabilities of connected and autonomous vehicles and multi-agent reinforcement learning to mitigate highway bottleneck congestion. arXiv preprint arXiv:2010.05436.
Ha, Y. J., Ghahari, S., Marfo, A., Labi, S. (2018). Hyperloop systems: An ex ante evaluation, ASCE International Conference on Automated People Movers and Automated Transit Systems, Tampa, FL, April 29 – May 2, 2018.
Ha, Y.J., Miralinaghi, M., Chen, S., Labi, S. (2019). Sustainability considerations in AV-exclusive lane deployment, ASCE International Conference on Transportation & Development (ICTD), Alexandria VA, June 9–12, 2019.
Ha, Y.J., Miralinaghi, M., Labi, S. (2019). Sustainability Considerations in AV Exclusive Lane Deployment, 2019 INFORMS Annual Meeting, Seattle, WA, Oct 20–23, 2019.
Haboucha, C. J., Ishaq, R., & Shiftan, Y. (2017). User preferences regarding autonomous vehicles. Transportation Research Part C: Emerging Technologies, 78, 37-49.
Hafiz, D.; Zohdy, I. (2021). The City Adaptation to the Autonomous Vehicles Implementation: Reimagining the Dubai City of Tomorrow. In Advanced Controllers for Smart Cities; Springer: Berlin/Heidelberg, Germany, 27–41.
Harb, M., Xiao, Y., Circella, G., Mokhtarian, P., Walker, J. (2018). Projecting travelers into a world of self-driving vehicles, Transportation, Vol. 45, 1671-1685 (https://link.springer.com/article/10.1007%2Fs11116-018-9937-9).
Harding, J., Powell, G., Yoon, R., Fikentscher, J., Doyle, C., Sade, D., Lukuc, M., Simons, J. and Wang, J. (2014). Vehicle-to-vehicle communications: Readiness of V2V technology for application (No. DOT HS 812 014). United States. National Highway Traffic Safety Administration.
Harper, C.D., Hendrickson, C.T., Mangones, S., Samaras, C. (2016). Estimating potential increases in travel with autonomous vehicles for the non-driving, elderly and people with travel-restrictive medical conditions. Transportation Research Part C: Emerging Technologies, 72, 1–9.
Harrington, R.J., Senatore, C., Scanlon, J.M., Yee, R.M.. (2018). The role of infrastructure in an automated vehicle future, The Bridge, National Academy of Engineering, 48(2), 48–55.
Harris, M. (2014). FBI warns driverless cars could be used as lethal weapons, The Guardian (www.theguardian.com), 16 July 2014; at https://bit.ly/1p7fQU6.
Harrop, P., Das, R. (2015). Autonomous vehicles: Land, water, air 2015-2035
Hars, A. (2014). Autonomous Vehicle Roadmap: 2015–2030. Driverless Future website Retrieved from http://www.driverless-future.com/?p=678
Hastings, D. and McManus, H. (2004). A framework for understanding uncertainty and its mitigation and exploitation in complex systems, MIT Engineering Systems Symposium, March 29–31, Cambridge, MA.
Hawkins, A. (2017, October 24). Tesla's autopilot is supposed to deliver full self-driving, so why does it feel stuck in the past? The Verge.
Hayeri, Y.M.; Hendrickson, C.T.; Biehler, A.D. Potential impacts of vehicle automation on

design, infrastructure and investment decisions—A state dot perspective. In Proceedings of the Transportation Research Board 94th Annual Meeting, Washington, DC, USA, 11–12 January 2015.
Hazen, G. B. (2003). A new perspective on multiple internal rates of return. The Engineering Economist. 48(2), 31–51.
HDL-64E, S. User's manual and programming guide; High Definition LiDAR Sensor; 2017; Available online: https://manualmachine.com/velodyneacoustics/hdl64es2/748380-user-manual/ (accessed on 2 February 2021).
He, X., Zheng, H., Peeta, S., & Li, Y. (2018). Network design model to integrate shelter assignment with contraflow operations in emergency evacuation planning. Networks and Spatial Economics, 18(4), 1027-1050.
Healey, J.R. (2012). Stick shifts popular again, despite lower gas mileage, USA Today, 30 April (www.usatoday.com); at https://bit.ly/2FoFPdc.
Heaslip, K., Goodall, N., Bumsik, K., Aad, M.A. (2020), Assessment of capacity changes due to automated vehicles on interstate corridors, Virginia Transportation Research Council (www.virginiadot.org); at https://bit.ly/3Aghf71.
Heide, A., Henning, K. (2006). The Cognitive Car: a roadmap for research issues in the automotive sector. IFAC Proceedings Volumes, 39(4), 44-50.
Heinrichs, D. (2016). Autonomous Driving and Urban Land Use. In Autonomous Driving; Springer: Berlin/Heidelberg, Germany, 213–231.
Henaghan, J. (2018). Preparing communities for autonomous vehicles, American Planning Association (www.planning.org); at https://bit.ly/2piKBhX.
Henao, A., and Marshall, W. (2018). The impact of ridehailing on vehicle miles traveled, Transportation (https://doi.org/10.1007/s11116-018-9923-2).
Hendrickson, C., Biehler, A., & Mashayekh, Y. (2014). Connected and autonomous vehicles 2040 Vision.
Hill, C.J., Garrett, K. (2011). AASHTO Connected Vehicle Infrastructure Deployment Analysis. Intell. Transp. Syst. Jt. Progr. Off. 1–104.
Hill, K., Dedon, L., Gander, S., and Eucalitto, G. (2018). State public safety and autonomous vehicle technology. Washington, DC: National Governors Association. https://www.nga.org/center/publications/state-public-safety-and-autonomous-vehicletechnology-recommended-actions-for-governors/
Hobert, L., Festag, A., Llatser, I., Altomare, L., Visintainer, F., Kovacs, A. (2015). Enhancements of V2X communication in support of cooperative autonomous driving. IEEE Commun. Mag. 53, 64–70.
Horton, F.E., Reynolds, D.R. (1971). Effects of urban spatial structure on individual behavior. Economic Geography 47(1), 36–48.
Howard, D., and Dai, D. (2014). Public perceptions of self-driving cars: the case of Berkeley, California. 93rd Annual Meeting of the Transportation Research Board. Washington, D.C.
Howell, A., Larco, N., Lewsi, R., Steckler, R. (2018). AVs in the Pacific Northwest: Reducing greenhouse gas emissions in a Time of Automation, Urbanism Next Center (https://urbanismnext.uoregon.edu): at https://bit.ly/2MHIXix.
Hsu, J. (2017). When it comes to safety, autonomous cars are still 'teen drivers,' Scientific American (www.scientificamerican.com); at http://bit.ly/2j9gFPT.
Hu, J., Kong, L., Shu, W., Wu, M.Y., 2012. Scheduling of connected autonomous vehicles on

highway lanes, in: GLOBECOM - IEEE Global Telecommunications Conference. https://doi.org/10.1109/GLOCOM.2012.6504005
Chai, H., Rodier, C., Song, J., Zhang, M., Jaller, M. (2020). The impacts of automated vehicles on center city parking demand, Transportation Research Part A: Policy and Practice, 175, 103764.
Huegle, M., Kalweit, G., Mirchevska, B., Werling, M., Boedecker, J. (2019). Dynamic input for deep reinforcement learning in autonomous driving.
Hyatt, K. (2020). Toyota had the most autonomous vehicle disengagements, Road Show (www.cnet.com); at www.cnet.com/roadshow/news/2019-california-self-driving-disengagement-report-baidu-waymo-cruise.
Hyland, M., Mahmassani, H.S. (2018). Dynamic autonomous vehicle fleet operations: Optimization-based strategies to assign AVs to immediate traveler demand requests. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2018.05.003
Kaparias, I., Bell, M. (2011). Key performance indicators for traffic management and intelligent transport systems, Imperial College London, London, UK, 218636.
Korn, J. (2022). Uber launching self-driving cars in Las Vegas, CNN Business, https://www.cnn.com/2022/12/07/tech/uber-motional-self-driving-vegas/index.html.
Iacobucci, R., Donhauser, J., Schmöcker, J., & Pruckner, M. (2023). The demand potential of shared autonomous vehicles: a large-scale simulation using mobility survey data, Journal of Intelligent Transportation Systems, DOI: 10.1080/15472450.2023.2205021
IHS Automotive (2014). Emerging technologies: Autonomous cars—not if, but when, Retrieved from http://collision.honda.com/ihs-automotive-forecasts-54-million-self-driving-cars-used-globally-by-2035-#.VbVnkPlViko.
IHS Markit (2018). Autonomous vehicle sales forecast and report. Retrieved from https://supplierinsight.ihsmarkit.com/shop/product/5001816/autonomous-vehicle-sales-forecast-and-report
Ilgin Guler, S., Menendez, M., Meier, L. (2014). Using connected vehicle technology to improve the efficiency of intersections. Transp. Res. Part C Emerg. Technol.
INDOT (2019). Traffic Count Database. Indiana Department of Transportation. Retrieved from https://indot.ms2soft.com/tcds/tsearch.asp?loc=Indot&mod=
Intellias (2018), How a self-driving car could save you money; at https://bit.ly/36ZVBDD.
Intervision (2019). Machine vision and contrast how automated vehicles see the roads, https://www.intertraffic.com/news/autonomous-driving/machine-vision-and-contrast-how-automated-vehicles
Iowa DOT (2017). Automated Vehicle Technologies Project, Vision Document Final, Report prepared by Iowa State University and the University of Iowa, for Iowa DOT. https://www.iowadot.gov/pdf_files/IowaVisionDocument.pdf
ITF (2014). Urban Mobility: System Upgrade, International Transport Forum (www.internationaltransportforum.org) and Corporate Partnership Board; at https://bit.ly/2JJrWUo.
ITF (2018). Safer roads with automated vehicles? International Transport Forum (www.itf-oecd.org); at www.itf-oecd.org/sites/default/files/docs/safer-roads-automated-vehicle.pdf.
Anderson, J., Kalra, N., Stanley, K.D., Sorensen, P., Samaras, C. (2016). Autonomous Vehicle Technology A Guide for Policymakers, Rand Corporation.
Jelokhani-Niaraki, M., Malczewski, J. (2015). A group multicriteria spatial decision support system for parking site selection problem: A Case Study. Land Use Policy, Vol. 42, pp.

