SUSTAINABILITY CONSIDERATIONS FOR OPTIMAL AUTONOMOUS VEHICLE LANE DEPLOYMENT

by

Paul (Young Joun) Ha

A Thesis

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Master of Science in Civil Engineering

Lyles School of Civil Engineering

West Lafayette, Indiana

December 2019

THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Samuel Labi, Chair

Lyles School of Civil Engineering

Dr. Jon Fricker

Lyles School of Civil Engineering

Dr. Konstantina Gkritza

Lyles School of Civil Engineering

Approved by:

Dr. Dulcy Abraham

Head of the Graduate Program

Dedicated to my parents, Jong-hyo and Ae-ri.

ACKNOWLEDGMENTS

I would like to take this opportunity to thank Dr. Samuel Labi, who has devoted his time and effort to mentor me. Thank you for the opportunities you have given me and for the kind words of encouragement and advice. You have been one of the most genuine people I have had the pleasure of knowing, and I hope to emulate you in my life.

I would also like to thank Dr. Nadia Gkritza and Dr. Jon Fricker for serving on my committee. The knowledge I gained in your courses have strengthened my understanding in transportation engineering, and I believe the lessons I learned from you are assets that I will value with me throughout my academic and professional career.

I also acknowledge Dr. Mohammad Miralinaghi, who has been working with me since the inception of the research idea. Thank you for the guidance you have provided in this research. The resources you have provided me have been important to this research. To my colleagues Sikai Chen and Shubham Aggrawal, thank you for taking the time to share your experiences and giving me your insights and advice. Your friendship and mentorship are greatly appreciated.

I would also like to offer special thanks to Drs. Samer Madanat, Jinwoo Lee, and Jonghae Suh for introducing to me the exciting world of transportation engineering. I would not be in this discipline had I not been blessed with the opportunity to work with you. Thank you for the kind words of encouragement and sincere advice even after I left NYU Abu Dhabi.

This thesis was supported by the Center for Connected and Automated Transportation (CCAT) at Purdue University under the project titled “Design and Management of Highway Infrastructure to Accommodate CAVs”, with Principal Investigators Dr. Kumares Sinha, Dr. Samuel Labi, and Dr. Mohammad Miralinaghi. I thank all the individuals and entities associated to this research grant, including the USDOT and the CCAT Consortium.

To my parents, thank you for your support and encouragement throughout my life. I am truly blessed to have you as my parents. I also thank my sister Bora, who has always been paving the way for me in all walks of life.

To Monika, your love, support, encouragement, advice, and friendship for the last 6 years have been the most incredible serendipity I could ever have imagined. Everything I achieve in my life will has more merit because you are there with me. Thank you for being who you are.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AV	Autonomous Vehicle
AVLL	Autonomous Vehicle Lane Location
BPR	Bureau of Public Roads
CACC	Cooperative Adaptive Cruise Control
CAV	Connected Autonomous Vehicle
DNDP	Discrete Network Design Problem
DTA	Dynamic Traffic Assignment
EUAC	Equivalent Uniform Annual Cost
EV	Electric Vehicle
GHG	Greenhouse Gas
HDV	Human Driven Vehicle
ICEV	Internal Combustion Engine Vehicle
KKT	Karush-Kuhn-Tucker
MO	Mobility Considerations Only
MPCC	Mathematical Problem with Complementarity Constraints
NDP	Network Design Problem
NE	Network Equilibrium
O-D	Origin-Demand
SAVLL	Sustainable Autonomous Vehicle Lane Location
SF	Sioux Falls
SO	System Optimal
UE	User Equilibrium
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-External (all other entities)
VI(P)	Variational Inequality (Problem)
VOT	Value of Time