492–508.
Jiang, Q., He, B.Y., Ma, J. (2022). Connected automated vehicle impacts in southern California part-ii: VMT, emissions, and equity, Transportation Research Part D: Transport and Environment, Vol. 109 (https://doi.org/10.1016/j.trd.2022.103381).
Johnson, C. (2017) Readiness of the road network for connected and autonomous vehicles. Royal Automobile Club Foundation (RAC), London, UK. Retrieved from https://www.racfoundation.org/wp-content/uploads/2017/11/CAS_Readiness_of_the_road_network_April_2017.pdf
Johnston, C., and Walker, J. (2017). Peak car ownership: The market opportunity for electric automated mobility services, Rocky Mountain Institute (www.rmi.org); at http://bit.ly/2rhJRNi.
Kagan, J. (2018). Expansion Option. Retrieved from https://www.investopedia.com/terms/e/expansion-option.asp
Kamali, M., Dennis, L.A., McAree, O., Fisher, M., Veres, S.M. (2017). Formal verification of autonomous vehicle platooning. Sci. Comput. Program. https://doi.org/10.1016/j.scico.2017.05.006
Kaohsiung EcoMobility Festival (2017), Kaohsiung strategies for the future of urban mobility, EcoMobility Festival (www.ecomobilityfestival.org); at https://bit.ly/2OMwsDD.
Kazazi Darani, S., Akbari Eslami, A., Jabbari, M., Asefi H. (2018). Parking lot site selection using a fuzzy AHP-TOPSIS framework in Tuyserkan, Iran. Journal of Urban Planning and Development, 144(3), 04018022.
Keeney, A. (2018, June 13) In the rear-view mirror, self-driving cars may be closer than they appear. Retrieved from: https://ark-invest.com/research/autonomous-vehicle-adoption-
Keeney, J. B. (2011). Dedicated short-range communications (DSRC) standards in the United States. Proceedings of the IEEE, 99(7), 1162-1182.
Keeney, T. (2017). Mobility-As-A-Service: Why self-driving cars could change everything, ARC Investment Research (http://research.ark-invest.com); at http://bit.ly/2xz6PNV.
Kellett, J., R. Barreto, A. van den Hengel, N. Vogiatzis. (2019). How might autonomous vehicles impact the city? The Case of Commuting to Central Adelaide. Urban Policy and Research, 37(4), 442–457.
Khondaker, B., Kattan, L. (2015). Variable speed limit: A microscopic analysis in a connected vehicle environment. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2015.07.014
Khoury, J.; Amine, K.; Saad, R.A. (2019). An initial investigation of the effects of a fully automated vehicle fleet on geometric design. J. Adv. Transp. 2019, 1–10.
Kim, M.K., Park, J.H., Oh, J., Lee, W.S., Chung, D. (2019). Identifying and prioritizing the benefits and concerns of connected and autonomous vehicles: A comparison of individual and expert perceptions. Res. Transp. Bus. Manag. https://doi.org/10.1016/j.rtbm.2020.100438
Kimley Horn (2016). NC readiness for Connected and Autonomous Vehicles (CAV) Final Report, Prepared for the North Carolina DOT, Raleigh, NC.
Knight, R. (2016). Paving the way for driverless cars. Inside Unmanned Systems, July 6 Edition, https://insideunmannedsystems.com/paving-the-way-for-driverless-cars/
Knight, W. (2020). Snow and ice pose a vexing obstacle for self-driving cars, Wired Magazine; at www.wired.com/story/snow-ice-pose-vexing-obstacle-self-driving-cars.
Kockelman, K., and Boyles, S. (2018), Smart transport for cities & nations: The rise of self-

driving & connected vehicles, The University of Texas at Austin (www.caee.utexas.edu); at https://bit.ly/3gDpEaa.
Kockelman, K., Avery, P., Bansal, P., Boyles, S. D., Bujanovic, P., Choudhary, T., Clements, L., Domnenko, G., Fagnant, D., Helsel, J., Hutchinson, R. (2016). Implications of connected and automated vehicles on the safety and operations of roadway networks, Final report FHWA/TX-16/0-6849-1). Retrieved from http://library.ctr.utexas.edu/ctr-publications/0-6849-1.pdf
Kockelman, K., Boyles, S., Stone, P., Fagnant, D., Patel, R., Levin, M.W., Sharon, G., Simoni, M., Albert, M., Fritz, H., Hutchinson, R., Bansal, P., Domnenko, G., Bujanovic, P., Kim, B., Pourrahmani, E., Agrawal, S., Li, T., Hanna, J., Nichols, A., Li, J. (2017). An assessment of autonomous vehicles: traffic impacts and infrastructure needs (No. FHWA/TX-17/0-6847-1). Center for Transportation Research, University of Texas at Austin.
Kockelman, K., et al. (2016). Implications of connected and automated vehicles on the safety and operations of roadway networks, University of Texas Center for Transportation Research (http://ctr.utexas.edu); at http://library.ctr.utexas.edu/ctr-publications/0-6849-1.pdf.
Kodukula, P., and Papudesu, V. (2006). Project valuation using real options: A practitioner's guide. Ft. Lauderdale, FL: J. Ross Publishing, Inc.
Kok, I., Zou, S.Y., Gordon, J., and Mercer, B. (2017). Rethinking transportation 2020-2030: The disruption of transportation and the collapse of the internal-combustion vehicle and oil industries. RethinkX, San Francisco, United States.
Koopman, P., and Wagner, M. (2017). Autonomous vehicle safety: An interdisciplinary challenge, IEEE Intelligent Transportation Systems, 9(1), http://ieeexplore.ieee.org/document/7823109.
Koopman, P., Fratrik, F. (2019). How many operational design domains, objects, and events? Safe AI 2019: AAAI Workshop on Artificial Intelligence Safety, Honolulu, HI.
Kornhauser, A., Chang, A., Clark, C., Gao, J., Korac, D., Lebowitz, B., Swoboda, A. (2013). Uncongested mobility for all: New Jersey's area-wide aTaxi system. Princeton University, Princeton, New Jersey. Retrieved from http://orfe.princeton.edu/~alaink/SmartDrivingCars/SDC051413.pdf.
KPMG (2020) Autonomous vehicles readiness index: Assessing countries' openness and preparedness for autonomous vehicles. Retrieved from: https://assets.kpmg.com/content/dam/kpmg/xx/pdf/2020/07/2020-autonomous-vehicles-readiness-index.pdf
Kreidieh, A.R., Wu, C., Bayen, A.M. (2018). Dissipating stop-and-go waves in closed and open networks via deep reinforcement learning, in: IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC. https://doi.org/10.1109/ITSC.2018.8569485
Krok, A. (2016). Chicago City Council might ban autonomous cars – Their reasoning, of course, involves thinking of the children, CNET, www.cnet.com/roadshow/news/chicago-city-council-might-ban-autonomous-cars/, accessed June 30, 2022.
Krueger, R., Rashidi, T. H., Rose, J. M. (2016). Preferences for shared autonomous vehicles. Transportation Research Part C: Emerging Technologies, 69, 343-355.
Kuepper, J. (2019). Put Option Definition. Retrieved from https://www.investopedia.com/terms/p/putoption.asp
Kyriakidis, M., Happee, R., De Winter, J.C.F. (2015) Public opinion on automated driving:

Results of an international questionnaire among 5000 respondents. Transportation Research Part F: Traffic Psychology and Behavior, 32, 127-140.
Labi, S. (2019). Preparing our infrastructure for connected and autonomous vehicle operations: Challenges and opportunities, Keynote Address, International Conference on Smart Cities, July 17, 2019, Seoul, Korea.
Labi, S., Saeed, T.U., Volovski, M., Al-Qadhi, S. (2015). An exploratory discussion of the impacts of driverless vehicle operations on the man-made environment. Keynote Address. 1st International Conference on Mechanical and Transportation Engineering (ICMTE '15), Kuala Lumpur, Malaysia, April 23–25, 2015.
Labi, S., Sinha, K.C. (2022). Emerging transportation innovations: Promises and pitfalls, Innovation and Emerging Technologies, 1-9, 2240001-1.
Labi, S., Saneii, M., Tabesh, M.T., Pourgholamali, M., Miralinaghi, M. (2023). Parking infrastructure location design and user pricing in the prospective era of autonomous vehicle operations, Journal of Infrastructure Systems, 29(4), ascelibrary.org/doi/10.1061/JITSE4.ISENG-2232
LaHood, R. (2011). Notice of funding availability for the Department of Transportation's National Infrastructure Investments under the full-year continuing appropriations. U.S. Department of Transportation Federal Register 76 (156) 50310.
Laidlaw, K., Sweet, M., Olsen, T. (2018). Forecasting the outlook for automated vehicles in the 1 Greater Toronto and Hamilton Area using a 2016 consumer survey. transformlab.ryerson.ca/wp-content/uploads/2018/03/Laidlaw, accessed December 20, 2018.
Lamptey, G., Labi, S., Li, Z. (2008). Decision support for optimal scheduling of highway pavement preventive maintenance within resurfacing cycle, Decision Support Systems 46(1), 376-387.
Larco, N. (2022), The road ahead for automated vehicles, U.S. House of Representatives Committee on Transportation & Infrastructure Director, Urbanism Next Center, University of Oregon (www.urbanismnext.org); at https://docs.house.gov/Committee/Calendar/ByEvent.aspx?EventID=114362.
Laslau, C., Holman, M., Saenko, M., See, K., Zhang, Z. (2014). Set autopilot for profits: Capitalizing on the $87 billion Self-driving car opportunity. Retrieved from http://www.giiresearch.com/report/lux301508-set-autopilot-profits-capitalizing-on-87-billion.html
Lavasani, M., and Jin, X. (2016). Market penetration model for autonomous vehicles on the basis of earlier technology adoption experience, Transportation Research Record 2597, 67–74.
Lawson, S. (2018). Tackling the Transition to automated vehicles, roads that cars can read, Report III, European Road Assessment Association (www.eurorap.org); at https://bit.ly/2IrYTTQ.
Le Vine, S., Zolfaghari, A., Polak, J. (2015). Autonomous cars: The tension between occupant experience and intersection capacity. Transportation Research Part C: Emerging Technologies, 52, 1–14.
LeBlanc, L. J., Morlok, E.K., Pierskalla, W.P. (1975). An efficient approach to solving the road network equilibrium traffic assignment problem, Transportation Research, 9(5), 309–318.
Leisch, J.P. (2018). Autonomous vehicles influence on freeway operations. Institution of Transportation Engineers Student Seminar. Purdue University.
Lendino, J. (2012). The history of car GPS navigation, PC Magazine (www.pcmag.com), 16

April; at www.pcmag.com/article2/0,2817,2402755,00.asp.
Lensink, R. and Sterken, E. (2002). The option to wait to invest and equilibrium credit rationing. Journal of Money, Credit and Banking, 221-225.
Leonard, J.J., Mindell, D.A., and Stayton, E.L. (2020). Autonomous vehicles, mobility, and employment policy, MIT Work of the Future (https://workofthefuture.mit.edu); at https://bit.ly/3eTRWeA.
Levin, M.W., Wong, E., Nault-Maurer, B., Khani, A. (2020). Parking infrastructure design for repositioning autonomous vehicles. Transportation Research Part C: Emerging Technologies, 120(1), 102838.
Levinson, D. (2015). Climbing mount next: The effects of autonomous vehicles on society. Minnesota Journal of Law, Science and Technology, 16(2),787-809.
Li., Y., Saeed, T., Alinizzi, M., Chen, S., Labi, S. (2019). Sustainability-related performance measures – Relevance in an era of smart transportation, 2ND Next Generation Transportation Systems (NGTS-1) Conference, W. Lafayette, IN, May 31, 2019.
Li, Y., Chen, S., Dong, J., Steinfeld, A., Labi, S. (2020a). Leveraging vehicle connectivity and autonomy to stabilize flow in mixed traffic conditions: Accounting for human-driven vehicle driver behavioral heterogeneity and perception-reaction time delay. arXiv preprint arXiv:2008.04351.
Li, Y., Chen, S., Du, R., Ha, P., Dong, J., Labi, S. (2020b). Using empirical trajectory data to design connected autonomous vehicle controllers for traffic stabilization. arXiv preprint arXiv:2010.05440.
Liang, X. (Joyce), Guler, S.I., Gayah, V. V. (2020). A heuristic method to optimize generic signal phasing and timing plans at signalized intersections using Connected Vehicle technology. Transp. Res. Part C Emerg. Technol. 111, 156–170. https://doi.org/10.1016/j.trc.2019.11.008
Liang, X., Correia, G.H, van Arem, B. (2017). An optimization model for vehicle routing of automated taxi trips with dynamic travel times, Transportation Research Procedia 27 (2017) 736–743.
Lin, P., Liu, J., Jin, P.J., Ran, B. (2017). Autonomous vehicle-intersection coordination method in a connected vehicle environment. IEEE Intell. Transp. Syst. Mag. https://doi.org/10.1109/MITS.2017.2743167
Li, Y., Saeed, T., Volovski, M., Labi, S. (2019), Emergence of big data in smart transportation: big reasons, big challenges, and bigger opportunities, 1st Next Generation Transportation Systems (NGTS-1) Conference, W. Lafayette, IN, May 31, 2019.
Litman (2017), Presentation to the Canadian Standing Senate Committee on Transport and Communication Concerning Connected and Self-driving Vehicles (http://bit.ly/2u2Grhe).
Litman, T. (2013), The new transportation planning paradigm, ITE Journal (www.ite.org), Vo. 83, No. 6, pp. 20-28, 2013; at www.vtpi.org/paradigm.pdf.
Litman, T. (2022). Autonomous vehicle implementation predictions–Implications for transport planning. Victoria Transport Policy Institute. Retrieved from http://www.vtpi.org/avip.pdf
Litman, T. (2018). Autonomous vehicle implementation predictions –Implications for transport planning, presentation at Oregon Public Transportation Conference, Bend, OR.
Litman, T. (2021). New mobilities: Smart planning for emerging transportation technologies, Island Press (https://islandpress.org/books/new-mobilities).
Liu, Y., Tight, M., Sun, Q., Kang, R. (2019). A systematic review: Road infrastructure

requirement for Connected and Autonomous Vehicles (CAVs), J. Phys. Conf. Ser., 1187, Article 042073, 10.1088/1742-6596/1187/4/042073
Losada-Rojas, L. L., and Gkritza, K. (2021). Individual and location-based characteristics associated with autonomous vehicle adoption in the Chicago Metropolitan Area: Implications for public health. Journal of Transport & Health, 22, 101232.
Lou, Y., Yin, Y., & Lawphongpanich, S. (2010). Robust congestion pricing under boundedly rational user equilibrium. Transportation Research Part B: Methodological, 44(1), 15-28.
Lu, N., Cheng, N., Zhang, N., Shen, X., Mark, J.W. (2014). Connected vehicles: Solutions and challenges. IEEE Internet Things J. https://doi.org/10.1109/JIOT.2014.2327587
Lu, X., Madadi, B., Farah, H., Snelder, M., Annema, J.A., Van Arem, B. (2019). Scenario-based infrastructure requirements for automated driving, in: CICTP 2019. American Society of Civil Engineers, Reston, VA, 5684–5695.
Lu, X.Y., Shladover, S.E., Jawad, I., Jagannathan, R., Phillips, T. (2015). Novel algorithm for variable speed limits and advisories for a freeway corridor with multiple bottlenecks. Transp. Res. Rec. 2489, 86–96. https://doi.org/10.1061/9780784482292.489.
Luenberger, D. G. (1997). Investment science. OUP Catalogue.
Lumiaho, A.; Malin, F. (2016). Road transport automation road map and action plan 2016–2020, Reports by Liikenneturva, Helsinki, Finland.
Lynott, J. (2018). Creating the transportation system we want: Building blocks for the road ahead, AARP Public Policy Institute (www.aarp.org); at https://bit.ly/2Xg3PpN.
Lyon, T. P., Rasmusen, E. (2004). Buyer-option contracts restored: Renegotiation, Inefficient Threats, and the Hold-Up Problem. Journal of Law, Economics, and Organization. 20(1), 148–169.
Ma, J., Li, X., Shladover, S., Rakha, H.A., Lu, X.-Y., Jagannathan, R., Dailey, D.J., 2016. Freeway speed harmonization. IEEE Trans. Intell. Veh. https://doi.org/10.1109/tiv.2016.2551540
Ma, J., Zhou, F., Demetsky, M.J., 2012. Evaluating mobility and sustainability benefits of cooperative adaptive cruise control using agent-based modeling approach, in: 2012 IEEE Systems and Information Engineering Design Symposium, SIEDS 2012. https://doi.org/10.1109/SIEDS.2012.6215145
Ma, Y., Easa, S., Cheng, J., Yu, B. (2021). Automatic framework for detecting obstacles restricting 3D highway sight distance using MLS data. J. Comput. Civ. Eng. 2021.
Ma, Z., Kargl, F., and Weber, M. (2009, October). Measuring location privacy in V2X communication systems with accumulated information. In 2009 IEEE 6th International Conference on Mobile Adhoc and Sensor Systems (322-331). IEEE.
Macfarlane, J. (2019). Your navigation app is making traffic unmanageable. IEEE Spectr.
Madadi, B., van Nes, R., Snelder, M., & van Arem, B. (2021). Multi-stage optimal design of road networks for automated vehicles with elastic multi-class demand. Computers & Operations Research, 136, 105483.
Mahlberg, J., Matthew, J.K., Deborah, H., McGavic, B., Wells, T., Bullock, D. M. (2022). Intelligent sidewalk de-icing and pre-treatment with connected campus maintenance vehicles, CCAT Report #42, Center for Connected and Automated Transportation, Purdue University, West Lafayette, IN. http://dx.doi.org/10.5703/1288284317572
Mahmassani, H.S. (2014). Autonomous vehicles: adoption factors, activity system impacts, in: Workshop on Travel Demand Modeling Implications of Driverless Cars, 93rd Annual Meeting of the Transportation Research Board, Washington, DC.

Mahmassani, H.S. (2016). 50th Anniversary invited article autonomous vehicles and connected vehicle systems: Flow and operations considerations. Transp. Sci. 50(4), DOI:10.1287/trsc.2016.0712

Mair, R. J., Soga, K., Jin, Y., Parlikad, A. K., and Schooling, J. (2016). Transforming the future of infrastructure through smarter information. Proceedings of the International Conference on Smart Infrastructure and Construction, 27–29 June 2016. Cambridge Centre for Smart Infrastructure in Construction. London. ICE Publishing.

Maiti, S., Winter, S., Kulik, L. (2017). A conceptualization of vehicle platoons and platoon operations. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2017.04.005

Malikopoulos, A.A., Hong, S., Park, B.B., Lee, J., Ryu, S. (2019). Optimal control for speed harmonization of automated vehicles. IEEE Trans. Intell. Transp. Syst. https://doi.org/10.1109/TITS.2018.2865561

Malysheva, E.V. (2020). Impact of automated vehicles on urban form, IOP Conf. Ser. Mater. Sci. Eng., 753 (2020), Article 032013, https://doi.org/10.1088/1757-899X/753/3/032013

Mannering, F., Kilareski, W., Washburn, S. (2016). Principles of highway engineering and traffic analysis. 6th Edition, Wiley & Sons.

Marc Schlossberg, et al. (2018), Rethinking the street in an era of driverless cars, Urbanism Next Research (www.urbanismnext.com); at www.urbanismnext.com/s/Rethinking_Streets_AVs_012618-27hcyr6.pdf.

Marowits, R. (2017). Self-driving Ubers could still be many years away, CTV News (www.ctvnews.ca); at http://bit.ly/2Dl48Y7.

Marsal-Llacuna, M.L. Colomer-Llinas, J., Melendez-Frigola, J. (2014). Lessons in urban monitoring taken from sustainable and livable cities to better address the Smart Cities initiative, Technological Forecasting and Social Change, 90(B), 611–622.

Marsden, I.D., and Dowling, D. (2020). Parking futures: Curbside management in the era of ‘new mobility’ services, land use policy, Vol. 91 (doi.org/10.1016/j.landusepol.2019.05.031).

Martin, E., & Shaheen, S. (2011). The impact of carsharing on household vehicle ownership. Access, 38(Spring), 22–27.

Maryland DOT (2021). 2021-2025 MDOT SHA Connected and Automated Vehicle Implementation Plan, https://www.roads.maryland.gov/OTMO/2021-2025_MDOTSHA_CAVImplementationPlan_Final.pdf

Masood, T., McFarlane, D., Schooling, J., Parlikad, A. (2015). The role of futureproofing in the management of infrastructural assets. International Symposium for Next Generation Infrastructure. Royal Academy of Engineering. UCL STEaPP, London, UK.

Mayorquin, O. (2022), Elon Musk's Tesla accused of fraud, false advertising of 'autopilot' Technology in Lawsuit, USA TODAY (www.usatoday.com); at https://bit.ly/3RJMLlL.

McCarville, I. How Autonomous Vehicles Will Reshape the Urban Landscape; City and Regional Planning Department, California Polytechnic State University: San Luis Obispo, CA, USA, 2019

McDonald, D.R. (2018). How might connected vehicles and autonomous vehicles influence 34 geometric design? In Proceedings of the Transportation Research Board 97th Annual Meeting, Washington, DC, USA.

McFadden, D. and Train, K. (2000). Mixed MNL models for discrete response, Journal of Applied Econometrics, 15(5), 447-470.

McFarland, M. (2015). Elon Musk vents about California’s lane markings confusing Tesla’s

autopilot, The Washington Post. https://www.washingtonpost.com/news/innovations/wp/2015/10/14/elon-musk-vents-about-californias-lane-markings-confusing-teslas-autopilot/?utm_term=.c1443e40ad2d, accessed December 15, 2018.
McGee, H.W. (1978). Decision sight distance for highway design and traffic control requirements (abridgement). Transp. Res. Board J. Transp. Res. Board 736, 11–13.
McKelvey, R. D., Zavoina, W. (1975). A statistical model for the analysis of ordinal level dependent variables. Journal of Mathematical Sociology, 4(1), 103-120.
McKinsey and Company (2016). Automotive revolution – Perspective towards 2030: How the convergence of disruptive technology-driven trends could transform the auto industry. Retrieved from https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/disruptive-trends-that-will-transform-the-auto-industry
McLeod, P. (2021), Technology Readiness Level Scale Explained, Prospect IP (www.prospectip.com); at www.prospectip.com/technology-readiness-level-scale-explained.
Meeks, A. (2019). 3M™ Connected roads enabling intelligent infrastructure. 105th Purdue Road School Transportation Conference and Expo, March 03-04, 2019.
Megens I.C.H. (2014). Vehicle users' preferences concerning automated driving: Implications for transportation and market planning, Eindhoven University of Technology.
Mekdeci, B., Ross, A. M., Rhodes, D. H., Hastings, D. E. (2014). Pliability and viable systems: maintaining value under changing conditions. IEEE Systems Journal, 9(4), 1173-1184.
Melo, M.T., S. Nickel, F. Saldanha-da-Gama. (2009). Facility location and supply chain management – A review. European Journal of Operational Research, 196(2), 401–412.
Mendiboure, L., Benzagouta, M.L., Gruyer, D., Syla, T., Adedjouma, M., Hedhli, A. (2023). Operational design domain for automated driving systems: Taxonomy definition and application, IEEE Intelligent Vehicles Symposium, Proceedings, June 2023.
Menon, N., Barbour, N., Zhang, Y., Pinjari, A.R., Mannering, F. (2019). Shared autonomous vehicles and their potential impacts on household vehicle ownership: An exploratory empirical assessment. Int. J. Sustain. Transp. https://doi.org/10.1080/15568318.2018.1443178
Merton, R. C. (1973). Theory of rational option pricing. The Bell Journal of Economics and Management Science, 141-183.
Mervis, J. (2017). Are we going too fast on driverless cars? Science Magazine (www.sciencemag.org); at www.sciencemag.org/news/2017/12/are-we-going-too-fast-driverless-cars.
Michel, P., Karbowski, D., Rousseau, A. (2016). Impact of connectivity and automation on vehicle energy Use, in: SAE Technical Papers. https://doi.org/10.4271/2016-01-0152
Milakis, D., Snelder, M., Van Arem, B., Van Wee, B., De Almeida Correia, G.H. (2017). Development and transport implications of automated vehicles in the Netherlands: Scenarios for 2030 and 2050, Eur. J. Transp. Infrastruct. Res., 17, 63-85, https://doi.org/10.18757/ejtir.2017.17.1.3180
Milakis, D., Van Arem, B., Van Wee, B. (2017). Policy and society related implications of automated driving: A review of literature and directions for future research. Journal of Intelligent Transportation Systems, 21(4), 324-348.
Millard-Ball, A. (2016). Pedestrians, autonomous vehicles, and cities, Journal of Planning Education and Research, pp. 1-7 (DOI: 10.1177/0739456X16675674); at