ABSTRACT

Autonomous vehicles (AVs) are a disruptive technology that is expected to vastly change the current transportation system. AV potential benefits in terms of safety, mobility, efficiency and other impacts types have been documented in the literature. AVs are expected to increase travel demand due to the enhanced ease of making trips and provision of mobility to people currently with travel-limiting disabilities. The potential increase in travel demand, with its attendant congestion, may probably be offset by the transportation network capacity increase due to the reduced operational headways between AVs. However, such capacity benefits can be fully realized only when AVs fully saturate the market, because operating at low headways may be unsafe for Human Driven Vehicles (HDVs). Thus, to promote AV ownership while capturing the capacity benefits of an AV-only traffic stream, the conversion of traditional lanes to AV-exclusive use is prescribed often. In the AV-exclusive lanes, the vehicles can operate at reduced headways and at higher speeds, sharply increasing throughput. However, the metric used frequently by researchers for AV-exclusive lane evaluation is the total system travel time. AV-exclusive lanes may appear to be beneficial in terms of total system travel time but may come at a cost of environmental protection and social equity, the other two elements of sustainable development. Appropriating HDV lanes for AV-exclusive use will cause congestion on HDV lanes thereby increasing their emissions. Further, the AVs benefits may be accompanied by increased cost of HDV travel, which raises questions about equity. This thesis therefore presents a sustainable AV-exclusive lane deployment strategy by formulating and solving a multicriteria bi-level optimization problem with equity-related constraints. Mathematically, the problem is described as a discrete network design problem. Recognizing the difficulty of solving this NIP hard problem, the thesis combines the active set method with heuristic conditionalities to improve computational efficiency. The thesis's framework can be used by agencies for evaluation and decision support regarding AV-exclusive lane deployment in a manner that fosters long-term sustainability.

CHAPTER 1. INTRODUCTION

1.1 Thesis Background and Motivation

Prelude

Autonomous vehicles are a potentially disruptive technology that are expected to have significant inherent benefits that are largely absent in the traditional human-driven vehicles (HDVs) (Gao et al., 2016; McGuckin et al., 2017; USDOT, 2019). Recent studies suggest, for example, that AV technologies can facilitate significant improvements in various aspects including safety, mobility, energy, and efficiency (Fagnant and Kockelman, 2015; Greenblatt and Saxena, 2015; Litman, 2014; Stephens et al., 2017; Tientrakool et al., 2011). Due to the uncertainty associated with the prospective impacts of AVs on the transportation system, it is needed to carry out thorough evaluation and appropriate governmental interventions to facilitate the seamless incorporation of this the disruptive technology in existing practice (AASHTO, 2018; FHWA, 2018; USDOT, 2019). Preparation for AV operations is taking place through a number of activities and initiatives in the academia, industry, and government; these activities can be placed in the following categories: enabling technologies, policy and planning, human factors, infrastructure design and management, operations and controls, modeling and implementation. For the most part, this thesis addresses primarily the infrastructure design and management. Nevertheless, there are some overlaps of this thesis with the other activity categories – AV policy and planning, and AV enabling technologies – as explained in subsequent chapters of the thesis.

Planning for AVs

Infrastructure preparedness for AVs is a primary concern of transportation agencies (AASHTO, 2018; FHWA, 2018; Saeed, 2019; USDOT, 2019). At the current time, highway infrastructure agencies already grapple multiple issues associated with the existing highway transportation infrastructure, including increased inventories and higher traffic loading due to increasing populations, and inadequate funds due to declining revenues from the fuel tax. The advent of AVs will require new construction or retrofit investments to existing facilities so that AVs can be accommodated without affecting the mobility and safety of not only AVs but also that of HDVs. This is will exacerbate an already tight funding situation. For this reason, it is imperative for highway agencies to study infrastructure preparation for AVs; that way, cost-effective solutions can be identified (so that the needed funding can be reliably estimated and solicited from the legislation or other funding sources and mechanisms, and also to facilitate the evaluation and implementation of specific AV investment choices from the context of sustainable development.