https://bit.ly/2hhYrxV.
Miller, J.S., and Kang, D. (2019). Ways to consider driverless vehicles in Virginia long-range travel demand models, Virginia Transport. Res. Council (www.virginiadot.org/vtrc); at https://bit.ly/33C5VBM.
Milton, A. (2018). Options In the money and out of the money. Retrieved from https://www.thebalance.com/determining-intrinsic-value-1031125
Miralinaghi, M., Davatgari, A., Seilabi, S. E., & Labi, S. (2022). Contract bundling considerations in urban road project scheduling. Computer-Aided Civil and Infrastructure Engineering, 37(4), 427-450.
Miralinaghi, M., Woldemariam, W., Abraham, D. M., Chen, S., Labi, S., & Chen, Z. (2020). Network-level scheduling of road construction projects considering user and business impacts. Computer-Aided Civil and Infrastructure Engineering, 35(7), 650-667.
Missel, J., (2014). Ipsos Mori loyalty automotive survey. Retrieved from https://www.ipsos-mori.com/researchpublications/researcharchive/3427/Only-18-per-cent-of-Britons-believe-driverless-cars-to-be-an-important-development-for-the-car-industry-to-focus-on.aspx
Mitchell, C. (2019). In the money – ITM. Retrieved from https://www.investopedia.com/terms/i/inthemoney.asp
Mohd Zulkefli, M.A., Mukherjee, P., Sun, Z., Zheng, J., Liu, H.X., Huang, P. (2017). Hardware-in-the-loop testbed for evaluating connected vehicle applications. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2017.02.019
Morgan Stanley (2013). Autonomous cars: Self-driving the new auto industry paradigm. Morgan Stanley Research Global.
Mourad, A., Puchinger, J. & Chu, C. (2019). Owning or sharing autonomous vehicles: comparing different ownership and usage scenarios. Eur. Transp. Res. Rev. 11 (31), https://doi.org/10.1186/s12544-019-0370-8
Moylan, M. (2018). Technology around self-driving cars drives forward, but future still uncertain. https://www.mprnews.org/story/2018/03/26/self-driving-cars-technology-drives-forward-future-uncertain
Mueller, A.S., Cicchino, J.B., and Zuby, D.S. (2020), What humanlike errors do autonomous vehicles need to avoid to maximize safety? Insurance Institute for Highway Safety (www.iihs.org); at www.iihs.org/topics/bibliography/ref/2205.
Mun, J. (2006). Real options analysis: Tools and techniques for valuing strategic investments. and decisions (Vol. 320), Wiley & Sons, Hoboken, NJ.
Mwamba I. C., Alabi, B.N.T., Nafakh, A., Labi S., Sinha K. (2023). Changes in highway expenditures and revenues in an era of CAVs, Volume A: Road Agencies, CCAT Report No. 33A, Center for Connected and Automated Transportation, W. Lafayette, IN.
Myers, S. C. (1977). Determinants of corporate borrowing. Journal of Financial Economics 5(2), 147-175.
Myr, D. (2002). Real time vehicle guidance and forecasting system under traffic jam conditions. Patent No.: US 6,480,783 B1, US Patent Office, Washington, DC.
Nadafianshahamabadi, R., Tayarani, M., and Rowangould, G. (2021), A closer look at urban development under the emergence of autonomous vehicles, Journal of Transport Geography, Vo. 94 (https://doi.org/10.1016/j.jtrangeo.2021.103113).
NAE (2018). Renewing the national commitment to the interstate highway system: A foundation for the future, The National Academies Press, Washington, D.C. doi.org/10.17226/25334.

Nafakh, A., Chen, S., Saeed, T., Labi, S., Ha, Y.J. (2018). Evaluation of an automated people mover in downtown Indianapolis, ASCE International Conference on Automated People Movers and Automated Transit Systems, Tampa, FL, April 29 – May 2, 2018.

Nair, G. S., Astroza, S., Bhat, C. R., Khoeini, S., Pendyala, R. M. (2018). An application of a rank ordered probit modeling approach to understanding level of interest in autonomous vehicles. Transportation, 45(6), 1623-1637.

Nazari, F., Noruzoliaee, M., Mohammadian, A. (2018). Shared mobility versus private car ownership: A multivariate analysis of public interest in autonomous vehicles (Paper No. 18-04289). 97th Transportation Research Board Annual Meeting, Washington D.C.

NCHRP (2020), Impacts of connected vehicles and automated vehicle technologies on the highway infrastructure, National Cooperative Highway Research Program, transportation Research Board, Washington DC.

Nembhard, H. B. and Aktan, M. (Eds.). (2009). Real options in engineering design, operations, and management, Boca Raton, FL: CRC Press.

NetworkNewsWire (2018, July 11) $7 Trillion annual market projected for autonomous autos by 2050. Retrieved from https://www.prnewswire.com/news-releases/-7-trillion-annual-market-projected-for-autonomous-autos-by-2050-877929258.html

New York Times (2023). 26 Empire state buildings could fit into New York's empty office space. https://www.nytimes.com/interactive/2023/05/10/opinion/nyc-office-vacancy-playground-city.html

NHTSA (2020) Ensuring American leadership in automated vehicle technologies, National Highway Traffic Safety Administration. US Department of Transportation, Washington DC. ahtsa.gov/vehicle-manufacturers/automated =drivingsystems

NHTSA (2016). Federal automated vehicles policy: Accelerating the next revolution in roadway safety. National Highway Traffic Safety Administration. US Department of Transportation, https://doi.org/12507-091216-v9

Nie, J., Zhang, J., Ding, W., Wan, X., Chen, X., Ran, B. (2016.) Decentralized Cooperative Lane-Changing Decision-Making for Connected Autonomous Vehicles∗. IEEE Access. https://doi.org/10.1109/ACCESS.2017.2649567

Nijssen, E. (2014). Entrepreneurial Marketing: an effectual approach. Chapter 2, Routledge.

Noorvand, H., Karnati, G., & Underwood, B. S. (2017). Autonomous vehicles: Assessment of the implications of truck positioning on flexible pavement performance and design. Transportation Research Record, 2640, 21–28. https://doi.org/10.3141/2640-03

Nordhoff, S. (2014) Mobility 4.0: Are consumers ready to adopt Google's self-driving car? University of Twente: Enschede, the Netherlands.

Norton, P. (2021). Autonorama: The illusory Promise of high-tech driving, Island Press (https://islandpress.org); at https://bit.ly/3JCo9bm; Michael Lewyn review https://bit.ly/3QnutWk.

Nourinejad, M., Bahrami, S., and Roorda, M.J. (2018). Designing parking facilities for autonomous vehicles, Transportation Research Part B: Methodological, 109, 110-127.

Nowakowski, C., Shladover, S.E., Chan, C.Y. and Tan, H.S. (2015). Development of California regulations to govern testing and operation of automated driving systems. Transportation Research Record: Journal of the Transportation Research Board. 2489, 137-144.

NSC (2015). Estimating the costs of unintentional injuries. National Safety Council. Washington, D.C.

Nunes, A., Huh, L., Kagan, N., Freeman, R.B. (2021). Estimating the energy impact of electric,

autonomous taxis: evidence from a select market, Environmental Research Letters (https://doi.org/10.1088/1748-9326/ac1bd9).
Nunes, A., and Hernandez, K.D. (2020). Autonomous taxis & public Health: High cost or high opportunity cost?, Transportation Research Part A, Vo. 138, pp. 28-36 (doi.org/10.1016/j.tra.2020.05.011).
O'Keefe, L. (2017). New kinds of street signs and highway markings can talk to autonomous vehicles. Retrieved from Bisnow National website: www.bisnow.com/national/news/technology/new-kinds-of-street-signs-and-highway-markings-can-talk-to-autonomous-vehicles-79921.%0A
Ødegård, I. Klein-Paste, A. (2021). Do we need a change in road winter maintenance to accommodate for automated vehicles? A state-of-the-art literature review considering automated vehicle technology's usage of road infrastructure during winter, Transp. Res. Rec. 2675 (2021), pp. 656-666 https://doi.org/10.1177/03611981211012415
OECD/ITF (2018). The shared-use city: Managing the curb, Organization for Economic Cooperation and Development and the International Transport Forum (www.itf-oecd.org); at https://bit.ly/2B8hLqG.
Ohnsman, A. (2014). Automated cars may boost fuel use, Toyota Scientist Says," Bloomberg Press, 16 July 2014 (www.bloomberg.com); at https://bloom.bg/2mDkmAu.
Oliver, N., Potočnik, K., Calvard, T. (2018). To make self-driving cars safe, we also need better roads and infrastructure, Technology and Analytics, Harvard Business Review, Cambridge, MA.
Olmos, L., Colak, S., González, M. (2016). Non-equilibrium dynamics in urban traffic networks. Nature Communications.
ORNL (annual reports), Transportation energy book, Oak Ridge National Lab (www-cta.ornl.gov/data).
Osichenko, D., Spielhofer, R. (2018). Future challenges for the road asset management, in: Road and Rail Infrastructure V, S. Lakusic (Ed.), 979-985, https://doi.org/10.5592/CO/CETRA.2018.708
O'sullivan, A., and Sheffrin, S. M. (2003). Economics: Principles in action. Prentice Hall. http://www.phschool.com/webcodes10/index.cfm?fuseaction=home.gotoWebCode&wcprefix=mnk&wcsuffix=1000
Othman K. (2021). Impact of autonomous vehicles on the physical infrastructure: Changes and challenges. Designs 5(3):40. https://doi.org/10.3390/designs5030040
Othman, K. (2021). Public acceptance and perception of autonomous vehicles: a comprehensive review. AI Ethics 1, 355–387 (2021). https://doi.org/10.1007/s43681-021-00041-8
Pakusch, C., Stevens, G., Boden, A., Bossauer, P. (2018). Unintended effects of autonomous driving: A study on mobility preferences in the future. Sustainability, 10(7), 2404.
Palmer, B. (2019). Should IRR or NPV be used in capital budgeting? Retrieved from https://www.investopedia.com/ask/answers/05/irrvsnpvcapitalbudgeting.asp
Papa, E., and Ferreira, A. (2018). Sustainable accessibility and the implementation of automated vehicles, Urban Science, Vo. 2/1 (doi:10.3390/urbansci2010005); at https://bit.ly/2DHjZQz.
Papa, E., and Ferreira, A. (2018). Sustainable accessibility and the implementation of automated vehicles: Identifying critical decisions. Urban Science, 2(1), 5.
Papadoulis, A., Quddus, M., Imprialou, M. 2019. Evaluating the safety impact of connected and

autonomous vehicles on motorways, Accident Analysis & Prevention 124(1), 12-22.
Patriksson, M. (1994). The traffic assignment problem: Models and methods. VSP, Utrecht, The Netherlands.
Payre, W., Cestac, J., Delhomme, P. (2014). Intention to use a fully automated car: Attitudes and a priori acceptability. Transportation research part F: Traffic Psychology & Behavior, 27, 252-263.
PBIC (2017), Automated and Connected vehicles, pedestrians, and bicyclists, Pedestrian and Bicycle Information Center (www.pedbikeinfo.org); at www.pedbikeinfo.org/AV.
Pei, Y.-L.; He, Y.-M.; Ran, B.; Kang, J.; Song, Y.-T. Horizontal alignment security design theory and application of superhighways. Sustainability 2020
Peters, L. (2016). Impact of probability distributions on real options valuation. Journal of Infrastructure Systems, 22(3), 04016005.
Pike, A. M., Whitney, J., Hedblom, T., and Clear, S. (2019). How might wet retroreflective pavement markings enable more robust machine vision? Transportation Research Record 2673, 361-366.
Pogue, M. (2010). Corporate investment decisions: Principles and practice. New York, NY, USA: Business Expert Press. Retrieved from http://www.ebrary.com
Pourgholamali, M., Miralinaghi, M., Ha, P. (Young J.), E. Seilabi, S., & Labi, S. (2023a). Sustainable deployment of autonomous vehicles dedicated lanes in urban traffic networks. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.4406881
Pourgholamali, M., Homem de Almeida Correia, G., Tarighati Tabesh, M., E. Seilabi, S., Miralinaghi, M., & Labi, S. (2023b). Robust design of electric charging infrastructure locations under travel demand uncertainty and driving range heterogeneity. Journal of Infrastructure Systems, 29(2). https://doi.org/10.1061/JITSE4.ISENG-2191
Pourgholamali, M., Davatgari, A., Wang, J., Benny, D., Miralinaghi, M., and Labi, S. (2023c). Facilitating electric-propulsion of autonomous vehicles through efficient design of a charging-facility network, CCAT Report #73, The Center for Connected and Automated Transportation, Purdue University, West Lafayette, IN. docs.lib.purdue.edu/ccat/42.
Pourgholamali, M., Ha, P. Miralinaghi, M., Seilabi, S.E., Labi, S. (2022). Sustainability considerations in AV-exclusive lane deployment. Transportation Research Board 101st Annual Meeting, Washington, DC.
PSCCAR (2017). Planning for connected and automated vehicles, Public Sector Consultants and Center for Automotive Research. Retrieved from www.publicsectorconsultants.com
Puget Sound Regional Council (2017). Puget Sound travel survey. Retrieved from https://www.psrc.Org/Household-Travel-Survey-Program
Pyrialakou, V.D., Gkartzonikas, C., Gatlin, J.D., and Gkritza, K. (2020). Perceptions of safety on a shared road: Driving, cycling, or walking near an autonomous vehicle. Journal of Safety Research, (72), 249-258.
Qiao, Y., Saeed, T. U., Chen, S., Nateghi, R., and Labi, S. (2018). Acquiring insights into infrastructure repair policy using discrete choice models. Transportation Research Part A: Policy and Practice, 113, 491-508.
Qualcomm, 2017. Accelerating C-V2X commercialization [WWW Document].
Ramezani, H., Benekohal, R. (2015). Optimized speed harmonization with connected vehicles for work zones, IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC. https://doi.org/10.1109/ITSC.2015.179
Rana, M.M., Hossain, K. (2021). Connected and Autonomous Vehicles and Infrastructures: A