The provision of any new infrastructure begins with a need assessment phase and planning phase (Labi, 2014). For the planning phase, Goodman and Hastak (Goodman and Hastak, 2006) identified the planning criteria in four "levels"): Level 1, where the planner considers the proposed location, configuration, and orientation of the infrastructure, its expected functions, costs, and capacities, costs, and in the case of tolled infrastructure, revenues. At Level 2, the planner considers the Level 1 criteria and life cycle economic efficiency of the project in terms of the net present value, for example. At Level 3, the level 2 criteria and environmental, social, and cultural criteria are considered. Then at Level 4, the Level 3 criteria and emerging criteria such as system resilience or vulnerability to natural or man-made threats including climate change, and uncertainty. In certain cases, a lower level study may include at least one criterion from the criteria at an upper level. As will be seen in subsequent chapters, this thesis addresses aspects of Level 2 (travel time) and Level 3 (environmental and social).

Standard texts in the infrastructure planning discipline including Goodman and Hastak, Parkin and Sharman, and Ramasubramanian and Albrecht espouse certain principles of infrastructure planning that are critical to the long-term technical, financial, and political success of the infrastructure (Goodman and Hastak, 2015; Parkin and Sharma, 1999; Ramasubramanian and Albrecht, 2018). This is true of all types of facilities including AV lanes. These principles include pursuit of farsightedness, consideration of (and communication with) the multiple stakeholders including the public, establishment of multiple alternative plans, integration and holism with existing and anticipated land uses, and accommodation of uncertainty. If these principles are followed, infrastructure agencies will be placed in a better position to maximize the anticipated benefits of AVs (while minimizing their expected disadvantages) that are associated with economic productivity, the environment, energy, safety, accessibility, and mobility.

One of the basic questions that will be addressed in any plan towards AV infrastructure will be whether to appropriate an existing human-driven lane for AV use or whether to construct a new lane. The former will likely be fraught with public opposition unless public buy-in is obtained early in the planning process. Riggs et al. provided an insightful discussion of the impacts of autonomous vehicles on the built environment in terms of various urban contexts (Riggs et al., 2019).

AV Enabling Technologies and Their Implications

Enabling technologies refer to the hardware, software, vehicle propulsion source (such as electric) that facilitate the safe and efficient deployment of AVs. With their sensing technology, AVs can fully detect and react to their surroundings in such a way that outperforms human drivers (Van Brummelen et al., 2018). An example is the reaction times to external stimuli; human drivers depend on a significant amount of perception-reaction time prior to making maneuvers and maneuver decisions (Triggs and Harris, 1982). An obvious benefit of the superior reaction time of AVs is the ability to react to emergency situations more quickly compared to HDVs, thus lowering the likelihood of collision. Further, the short reaction time enables AVs to perform operational endeavors such as safe and effective platooning. Platooning allows long chains of vehicles to form and travel at reduced headways with reduced likelihood of collision and string instability, which would otherwise cause significant congestion or crashes. In practice, the formation of platoons could translate to greater throughput. Further, given enhanced string stability, traffic streams comprised of both AVs and HDVs can help avoid stop-and-go traffic, thereby reducing tailpipe emissions (Zhang et al., 2011).

Further, it is expected that AVs will be connected electronically (through information and communication technologies) to other vehicles and roadway and other infrastructure (Gao et al., 2016; Talebpour and Mahmassani, 2016). Therefore, additional benefits can be obtained through connectivity. With their ability to communicate with each other, the roadway infrastructure, and pedestrians via a central cloud, AVs will be expected to make decisions solely or jointly based on real-time receipt of shared information (Kim et al., 2015). The implications of such connectivity capabilities are significant. While AV sensing technology allows the vehicle to make decisions at an individual level by using locally available information (position and velocity of surrounding vehicles, objects on the road, etc.), connectivity allows the AVs to have information from the entire network and make decisions with other vehicles. In practice, this means that even longer platoons can be established on the road with greater reliability of increases in safety and string stability (string instability is the property where small disturbances are amplified along a chain of vehicles to cause stop-and-go traffic). Improving string stability by minimizing stop-and-go traffic, can help reduce traffic emissions significantly (Elfar et al., 2018; Kreidieh et al., 2018; Stern et al., 2018; Talebpour et al., 2017; Talebpour and Mahmassani, 2016). Therefore, connected and automated vehicles (CAVs) will be expected to dramatically improve travel time, safety, and reduce emissions.

Along with features that enhance connectivity and automation, another enabling technology is alternative sources of propulsion power, specifically, electric propulsion. In recent years, electric vehicle adoption has grown rapidly due to improvements in battery technology and environmental concerns (Cordera et al., 2019; Gao et al., 2016). As such, leading AV manufacturers, such as Tesla and Mercedes-Benz, developing AVs with electric engines. Therefore, it may be realistic to assume that most CAVs will also be EVs. The combination of CAV technology with electric propulsion is expected to reduce emissions significantly compared to the traditional traffic stream that is comprised mostly of human-driven cars that have internal combustion engines (ICVs).

Role of the Transportation Agency in the Era of Autonomous Vehicles

Given these enabling technologies and their implications on individual efficiency and safety, the transportation agencies such as the USDOT and FHWA have begun studying and preparing for the emergence of AVs in the transportation system (McGuckin et al., 2017; USDOT, 2019). However, it is important to further evaluate and determine whether the agencies should promote AV ownership to the public. While the inherent benefits of AVs due to their enabling technologies obviously benefits the general public, the transportation agency is more concerned about AVs impacts on the transportation system as a whole. Even without considering the emergence of AVs, many researchers project that congestion will continue to increase in the future due to increased urbanization and growing global population (Polzin et al., 2004). Researchers have shown that the introduction of AVs will likely lead to increased travel demand and possibly congestion (Childress et al., 2015; Fagnant and Kockelman, 2014; Harb et al., 2018; Harper et al., 2016; LaMondia et al., 2016; Levin and Boyles, 2015; Litman, 2014; Mahmassani, 2014; Menon et al., 2019). This may worsen emissions and decrease travel safety. Therefore, the agency must carefully assess the effect of AVs at the systemic level in both the near and far future. It may be costly to undertake investments without a complete understanding of the systemic impact of AVs to all stakeholders. To assess the effect of AVs in the short and long term, it is necessary to understand the transportation system as an interrelationship between the transportation supply and the travel demand (R. et al., 1956). If the travel demand is not met by the network capacity, then congestion will occur, and systemic efficiency will consequently suffer.

The potential increase in travel demand in the AV era (Azevedo et al., 2016; Fagnant and Kockelman, 2014; Harb et al., 2018; Harper et al., 2016; Labi et al., 2015; Menon et al., 2019) can be attributed to the ease of travel and elimination of the need for on a driver. Without the stress of driving, locating parking spots, and (potentially) traveling a last mile to the destination, it is anticipated that people will find travel much easier. As such, there is reduced deterrence from making trips, ultimately increasing the total travel demand. Further, people who depend on others for mobility such as children, seniors, and physically impaired people, can make trips without the assistance of someone else. As such, the total number of trips made will increase due to AVs.

For the transportation agency, infrastructure supply can be measured in terms of the road capacity. The agency has direct control of supply, as it is within their authority to construct new roads and bridges. With the introduction of AVs, the transportation agency can potentially increase the supply of highways. Advanced sensing and communication technologies allow AVs to operate at small headways and at increased speeds, thereby allowing more vehicles to occupy a given corridor (Tientrakool et al., 2011). As such, the transportation agency may be inclined to promote AV ownership in order to harness the network capacity benefits. However, the capacity benefits will not exist during the mixed flow phase of AVs and HDVs, as AVs cannot be expected to maintain short headways with HDVs due to safety concerns (Talebpour et al., 2017; Van Arem et al., 2006; Yu et al., 2019).

The transportation agency can promote full market penetration of AVs by providing AV-exclusive lanes. Doing this will lead to higher throughput and lower travel time at the AV lane compared to the traditional (HDV) lanes, and will provide an incentive for AV ownership (Chen et al., 2016b; Hedrick et al., 1994; Shladover, 1992; Talebpour et al., 2017; Van Arem et al., 2006; Yu et al., 2019). Further, if exclusive AV lanes improve system-level goals such as travel time, emission reduction, equity protection, and safety improvements, it will simultaneously yield systemic benefits, and promote AVs.