Literature Review, Int. J. Pavement Res. Technol. https://doi.org/10.1007/s42947-021-00130-1
Razmi Rad, S., Farah, H., Taale, H., van Arem, B., Hoogendoorn S.P. (2020). Design and operation of dedicated lanes for connected and automated vehicles on motorways: A conceptual framework and research agenda, Transp. Res. Part C Emerg. Technol., 117 102664, https://doi.org/10.1016/j.trc.2020.102664
Reddy, N., Farah, H., Huang, Y., Dekker, T., Van Arem, B. (2020). Operational design domain requirements for improved performance of lane assistance systems: A field test study in The Netherlands, IEEE Open J. Intell. Transp. Syst., 1 (2020), pp. 237-252 https://doi.org/10.1109/OJITS.2020.3040889
Reid, R. (2021). How autonomous vehicles will change road designs, Innovation, Civil Engineering Source, ASCE.
Reighmuth, D. (2020). Are electric vehicles really better for the climate? Yes, here's why, Union of Concerned Scientists (https://blog.ucsusa.org); at https://bit.ly/2ZPLku3.
Rodier, C. (2018), Travel effects and associated greenhouse gas emissions of automated vehicles, UC Davis Institute for Transportation Studies (https://ncst.ucdavis.edu); at https://bit.ly/3iJVlB5.
Ross, A. M., Rhodes, D. H., Hastings, D. E. (2008). Defining changeability: Reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining system lifecycle value. Systems Engineering, 11(3), 246-262.
Row, S. (2013), The future of transportation: connected vehicles to driverless vehicles…what does it mean to me? ITE Journal (www.ite.org), Vol. 83, No. 10, pp. 24-25.
Rowe, R. (2015, July 20). Self-Driving Cars, Timeline. Retrieved from http://www.topspeed.com/cars/car-news/self-driving-cars-timeline-ar169802.html
Rowland, J.D. (2019). Parking structure cost outlook for 2019. Industry Insights.
Rubinstein, M. (1991) Somewhere over the rainbow. Risk 4(11), 61-63.
Ruiz, D., 2020. Connectivity is the key to early wins in connected and automated mobility. Connect. Autom. Mobility, Issue 5
SAE (2014) J2945/x family of standards. Society of Automotive Engineers. (http://standards.sae.org/wip/j2945/)
SAE (2014), Levels of driving automation are defined in New SAE International Standard J3016, Society of Automotive Engineers (www.sae.org); at www.sae.org/misc/pdfs/automated_driving.pdf.
SAE (2016) Taxonomy and definitions for terms related to on-road motor vehicle automated driving systems. SAE International. Issued in 2014-01 and revised in 2016-09. On-Road Automated Vehicle Standards Committee. Retrieved from https://saemobilus.sae.org/content/j3016_201609
SAE International (2018). J3016_201806: Taxonomy and definitions for terms related to driving automation systems for on-road motor vehicles (Warrendale: SAE International, 15 June 2018), https://www.sae.org/standards/content/j3016_201806/.
SAE. (2021). SAE Levels of Driving Automation™ Refined for Clarity and International Audience, SAE, Warrendale, PA.
Saeed, T. Burris, M., Labi, S., and Sinha, K.C. (2020). An empirical discourse on forecasting the use of autonomous vehicles using consumers' preferences. Technol. Forecasting & Social Change 158 (120130). https://doi.org/10.1016/j.techfore.2020.120130.
Saeed, T.U. (2018). Investigating the level of interest in AV adoption in Small- and Medium-

Sized Metropolitan Areas of the United States. Institute of Transportation Engineers Seminar. Purdue University.

Saeed, T.U. (2019). Road infrastructure readiness for autonomous mobility, Ph.D. Dissertation, Purdue University, W. Lafayette, IN.

Saeed, T.U., Alabi, B.N.T., Labi, S., Sinha, K.C. (2021). Preparing Road Infrastructure to Accommodate Connected and Automated Vehicles: System-Level Perspective, Journal of Infrastructure Systems, Volume 27, Issue 1, doi/full/10.1061/%28ASCE%29IS.1943-555X.0000593.

Sage, A. (2016) Where's the lane? Self-driving cars confused by shabby U.S. roadways. Reuters. Retrieved from https://www.reuters.com/article/us-autos-autonomous-infrastructure-insig/wheres-the-lane-self-driving-cars-confused-by-shabby-u-s-roadways-idUSKCN0WX131

Saleh, J. H., Mark, G., Jordan, N. C. (2009). Flexibility: a multi-disciplinary literature review and a research agenda for designing flexible engineering systems. Journal of Engineering Design, 20(3), 307-323.

Saleh, J., Marais, K., Hastings, D., and Newman, D. (2001). The case for flexibility in system design, Proceedings 11th International Symposium INCOSE, Melbourne.

Sánchez-Silva, M. (2019). Managing Infrastructure Systems through Changeability. Journal of Infrastructure Systems, 25(1), p.04018040.

Saneii, M., Kazemeini, A., Seilabi, S. E., Miralinaghi, M., & Labi, S. (2022). A methodology for scheduling within-day roadway work zones using deep neural networks and active learning. Computer-Aided Civil and Infrastructure Engineering.

Sarrias, M. (2016). Discrete choice models with random parameters in R: The R Package. Journal of Statistical Software, 74(10), 1-31.

Schaller, B. (2017). Empty seats, full streets: Fixing Manhattan’s traffic problem, Schaller Consulting, http://schallerconsult.com; at http://schallerconsult.com/rideservices/emptyseats.pdf.

Schoettle, B. and Sivak, M. (2014). A survey of public opinion about autonomous and self-driving vehicles in the U.S., The U.K., And Australia, Report UMTRI-2014-21, Transportation Research Institute, University of Michigan.

Schoettle, B., and Sivak, M. (2016). Motorists’ preferences for different levels of vehicle automation, Transportation Research Institute, University of Michigan (www.umich.edu/~umtriswt).

Schrank, D., Eisele, B., and Lomax, B. (2012). 2012 Urban mobility report. Texas Transportation Institute. College Station, TX.

Schwab, K and Sala-i-Martin, X. (2011). The Global competitiveness report 2014-2015. In World Economic Forum. Retrieved from: http://www3.weforum.org/docs/WEF_GlobalCompetitivenessReport_2014-15. pdf.

Scott, G. (2018). Abandonment option. Retrieved from https://www.investopedia.com/terms/a/abandonmentoption.asp

Seilabi, S., Pourgholamali, M., Miralinaghi, M., Correia, G. H. de A., & Labi, S. (2022a). Robust design of CAV-dedicated lanes considering CAV demand uncertainty and lane reallocation policy. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.4141651

Seilabi, S., Pourgholamali, M., Miralinaghi, M., He, X., Labi, S. (2022b). Managing dedicated lanes for connected and autonomous vehicles to address bottleneck congestion considering morning peak commuter departure choices, SSRN Electronic

Journal. https://doi.org/10.2139/ssrn.4142516
Seilabi, S., Tabesh, M., Davatgari, A., Miralinaghi, M., Labi, S. (2020). Promoting autonomous vehicles using travel demand and lane management strategies, Frontiers in the Built Environment, doi.org/10.3389/fbuil.2020.560116
Sengupta, R., Rezaei, S., Shladover, S.E., Cody, D., Dickey, S., Krishnan, H. (2007). Cooperative collision warning systems: Concept definition and experimental implementation. J. Intell. Transp. Syst. Technol. Planning, Oper. https://doi.org/10.1080/15472450701410452
Sethi, A. K., and Sethi, S. P. (1990). Flexibility in manufacturing: a survey. International journal of flexible manufacturing systems, 2(4), 289-328.
Shaheen, S., & Cohen, A. (2013). Carsharing and personal vehicle services: Worldwide market developments and emerging trends. International Journal of Sustainable Transportation, 7(1), 5–34. https://doi.org/10.1080/15568318.2012.660103
Shaheen, S., Totte, H., and Stocker, A. (2018). Future of mobility white paper, ITS Berkeley. Retrieved from https://escholarship.org/uc/item/68g2h1qv.
Shared Mobility Principles for livable cities (www.sharedmobilityprinciples.org). Principles to guide decision-makers and stakeholders toward the best outcomes for new mobility options.
Sheela, P. V., Mannering, F. (2019). The effect of information on changing opinions toward autonomous vehicle adoption: An exploratory analysis. International Journal of Sustainable Transportation, 1-13.
Shladover S.E. (2018). Connected and automated vehicle systems: Introduction and overview, Journal of Intelligent Transportation Systems, 22(3), 190-200.
Shladover, S. E., Su, D., Lu, X. Y. (2012). Impacts of cooperative adaptive cruise control on freeway traffic flow. Transportation Research Record, 2324(1), 63-70.
Siddiqi, A., de Weck, O. L. (2008). Modeling methods and conceptual design principles for reconfigurable systems. Journal of Mechanical Design, 130(10), 101102.
Siddiqui, F., Lerman, R., and Merrill, J.B. (2022). Teslas running autopilot involved in 273 crashes reported since last year, Washington Post (www.washingtonpost.com); at www.washingtonpost.com/technology/2022/06/15/tesla-autopilot-crashes.
Silberg, G., Manassa, M., Everhart, K., Subramanian, D., Corley, M., Fraser, H., Sinha, V., and Ready, A.W. (2013). Self-driving cars: Are we ready? Technical Report, KPMG. Retrieved from https://home.kpmg/content/dam/kpmg/pdf/2013/10/self-driving-cars-are-we-ready.pdf
Silberg, G., Wallace, R. (2017). Self-driving cars: The next Revolution [WWW Document]. www.cargroup.org/wp-content/uploads/2017/02/Self_driving-cars-The-next-revolution.pdf
Simko, D. J. (2016). Increasing road infrastructure capacity through the use of autonomous vehicles, Ph.D. Dissertation, Naval Postgraduate School, Monterey, CA.
Simoni, M.D. et al. (2019). Congestion pricing in a world of self-driving vehicles: An analysis of different strategies in alternative future scenarios, TRB Annual Meeting; at https://bit.ly/3Kn1EqS.
Simonite, T. (2016). Prepare to be Underwhelmed by 2021's Autonomous Cars, MIT Technology Review (www.technologyreview.com); at https://bit.ly/2PZxH6X.
Simonite, T. (2016, August 23). Prepare to be underwhelmed by 2021's autonomous cars: Ford, Uber, and BMW promise fully self-driving cars in five Years—But They Will Probably

Only Work in Very Limited Areas. MIT Technology Review. https://www.technologyreview.com/s/602210/prepare-to-be-underwhelmed-by-2021s-autonomous-cars/

Singh, V., Skiles, S. M., Krager, J. E., Wood, K. L., Jensen, D., Sierakowski, R. (2009). Innovations in design through transformation: A fundamental study of transformation principles. Journal of Mechanical Design, 131(8), 081010.