Transition phase strategies that are associated with separation of HDV and AV include the following options: (1) New construction of AV-exclusive lanes and (2) Conversion of traditional lanes for AV-exclusive use.

With regard to the new-construction option, agencies have the option of lateral location, vertical location above existing lane(s), and vertical location below existing lane(s). However, constructing new infrastructure is costly, and the agency may seek to reduce costs by implementing tolling or considering a less costly alternative such as conversion of traditional lanes for AV-exclusive use. Further, the deployment is not immediate and dependent on construction duration, during which the traffic operations will be disrupted.

With regard to the conversion option, minimal infrastructure direct and indirect costs will be involved, due to the avoidance of system downtime due to construction, workzones and travel delays, purchase of land, and right-of-way clearance problems. However, it does raise a new concern by taking away capacity from HDVs.

Table 1 presents a summary of the pros and cons of infrastructure preparation options.

Table 1: Merits and demerits of various preparation options for AV infrastructure

Infrastructure Preparation Options	**Pros**	**Cons**
New construction of tolls for AV-exclusive use	Promotes AV ownership	Requires construction and land
	Separates AVs from HDVs	Deployment is not immediate (construction time)
	Does not take away capacity from HDVs	Disrupts traffic operations during construction
	Tolls can cover some or all parts of the construction costs	
Conversion of traditional lanes for AV-exclusive use	Promotes AV ownership	Takes away capacity from HDVs
	Separates AVs from HDVs	
	Does not require construction or land	

The Context of Sustainability

The subject of AV-exclusive lanes is being increasingly studied by researchers. The California PATH programs was one the first to present the concept of AV-exclusive lanes and platooning, which can benefit throughput of the system (Bergenhem et al., 2012; Hedrick et al., 1994; Shladover, 1992). Further, Talebpour et al. (Talebpour et al., 2017) assessed the mobility impact of AVs in terms of travel time and travel time reliability. Similarly, Chen et al. (Chen et al., 2016b) assessed the efficacy of AV-exclusive lanes in improving total travel time over a long-term planning horizon. Yu et al. (Yu et al., 2019) investigated the safety benefits of AV-exclusive lanes.

Much of literature is focused on single systemic objectives (most of these focus on mobility). This thesis uses criteria that are related to the three elements of sustainable development established by the United Nations (UN): economic impact, environmental protection, and social equity. The Brundtland Report defines sustainable development as "…development that meets the needs of the present without compromising the ability of the future generations to meet their own needs," (Brundtland et al., 1987; Keeble, 1988). Sustainable development is achieved when all three elements are satisfied (Figure 1). In certain cases, the accomplishment of one element helps address at least one of the two other elements; for example, Connolly et al. determined that emission reduction can help foster distributional equity (Connolly et al., 2018). The UN highlights the importance of balancing these three elements for sustainable development (Ferranti, 2019; United Nations, 2017, 2015, 2007). The UN further emphasizes the need for sustainability considerations by establishing their sustainable development goals (UN SDG), one of which is developing sustainable cities and communities (United Nations, 2017). Therefore, the methodology presented in this thesis is consistent with the goals of sustainable development, specifically, economic impact, environmental protection, and social equity.

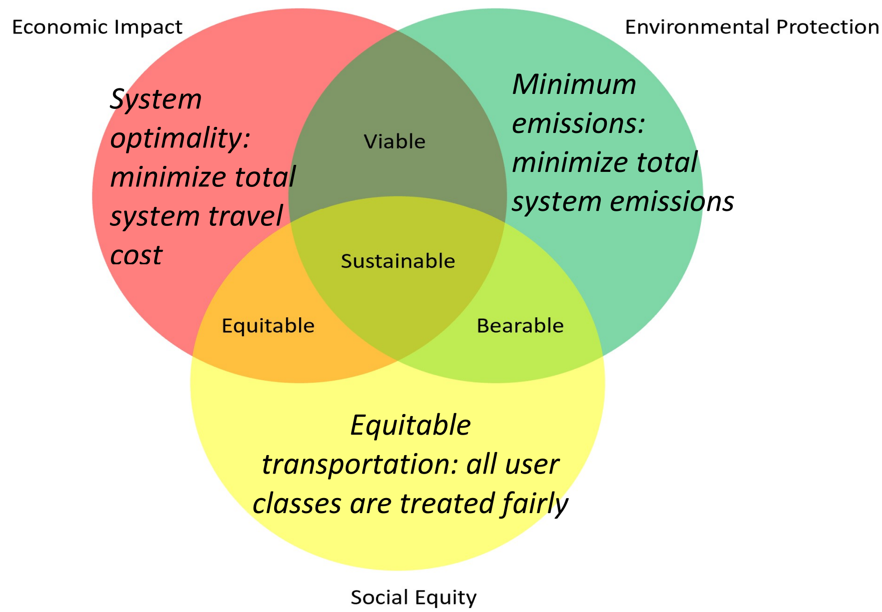

Figure 1: The three elements of sustainable development and their confluences (adapted from Barbier, 1987)

Therefore, this thesis advocates that in preparing for AV through initiatives and projects such as AV-only lane deployment, transportation agencies should strive to address the goals of sustainable development.

Economic Efficiency

Congestion pricing and managed-lane policies often directly impact the travel time of travelers. Given the travelers' value of travel time, the changes in travel time due to an action from the transportation agency can be monetized (Sinha and Labi, 2007). In reality, the monetized travel cost can come from hours of productivity missed due to travelling, and the system-level economic impact can be evaluated. AV-exclusive lane deployment will produce similar economic benefits for AVs because the total system travel time of the AV traveler will be reduced. Therefore, AV travelers will be afforded more time of their day to be economically or socially productive. The aggregate additional productive hours gained from AV-exclusive lanes can translate into economic efficiency. For AV drivers, not only is the total system travel time reduced but also the AV driver can engage in productive activity during the trip. Nevertheless, Singleton (2019) questioned whether AV drivers will really use the in-vehicle trip time in a productive manner.

Environmental Impact

Ever since emissions became a key consideration in transportation systems evaluation, researchers and transport agencies have grappled with ways to reduce transportation emissions by reducing or redistributing demand, increase the quantity or quality of supply, or both. These have been done through physical interventions such as EV-lane or HOV-lane construction or appropriation, travel policy, and so on (Sinha and Labi, 2007). Other ways to do this include promotion of ridesharing and the implementation of tradable credit schemes (Miralinaghi and Peeta, 2019, 2016; Miralinaghi, 2018). In the context of AVs, excusive AV-only lanes can be a promising solution. The environmental impact of AV-exclusive lane deployment can be attributed to three phenomena: (a) reduced stop-and-go instances at the AV exclusive lane compared with the HDV lane (Barth and Boriboonsomsin, 2009, 2008a; Veurman et al., 2002; Zhang et al., 2011), (b) elimination of tailpipe emissions at the AV lanes because all AVs are assumed to be EVs, and (c) increased emission due to increased congestion in traditional (HDV) lanes (Chen et al., 2016b; Weinstein and Sciara, 2006). The net emissions effect of the AV-exclusive lane be positive (emissions decrease) or negative (emissions increase). Therefore, it is beneficial for the transportation agency to have a framework to analyze and alternative deployment plans so they can identify the plan that minimizes the negative environmental effects (on the HDV lanes) and maximizes the emissions reduction effects (on the AV lanes).

Social Equity Concerns

Social equity and environmental justice are key considerations in any transportation project evaluation problem (Sinha and Labi, 2007). In the context of AV-exclusive lane deployment, social equity concerns arise from sources including from the differences between AV and HDV purchase costs. Studies suggest that in their initial phase of deployment, AVs will be more readily adopted by the educated and wealthier segments of the society (Abraham et al., 2016; Menon et al., 2019; Zhang et al., 2018). In that case, in the initial phases of AV operations, the primary beneficiary of any AV-exclusive lane deployment will be the wealthier segments of the population. This raises social equity concerns, which will be expected to arise irrespective of the deployment strategy applied, that is, whether it involves new lane construction or conversion of a traditional lane. In the case of the former, the transportation agency often uses tax-payer money to benefit a specific social class at the expense of another. On the other hand, conversion of traditional lanes for AV-exclusive use can cause increased congestion in the traditional lanes due to their overall reduced capacity. As such, the transportation agency needs to strategically mitigate any inequity effects and therefore minimize possible public opposition to AV-exclusive lanes.