Sinha, K. C. and Labi, S. (2007). Transportation decision making: Principles of project evaluation and programming. Hoboken, NJ: Wiley and Sons, Inc.

Sinha, K.C. (2018). What have I learned over half a century of studying transportation engineering? Celebration of Faculty Careers Colloquium, The College of Civil Engineering, Purdue University, West Lafayette.

Sinha, K.C., Patidar, V., Li, Z., Labi, S., Thompson, P.D. (2009). Establishing the weights of performance criteria: case studies in transportation facility management. Journal of Transportation Engineering, 135(9), 619–631. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000039

Sinha, K.C. (2019). Road infrastructure preparedness for autonomous mobility, 2019 Global Symposium on Connected & Automated Transportation, Washtenaw Community College, Ann Arbor, MI, February 27, 2019.

Sivak, M., and Schoettle, B. (2015a). Road safety with self-driving vehicles, Sustainable Worldwide Transportation Program (www.umich.edu/~umtriswt), University of Michigan.

Sivak, M., and Schoettle, B. (2015b). Potential impact of self-driving vehicles on household vehicle demand and usage, Sustainable Worldwide Transportation Program (www.umich.edu/~umtriswt).

Smit, H. T. (2003). Infrastructure investment as a real options game: The case of European airport expansion. Financial Management, 27-57.

Smit, H. T. and Trigeorgis, L. (2006). Real options and games: Competition, alliances and other applications of valuation and strategy. Review of Financial Economics 15(2), 95-112.

Smit, J. T. J. and Trigeorgis, L. (2009). Valuing infrastructure investment: An option games approach. California Management Review 51(2), 82-104.

Snyder, R. (2018). Street design implications of autonomous vehicles, Public Square, A CNU Journal.

Snyder, R. (2018). Street design implications of autonomous vehicles; Public Square: A CNU Journal. Washington, DC, USA, available online: https://www.cnu.org/publicsquare/2018/03/12/street-design-implications-autonomous-vehicles (accessed on 7 July 2021).

Sohrabi, S., Khreis, H., and Lord, D. (2020). Impacts of autonomous vehicles on public health: A conceptual model and policy recommendations, Sustainable Cities and Society, Vo. 63 (https://doi.org/10.1016/j.scs.2020.102457); at https://bit.ly/3fCbOWs.

Somers, A.; Weeratunga, K. Automated vehicles: Are we ready? Internal Report on Potential Implications for Main Roads WA; Main Roads Western Australia: Perth, Australia, 2015.

Soteropoulos, A., Berger, M., and Ciari, F. (2019). Impacts of automated vehicles on travel behavior and land use: an international review of modelling studies. Transport reviews, 39(1), 29-49.

Sou, S. and Tonguz, O.K. (2011). Enhancing VANET connectivity through roadside units on highways, IEEE Transactions on Vehicular Technology 60(8), 3586-3602.

Špačková, O., Straub, D. (2017). Long-term adaption decisions via fully and partially observable Markov decision processes. Sustainable and Resilient Infrastructure, 2(1), 37-58.
Speck, J. (2017). Autonomous vehicles, United Conference of Mayors. Retrieved from www.youtube.com/watch?v=2kBEvg8bftE
Sperling, D. (2017). Three revolutions: steering automated, shared, and electric vehicles to a better future, Island Press (https://islandpress.org).
Spieser, K., Treleaven, K., Zhang, R., Frazzoli, E., Morton, D., and Pavone, M. (2014). Toward a systematic approach to the design and evaluation of automated mobility-on-demand systems: A case study in Singapore. In Road Vehicle Automation; Springer: New York, NY, USA, 229–245.
State of California (2023). Autonomous Vehicle Regulations for development of driverless testing programs and deployment regulations, Sacramento, CA. https://www.dmv.ca.gov/portal/vehicle-industry-services/autonomous-vehicles/california-autonomous-vehicle-regulations/autonomous-vehicle-milestones/
Stephens, T. Gondar, J., Lin, Z., Liu, C., Gohlke, D., Chen, Y. (2016). Estimated bounds and important factors for fuel use and consumer costs of connected and automated vehicles, Technical Report, National Renewable Energy Laboratory (www.nrel.gov); at www.nrel.gov/docs/fy17osti/67216.pdf.
Stead, D., Vaddadi, B. (2019). Automated vehicles and how they may affect urban form: A review of recent scenario studies, Cities, 92, 125-133, https://doi.org/10.1016/j.cities.2019.03.020
Stern, R.E., Cui, S., Delle Monache, M.L., Bhadani, R., Bunting, M., Churchill, M., Hamilton, N., Haulcy, R., Pohlmann, H., Wu, F., Piccoli, B., Seibold, B., Sprinkle, J., Work, D.B., (2018). Dissipation of stop-and-go waves via control of autonomous vehicles: Field experiments. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2018.02.005
Stocker, A., Lazarus, J., Becker, S., and Shaheen, S. (2016, September). Effects on vehicle use and ownership, travel behavior, quality of life, and environmental impacts. Retrieved from http://innovativemobility.org/wp-content/uploads/Zipcar-College-Market-Study-2015.pdf
Stocker, A., Shaheen, S. (2017). Shared automated vehicles: review of business models, Roundtable on Cooperative Mobility Systems and Automated Driving (6-7 December 2016),Transportation Sustainability Research Center, University of California, Berkeley, Berkeley, CA
Straubinger, A., Rothfeld, R., Shamiyeh, M., Büchter, K.D., Kaiser, J., Plötner, K.O. (2020). An overview of current research and developments in urban air mobility – Setting the scene for UAM introduction. J. Air Transp. Manag. https://doi.org/10.1016/j.jairtraman.2020.101852
Su, Q., Wang, D.Z.W. (2020). On the morning commute problem with distant parking options in the era of autonomous vehicles. Transportation Research Part C: Emerging Technologies, 120, 102799. https://doi.org/10.1016/J.TRC.2020.102799
Sundheim, D. (2013). Do women take as many risks as men? Harvard Business Review, https://hbr.org/2013/02/do-women-take-as-many-risks-as
Swei, O. A. (2016). Material diversification in pavement management: a technique to proactively deal with an uncertain future, Ph.D. Dissertation, Massachusetts Institute of Technology, Cambridge, MA.

Tachet, R., Sagarra, O., Santi, P., Resta, G., Szell, M., Strogatz, S. H., Ratti, C. (2017). Scaling law of urban ride sharing. Scientific reports, 7, 42868.
Tachet, R., Santi, P., Sobolevsky, S., Reyes-Castro, L. I., Frazzoli, E., Helbing, D., Ratti, C. (2016). Revisiting street intersections using slot-based systems. PLoS ONE, 11(3), 1–9. https://doi.org/10.1371/journal.pone.0149607
Taeihagh, A., and Lim, H.S.M. (2018). Governing autonomous vehicles: Emerging responses for safety, liability, privacy, cybersecurity, and industry risks, Transport Reviews, at https://bit.ly/2DYQaLd.
Taguchi, G. (1993) Taguchi on robust technology, ASME Press, New York, NY.
Taiebat, M., Stolper, S., and Xu, M. (2019). Forecasting the impact of connected and automated vehicles on energy use: A microeconomic study of induced travel and energy rebound, Applied Energy, 247(1), 297-308 (https://doi.org/10.1016/j.apenergy.2019.03.174).
Tajalli, M., Hajbabaie, A. (2018). Dynamic speed harmonization in connected urban street networks. Comput. Civ. Infrastruct. Eng. https://doi.org/10.1111/mice.12360
Talebian, A., Mishra, S. (2018). Predicting the adoption of connected autonomous vehicles: A new approach based on the theory of diffusion of innovations. Transportation Research Part C: Emerging Technologies, 95, 363-380.
Talebpour, A., Mahmassani, H.S. (2016). Influence of connected and autonomous vehicles on traffic flow stability and throughput. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2016.07.007
Tengilimoglu, O., Carsten, O., Wadud, Z. (2023). Implications of automated vehicles for physical road environment: A comprehensive review, Transportation Research Part E: Logistics and Transportation Review, Volume 169, January 2023, 102989
Tengilimoglu, O., Carsten, O., Wadud, Z. (2023). Infrastructure-related challenges in implementing connected and automated vehicles on urban roads: Insights from experts and stakeholders, IET Intelligent Transport Systems 17(12), 2352-2368.
Tengilimoglu, O., Carsten, O., Wadud, Z. (2023). Infrastructure requirements for the safe operation of automated vehicles: Opinions from experts and stakeholders, Transport Policy 133, 209-222.
The Economist (2015, July 01) If autonomous vehicles rule the world, From Horseless to Driverless. Retrieved from http://worldif.economist.com/article/12123/horseless-driverless
The Economist (2016, September 03) Uberworld. Economist. Retrieved from https://www.economist.com/news/leaders/21706258-worlds-most-valuable-startup-leading-race-transform-future
The Economist (2019). Driverless cars are stuck in a jam, 10 October (www.economist.com); at www.economist.com/leaders/2019/10/10/driverless-cars-are-stuck-in-a-jam.
The Economist. (2018, March 01). Autonomous vehicles are just around the corner - Reinventing wheels. Retrieved from https://www.economist.com/news/special-report/21737418-driverless-vehicles-will-change-world-just-cars-did-them-what-went-wrong
The Guardian (2015, March 18) Elon Musk: self-driving cars could lead to ban on human drivers. Retrieved from https://www.theguardian.com/technology/2015/mar/18/elon-musk-self-driving-cars-ban-human-drivers
The Guardian (2018, March 31) Tesla car that crashed and killed driver was running on Autopilot. Retrieved from https://www.theguardian.com/technology/2018/mar/31/tesla-car-crash-autopilot-mountain-view.

TIRG (2023). The safety bump associated with CAVs, Working Paper, The Infrastructure Research Group, Lyles School of Civil Engineering, Purdue University.

The New York Times (2018, March 19) Self-driving Uber car kills pedestrian in Arizona, where robots roam. Retrieved from https://www.nytimes.com/2018/03/19/technology/uber-driverless-fatality.html.

Thompson, C. (2016). No parking here, 2. Mother Jones Magazine. Waymo. On the road. https://waymo.com/ontheroad/.

Thompson, C. (2017). 11 super-smart technologies in the 2017 Mercedes E-Class. Business Insider. Retrieved from http://www.businessinsider.com/mercedes-2017-e-class-driverless-technology-2017-3

Thorn, E., Kimmel, S., Chaka, M. (2018). A framework for automated driving system testable cases and scenarios, Virginia Tech Transportation Institute; Southwest Research Institute; and Booz Allen Hamilton, Inc., for the United States Department of Transportation and the National Highway Traffic Safety Administration, Report Number : DOT HS 812 623, https://rosap.ntl.bts.gov/view/dot/38824

Tian, D., Wu, G., Boriboonsomsin, Barth, M. (2017). Performance measurement evaluation framework and co-benefit/tradeoff analysis for connected and automated vehicles (CAV) applications: A Survey, National Center for Sustainable Transportation, Riverside, CA.

Tian, L.J., Sheu, J.B., Huang, H.J. (2019). The morning commute problem with endogenous shared autonomous vehicle penetration and parking space constraint. Transportation Research Part B: Methodological, 123, 258-278.

Tientrakool, P., Ho, Y.C., Maxemchuk, N.F. (2011). Highway capacity benefits from using vehicle-to-vehicle communication and sensors for collision avoidance, in: IEEE Vehicular Technology Conference. https://doi.org/10.1109/VETECF.2011.6093130

Tohme, R., Yarnold M. (2020). Steel bridge load rating impacts owing to autonomous truck platoon, Transp. Res. Rec. J. Transp. Res. Board, 2674 (2020), pp. 57-67 https://doi.org/10.1177/0361198120902435

Tracy, P. (2017) America's failing infrastructure is a serious problem for autonomous vehicles. The Daily Dot. Retrieved from: https://www.dailydot.com/debug/autonomous-vehicle-america-road-infrastructure/

Trager, W., Ahmadjian, V., Paracer, S. (1988). Symbiosis: An Introduction to biological associations. J. Parasitol. https://doi.org/10.2307/3282073

Train, K. (2003). Discrete choice models with simulation. Cambridge University Press, Cambridge, MA.

TRB (2014). Automated vehicles symposium 2014. Transportation Research Board (TRB). Burlingame, CA. http://www.auvsi.org/avs2014/home

TRB (2017). Strategies to advance automated and connected vehicles, Transportation Research Board (www.trb.org); at www.nap.edu/download/24873.

TRB (2018). Dedicating lanes for priority or exclusive use by connected and automated vehicles, The National Academies Press, Washington, DC, doi.org/10.17226/25366

TRB (2019). Socioeconomic impacts of automated and connected vehicles, European Commission and the Transportation Research Board (www.trb.org); at www.trb.org/Publications/Blurbs/178576.aspx.

Trommer, S., Kolarova, V., Fraedrich, e., Kroger, L. (2016). Autonomous driving: The impact of vehicle automation on mobility behavior, Institute of Transport Research (www.ifmo.de); at http://bit.ly/2kIAOOQ.

Truett, R. (2016, October 10). Fully autonomous vehicles won't arrive for a long time. Retrieved from https://www.autonews.com/article/20161010/OEM06/310109972/fully-autonomous-vehicles-won-t-arrive-for-a-long-time
Uhlemann, E. (2015). Introducing connected vehicles [Connected vehicles]. IEEE Veh. Technol. Mag. https://doi.org/10.1109/MVT.2015.2390920
UK Autodrive. (2018). Paving the way: Building the road infrastructure of the future for the connected and autonomous vehicles. 2018. http://www.ukautodrive.com/downloads/ (accessed 2 February 2021).
ULC (2019). Automated operations of vehicles. act, uniform law commission, National Conference of Commissioners, July 12., Anchorage, Alaska.
US Census Bureau (2018). Metropolitan statistics. Retrieved from: https://www.census.gov/
US Department of Transportation (2016). Road and Bridge Data by State. Retrieved from: https://www.transportation.gov/policy-initiatives/grow-america/road-and-bridge-data
USDOT (2019). A variable speed limit system consisting of multiple ITS components and covering 40 miles over the Snoqualmie Pass in Washington was designed and implemented for $5 million. US Department of Transportation, Washington D.C. Retrieved from https://www.itsknowledgeresources.its.dot.gov/ITS/benecost.nsf/ID/C2F9983AD6C6E78E85256DB100458933?OpenDocument&Query=CApp
USDOT (2016). Planning for connected automated vehicles in smart cities. Fort Worth, TX.
USDOT. (2018). Preparing for the future of transportation: Automated vehicles 3.0. U.S. Department of Transportation, Washington, DC. Retrieved from www.transportation.gov/sites/dot.gov/files/docs/policy- initiatives/automated-vehicles/320711/preparing-future-transportation-automated-vehicle-30.pdf
Vahidi, A., Sciarretta, A. (2018). Energy saving potentials of connected and automated vehicles. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2018.09.001
Van Arem, B., Van Driel, C.J.G., Visser, R. (2006). The impact of cooperative adaptive cruise control on traffic-flow characteristics. IEEE Trans. Intell. Transp. Syst. https://doi.org/10.1109/TITS.2006.884615
Van den Berg, V.A., Verhoef, E.T. (2016). Autonomous cars and dynamic bottleneck congestion: The effects on capacity, value of time and preference heterogeneity. Transportation Research Part B: Methodological, 94, 43-60.
Vinitsky, E., Parvate, K., Kreidieh, A., Wu, C., Bayen, A. (2018). Lagrangian control through Deep-RL: Applications to bottleneck decongestion, in: IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC. https://doi.org/10.1109/ITSC.2018.8569615
Wang, J., Wang, C., Lv, J., Zhang, Z., Li, C. (2017). Modeling travel time reliability of road network considering connected vehicle guidance characteristics indexes. J. Adv. Transp. https://doi.org/10.1155/2017/2415312
Wang, J., Wang, C., Lv, J., Zhang, Z., Li, C. (2017). Modeling travel time reliability of road network considering connected vehicle guidance characteristics indexes. J. Adv. Transp. https://doi.org/10.1155/2017/2415312
Wang, S., Yu, B., Ma, Y., Liu, J., Zhou, W. (2021). Impacts of different driving automation levels on highway geometric design from the perspective of trucks, J. Adv. Transp. 1–17.
Wang, T. and de Neufville, R. (2005). Real options "in" projects. In 9th Annual International Conference on Real Options Theory and Practice, Paris, France, June 23-25, 2005

Wang, T. and de Neufville, R. (2006). Identification of real options "in" projects. In 16th Annual International Symposium of the International Council on Systems Engineering (INCOSE), Orlando, FL, July 10-13, 2006.
Washburn S.S., and Washburn L.D. (2018). Future highways – automated vehicles. Retrieved from https://s3.amazonaws.com/suncam/docs/208.pdf?1536490909
Washington, S. P., Karlaftis, M. G., Mannering, F. L., Anastasopoulos, P. (2020). Statistical and econometric methods for transportation data analysis. Chapman Hall/CRC, Boca Raton, FL.
Waymo (2018, July 20). Transition to autonomous cars will take longer than you think, Waymo CEO tells Governors. Retrieved from: https://www.forbes.com/sites/samabuelsamid/2018/07/20/waymo-ceo-tells-governors-av-time-will-be-longer-than-you-think/#507b82d6d7da
Waymo Team. (2021). Introducing Waymo's suite of custom-built, self-driving hardware. Available online: https://medium.com/waymo/introducing-waymos-suite-of-custom-built-self-driving-hardwarec47d1714563urmson (accessed on 2 February 2021).
Waymo. (2021). On the Road. Available online: https://waymo.com (accessed on 2 February 2021).
WEF (2020). Guidelines for city mobility: Steering towards collaboration, World Economic Forum (www.weforum.org/reports/guidelines-for-city-mobility-2020)
Weigl, K., Nees, M.A., Eisele, D., Riener, A. (2022). Acceptance of automated vehicles: Gender effects, but lack of meaningful association with desire for control in Germany and in the U.S., Transportation Research Interdisciplinary Perspectives, 13, 100563
Weiss, A., Salehin, M.F., and Habib, K.N. (2019). A joint RP-off-SP survey to understand the impacts of autonomous vehicle on travel mode choices in the Greater Toronto Area. Transportation Research Board 98th Annual Meeting, Washington D.C.
Wharton (2017). The road ahead for connected vehicles, Wharton School of Management (http://wharton.upenn.edu); at http://whr.tn/2BqKIuT.
Wilson, K. (2022). Why Tesla can program its cars to break road safety laws, StreetBlog USA (https://usa.streetsblog.org); at https://bit.ly/3fGTmMg.
Wood, J., Donnell, E. (2014). Stopping sight distance and horizontal sight line offsets at horizontal curves. Transp. Res. Record 2014, 2436, 43–50
World Bank (2005). A framework for the economic evaluation of transport projects (www.worldbank.com) ; at https://bit.ly/2wPF7Sg.
WSJ (2017). Why your next car may look like a living room, Wall Street Journal (www.wsj.com); at http://on.wsj.com/2tlCvYp.
WSP (2018). Minnesota Department of Transportation connected corridor system: Concept of operations. Report prepared in conjunction with SRF, https://www.dot.mn.gov/its/projects/2016-2020/connectedcorridors/conopsfinal.pdf
Wu, X., Cao, J., Douma, F. (2021). The impacts of vehicle automation on transport-disadvantaged people, Transportation Research Interdisciplinary Perspectives, Volume 11, 100447
Xia, F., Yang, L.T., Wang, L., Vinel, A. (2012). Internet of things. Int. J. Commun. Syst. 25, 1101.
Yang, H., Oguchi, K. (2018). Connected vehicle enhanced vehicle routing with intersection turning cost estimation, in: IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC. https://doi.org/10.1109/ITSC.2018.8569246

Yang, B., Monterola, C. (2016). Efficient intersection control for minimally guided vehicles: a self-organized and decentralized approach. Transp. Res.

Yang, H., Wang, Z., Xie, K. (2017). Impact of connected vehicles on mitigating secondary crash risk. Int. J. Transp. Sci. Technol. https://doi.org/10.1016/j.ijtst.2017.07.007

Ye, X., Wang, X., Liu, S., Tarko, A.P. (2021). Feasibility study of highway alignment design controls for autonomous vehicles, Accid. Anal. Prev., 159 (2021), p. 106252 https://doi.org/10.1016/j.aap.2021.106252

Yeganeh, A., Vandoren, B., Pirdavani, A. (2022). Impacts of load distribution and lane width on pavement rutting performance for automated vehicles, Int. J. Pavement Eng., 23(1), 4125-4135, https://doi.org/10.1080/10298436.2021.1935938

Yoshida, J. (2013) If a car's really 'autonomous,' why V2X? Retrieved from https://www.eetimes.com/document.asp?doc_id=1319468

Young, A. (2017). Self-driving cars vs. American roads: will infrastructure speed bumps slow down the future of transportation? Retrieved from https://www.salon.com/2017/04/20/self-driving-cars-vs-crummy-american-roads-will-infrastructure-speed-bumps-slow-down-the-future-of-transportation/

Yue, L., Abdel-Aty, M., Wu, Y., Wang, L. (2018). Assessment of the safety benefits of vehicles' advanced driver assistance, connectivity and low level automation systems. Accid. Anal. Prev. https://doi.org/10.1016/j.aap.2018.04.002

Yvkoff, L. (2012). Many car buyers show interest in autonomous car tech. Retrieved from <http://www.cnet.com/news/many-car-buyers-show-interest-in-autonomous-car-tech/.

Zanjirani, R., Masoud Hekmatfar, F. (2009). Facility location concepts, models, algorithms and case studies, Physica-Verlag A Springer Company.

Zhang, W., and Wang, K. (2020). Parking futures: Shared automated vehicles and parking demand reduction trajectories in Atlanta, Land Use Policy, Vo. 91 (doi.org/10.1016/j.landusepol.2019.04.024).

Zhang, W., Guhathakurta, S. (2017). Parking spaces in the age of shared autonomous vehicles: How much parking will we need and where? Transp. Res. Rec., 2651, 80–91.

Zhang, X., E. Robson, S.T. Waller. (2020). An integrated transport and economic equilibrium model for autonomous transportation systems considering parking behavior. Computer-Aided Civil and Infrastructure Engineering, mice.12611.

Zhang, X., Liu, W., Waller, S. T., & Yin, Y. (2019b). Modelling and managing the integrated morning-evening commuting and parking patterns under the fully autonomous vehicle environment. Transportation Research Part B: Methodological, 128, 380-407.

Zhang, X., W. Liu, S.T. Waller. (2019a). A network traffic assignment model for autonomous vehicles with parking choices. Computer-Aided Civil and Infrastructure Engineering, mice.12486.

Zhang, X., Zhao, C., Liao, F., Li, X., Du, Y. (2022). Online parking assignment in an environment of partially connected vehicles: A multi-agent deep reinforcement learning approach. Transportation Research Part C: Emerging Technologies, 138. https://doi.org/10.1016/J.TRC.2022.103624

Zhao, C., Liao, F., Li, X., Du, Y. (2021). Macroscopic modeling and dynamic control of on-street cruising-for-parking of autonomous vehicles in a multi-region urban road network. Transportation Research Part C: Emerging Technologies 128, 103176. https://doi.org/10.1016/J.TRC.2021.103176

Zhao, T. and Tseng, C. L. (2003). Valuing flexibility in infrastructure expansion. Journal of

Infrastructure Systems 9(3), 89-97.
Zheng, J., Liu, H.X. (2017). Estimating traffic volumes for signalized intersections using connected vehicle data. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2017.03.007
Zhong, H., Li, W., Burris, M. W., Talebpour, A., Sinha, K.C. (2020). Will autonomous vehicles change auto commuters' value of travel time? Transportation Research Part D: Transport and Environment, 83, 102303. https://doi.org/10.1016/J.TRD.2020.102303
Zhu, F., Ukkusuri, S. V. (2015). A linear programming formulation for autonomous intersection control within a dynamic traffic assignment and connected vehicle environment. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2015.01.006
Zipper, D. (2021). When cities say no to new transportation technology, City Lab (www.bloomberg.com/citylab); https://bloom.bg/3ioMpSL.
Zmud, J. P., Sener, I. N. (2017). Towards an understanding of the travel behavior impact of autonomous vehicles. Transportation Research Procedia, 25, 2500-2519.
Zong, S., Li, Y., Chen, S., Mou, S., Labi, S. (2023). Facilitating UAV application for CAV deployment, CCAT Report #73, The Center for Connected and Automated Transportation, Purdue University, West Lafayette, IN.