1.2 Problem Statement and Research Contributions

Due to the rapid advancements in AV technology, government transportation agencies, such as the Federal Highway Administration (FHWA), emphasize the urgency in preparing the proper infrastructure and policy for AVs (FHWA, 2018; McGuckin et al., 2017). However, the goals and constraints of an agency can often create barriers to initiatives that increase AV infrastructure readiness. Financial limitations often constrain agencies from investing in high-cost projects that are associated with AV-infrastructure preparation. Multiple objectives due to the large number of stakeholders and their concerns also create challenges to effective long-term planning. As such, there is a need for a decision-support model that flexibly allows the transportation agency to examine options regarding infrastructure preparation of AVs.

In the literature, there is discussion about AV-exclusive lanes as a policy and its effectiveness in addressing some of these concerns. The conversion of traditional lanes for AV-exclusive use can be much lower compared to new lane construction, and several studies have examined the efficacy of AV-exclusive lanes in minimizing the total system travel time. However, focusing on only total system travel time can be considered rather short sighted and not comprehensive. While conversion of traditional lanes for AV-exclusive use can be financially feasible from the agency's perspective, the increased travel time in traditional lanes can cause significant increases in HDV travel time. The resulting congestion involving the internal combustion engine HDVs causes increased emissions and exacerbates social equity concerns. Clearly, there is a need for a comprehensive decision framework for AV-exclusive lane deployment that considers social equity, environmental protection, and economic feasibility. The thesis presents a sustainable AV-exclusive lane location formulation intended for evaluating AV-exclusive lane deployment initiatives for the following reasons:

- AV promotion: the transportation agency may be interested in promoting AV adoption due to the prospective benefits of AVs in terms of mobility, safety, and environmental protection.
- Meeting sustainability goals

- Low implementation cost: the AV-exclusive lane deployment presented in this study requires conversion of traditional lanes, thereby avoiding higher cost alternatives.

This thesis has a two-fold contribution: it provides an objective framework that holistically considers sustainability in the context of AV-exclusive lane deployment. Further, the thesis also seeks to incorporate user and vehicle class heterogeneity of travel demand.

1.3 Study Objectives

The primary objective of this thesis is to develop a multi-period AV-exclusive lane deployment scheme that optimally addresses the three elements of sustainable development, i.e., improving economic efficiency, reducing environmental impact, and managing social equity. The thesis also extends a robust solution approach to solve this rather difficult mathematical problem.

1.4 Organization of the Thesis

This thesis consists of six chapters. Chapter 2 presents a comprehensive literature review of AV technology and effects, AV-exclusive lanes and their impacts, considerations of social equity and emission reduction in managed lanes, and solution approaches to the network optimization problem associated with the study objective. Chapter 3 proposes the mathematical model for the AV-exclusive lane deployment problem considering the three elements of sustainability as the system-level goals. The thesis duly states any assumptions that were made in formulating the problem and offering a solution. Chapter 4 of the thesis describes the solution approach to solve the problem, which involves reformulating the MPCC as a restricted-set problem. It also provides an application of the approach to hypothetical and real-life transportation networks, network characteristics of which are described in detail. Chapter 5 presents the results and the practical implications of the solution approach and the study limitations. Chapter 6 concludes the study with a brief summary, and some insights are presented regarding future research opportunities from this research.