APPENDIX

CCAT Project: Design and Management of Highway Infrastructure to Accommodate CAVs

Published Related Work

Paper 1: Seilabi, S., Tabesh, M., Davatgari, A., Miralinaghi, M., Labi, S. (2020). Promoting autonomous vehicles using travel demand and lane management strategies, *Frontiers in the Built Environment*, doi.org/10.3389/fbuil., Vol. ,6 560116 (awarded the Joe Sussman best paper prize, by the Journal, 2020]

Abstract

A key challenge facing cities of today is the persistent and growing urban congestion that has significant adverse effects on economic productivity, emissions, driver frustration, and quality of life. The concept of smart cities, which can revolutionize the management of metropolitan transportation operations and infrastructure, shows great promise in mitigating this problem. Specifically, the automation and connectedness (A&C) of smart city entities such as its infrastructure, services, and vehicles, can be helpful. In this regard, this paper focuses on the potential of autonomous vehicles (AVs) and AV infrastructure, particularly during prospective transition era where there will be mixed streams of AVs and human driven vehicles (HDVs). The paper considers two aspects of this potential: connectivity-enabled travel demand management and travel infrastructure supply through lane management. To demonstrate the opportunity associated with this potential, this paper first presents an AV-enabled tradable credit scheme (TCS) to manage travel demand. Here, the transportation authority distributes travel credits to travelers directly and instantaneously using the AV's A&C features. Travelers use their A&C features to pay these credits for travel at specific locations or times-of-day according to their choices of lane types and links. With regard to supply, this paper considers that the road network consists of two lane types: AV-dedicated, and mixed traffic lanes, and develops a scheme for travel demand and lane management strategies in the AV transition era (TLMAV). Firstly, the paper models the expected travel choices based on user equilibrium concepts, at different levels of AV market penetration. Then, the existence of the optimal solution in terms of link flows and the prevailing travel credit price is demonstrated. Then the paper establishes the optimal TLMAV that minimizes total travel time subject to user equity constraints. The results demonstrate the extent to which HDV users will suffer an increase in travel cost if equity is not considered in the model. The results also show how the transportation agency can use TLMAV to keep HDV travel costs to acceptable levels, particularly during the early stages of the AV transition period. Further, the paper shows how TLMAV could be designed to gradually diminish inequity effects so that travelers, in the long term, are motivated to shift to AVs.

Paper 2: Saeed, T.U., Burris, M., Labi, S., Sinha, K.C. (2020). An empirical discourse on forecasting the use of autonomous vehicles using consumers' preferences. *Technological Forecasting and Social Change Volume 158, September 2020, 120130,* https://doi.org/10.1016/j.techfore.2020.120130

Abstract

Given many known and unknown uncertainties, it is hard to forecast reliably the mode choices, expected to prevail with autonomous vehicle (AV) technology; however, the key to getting some idea lies in understanding the preferences of end users. In this vein, a random parameters logit model is employed to study the consumers' preferences in small- and medium-sized metropolitan areas, based on their travel behavior and household characteristics, socio-demographic features, awareness about AV technology and new travel choices, psychological factors, and built environment features. Most of the past studies hypothesize that due to a wide range of anticipated benefits, there would be increased use of AVs especially as a shared service where multiple travelers use the same AV concomitantly. However, the results from this study do not support the hypothesis that vehicle ownership will be an obsolete model at least during the early phase of transitioning to the self-driving era (when roads are expected to contain vehicles with and without human drivers). The findings of this study reveal key factors influencing consumer preferences and offer important insights to technology developers and service providers in understanding the ways consumers would like to use this technology and hence, defining the business model.

Paper 3: Labi, S. (2021). Measuring the benefits of civil systems connectivity and automation – A discussion in the context of highway transport, *Civil Engineering & Environmental Systems*, 1-21, https://doi.org/10.1080/10286608.2021.2013474

Abstract

Connectivity refers to the ability of civil engineering system components to transmit/receive data for making strategic, tactical and operational decisions towards enhanced efficiency, effectiveness, and lower costs to the system stakeholders. Automation is the capability of a system or its component to carry out control functions or decisions that are traditionally done by humans. As the benefits of these two technologies become increasingly apparent in various civil engineering disciplines, it seems useful to measure such impacts to generate information for evaluating the feasibility of past or prospective future applications related to connectivity and automation (C/A) or for comparing alternative C/A applications. This paper discusses some constructs for measuring the benefits or effectiveness (MOEs) of C/A applications. An MOE expressed in terms of an appropriate system performance indicator (SPI) can help ascertain the extent to which a C/A application has accomplished or is expected to accomplish its specified goals or to compare the efficacy of alternative C/A applications. This paper identifies a number of SPIs and establishes a number of MOEs for measuring the effectiveness of C/A applications in terms of the relevant SPIs. The paper provides illustrations to the concepts discussed in the context of highway transport.

Paper 4: Saeed, T.U., Alabi, B.N.T., Labi, S., Sinha, K.C. (2021). Preparing Road Infrastructure to Accommodate Connected and Automated Vehicles: System-Level Perspective, *Journal of Infrastructure Systems, Volume 27, Issue 1, https://doi.org/10.1061/(ASCE)IS.1943-555X.0000593*

Abstract

Highway agencies seek knowledge of the changes in infrastructure design and management necessary for connected and automated vehicle (CAV) operations. This technical note presents preliminary and partial results of ongoing research. The note establishes a classification of roadway infrastructure, and discusses the challenges and opportunities associated with infrastructure preparation for CAVs. The technical note also identifies stakeholder roles regarding CAV infrastructure provision and discusses uncertainties regarding CAV market penetration and level of autonomy during the CAV transition period.

Paper 5: Feng, J., Chen, S., Ye, Z., Miralinaghi, M., Labi, S., Chai, J. (2021). Repositioning shared urban personal transport units: considerations of travel cost and demand uncertainty, *Journal of Infrastructure Systems* 27 (3), 04021011, https://doi.org/10.1061/(ASCE)IS.1943-555X.0000619

Abstract

Operators of personal transport units (PTUs) face the challenge of intelligently balancing the locational demand and supply of PTUs in order to mitigate surpluses or deficits at PTU pickup stations. To accomplish this goal, operators need to be able to reliably predict the spatial distribution of PTU demand and to optimize the distributional allocation of resources to meet this demand. This paper proposes a three-step mathematical programming approach that addresses PTU supply vehicle routing and PTU repositioning that minimize the weighted total travel costs and unmet user demand. The methodology combines discrete wavelet transform (DWT) and artificial neural network (ANN) techniques to predict the demand at PTU stations, considers travel cost and unmet user demand in a multiobjective model and solves it with a multiobjective coevolutionary algorithm (MOCA), and incorporates the demand uncertainty to ensure robustness of the optimal repositioning and routing strategy for all the PTU stations. The paper demonstrated the proposed approach using real-world bicycle-sharing data from Nanjing, China, and showed that the proposed approaches for demand prediction (DWT-ANN) and optimization (MOCA) significantly produce superior results compared with traditional methods. Sensitivity analysis demonstrated the robustness of the proposed approaches.

Paper 6: Labi, S., Sinha, K.C. (2022). Emerging transportation innovations: Promises and pitfalls, *Innovation and Emerging Technologies*, 1-9, 2240001, 1–9. https://doi.org/10.1142/S2737599422400011

Abstract

Rapid growth in information and communication technologies has spawned a number of major innovations in transportation area, including automation and connectivity. At the same time, the advancement in battery technology has accelerated the electrification of transportation vehicle propulsion. This paper, focusing on highway-oriented surface transportation, examines the current development of these innovations, along with their synergies, benefits, pitfalls, trends, possible barriers to deployment, and wider impacts.

Paper 7: Labi, S., Saneii, M., Tabesh, M.T., Pourgholamali, M., Miralinaghi, M. (2023). Parking Infrastructure Location Design and User Pricing in the Prospective Era of Autonomous Vehicle Operations, *Journal of Infrastructure Systems 29(4), DOI: 10.1061/JITSE4.ISENG-2232*

Abstract

The lack of parking infrastructure continues to pose a problem for urban commuters, as parking demand in most cities outstrips supply and significant driver time is expended searching for parking. The emergence of vehicle automation offers an opportunity to help mitigate this issue. In the autonomous vehicle (AV) era, it is expected that after dropping off its passengers at their destinations, the AV will park at a relatively inexpensive parking facility located outside the downtown area instead of the existing, higher-priced facilities in the central business district (CBD). This is expected to decrease CBD parking demand, ultimately leading to the possible decommissioning and repurposing of some existing parking infrastructure in the CBD and the construction of new infrastructure in the city's outlying areas. What is needed, therefore, is a framework for city road agencies for decommissioning/relocating/locating and user pricing of parking infrastructure to serve human-driven vehicles (HDVs) and AVs. To address this issue, this study presents a bi-level framework. The road agency (at the upper level) seeks to: (1) minimize travelers' cost systemwide, and (2) maximize monetary benefits of infrastructure decommissioning and parking fee revenue at the upper level. Travelers (at the lower level) seek to reduce their costs of travel in response to the road agency's decisions made at the upper level. A hybridized solution approach (optimization heuristics and machine learning) is implemented for this mixed-integer nonlinear problem. The numerical experiments provided a number of insights regarding parking infrastructure location design and user pricing in the prospective AV era.

Paper 8: Chen, S., Zong, S., Chen, T., Huang, Z., Chen, Y., Labi, S. (2023). A Taxonomy for Autonomous Vehicles Considering Ambient Road Infrastructure. Sustainability 15, 11258. https://doi.org/10.3390/su151411258

Abstract

To standardize definitions and guide the design, regulation, and policy related to automated transportation, the Society of Automotive Engineers (SAE) has established a taxonomy consisting of six levels of vehicle automation. The SAE taxonomy defines each level based on the capabilities of the automated system. It does not fully consider the infrastructure support required for each level. This can be considered a critical gap in the practice because the existing taxonomy does not account for the fact that the operational design domain (ODD) of any system must describe the specific conditions, including infrastructure, under which the system can function. In this paper, we argue that the ambient road infrastructure plays a critical role in characterizing the capabilities of autonomous vehicles (AVs) including mapping, perception, and motion planning, and therefore, the current taxonomy needs enhancement. To throw more light and stimulate discussion on this issue, this paper reviews, analyzes, and proposes a supplement to the existing SAE levels of automation from a road infrastructure perspective, considering the infrastructure support required for automated driving at each level of automation. Specifically, we focus on Level 4 because it is expected to be the most likely level of automation that will be deployed soon. Through an analysis of driving scenarios and state-of-the-art infrastructure technologies, we propose five sub-levels for Level 4 automated driving systems: Level 4-A (Dedicated Guideway Level), Level 4-B (Expressway Level), Level 4-C (Well-Structured Road Level), Level 4-D (Limited-Structured road Level), and Level 4-E (Disorganized Area Level). These sublevels reflect a progression from highly structured environments with robust infrastructure support to less structured environments with limited or no infrastructure support. The proposed supplement to the SAE taxonomy is expected to benefit both potential AV consumers and manufacturers through defining clear expectations of AV performance in different environments and infrastructure settings. In addition, transportation agencies may gain insights from this research towards their planning regarding future infrastructure improvements needed to support the emerging era of driving automation.