CHAPTER 2. REVIEW OF LITERATURE

2.1 Introduction

As discussed in the introductory chapter of this thesis, the advent of autonomous vehicle operations is expected to significantly influence the operational performance of the highway transportation system. This is will likely happen in a number of ways, such as travel demand, safety, mobility (specifically, travel time), economic efficiency, economic development, land use, emissions, noise, social contexts that have been identified and discussed extensively in the literature (AASHTO, 2018; Hill and Garrett, 2011; Litman, 2014; USDOT, 2019). In this literature review, the focus is on the AV impacts on travel demand and behavior, network operational performance, and the environment. Consequently, this chapter presents a review of literature on AV-exclusive lane impacts on travel time which is best evaluated from the perspective of traffic assignment.

2.2 AV Impact on Travel Demand and Behavior

With regard to the various impacts of AV operations, probably the most studied impact is that of travel demand. It has been postulated that AVs will provide more benefits to travelers compared to HDVs. For example, dependent travelers, that is, those who previously relied on another driver to drive them in the pre-AV era, will be able to make trips independently in the era of AVs. Figure 2 (adapted from the USDOT and FHWA 2017 National Household Survey results) presents on the travel-related options for persons with travel-limiting disabilities (USDOT, 2019). A majority of the respondents had stated that they require assistance for making their trips. In the prospective era of AVs, these individuals will be able to make the trips they were unable to make in the pre-AV era. Further, human drivers will be relieved of driving errands such as pick-ups and drop-offs.

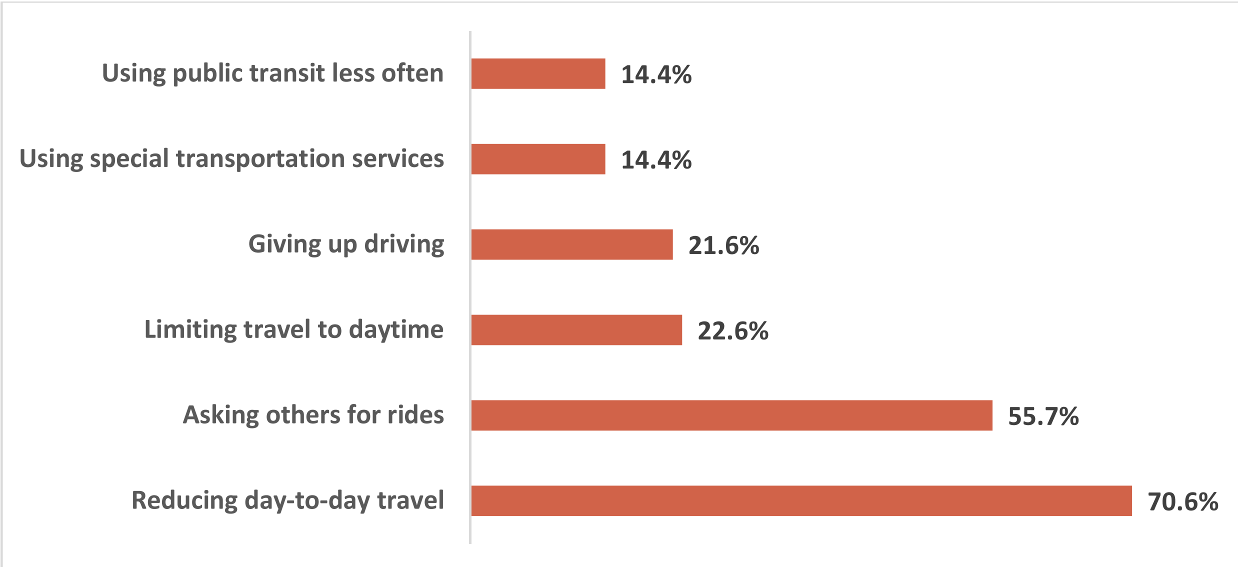

Figure 2: Travel-related options for persons with travel-limiting disabilities (adapted from USDOT, 2019)

For these and other reasons, several studies have predicted that AVs can be expected to increase the total travel demand regarding highway transportation (Childress et al., 2015; Fagnant and Kockelman, 2014; Gkartzonikas and Gkritza, 2019; Harb et al., 2018; Harper et al., 2016; LaMondia et al., 2016; Levin and Boyles, 2015; Litman, 2014; Mahmassani, 2014; Menon et al., 2019). LaMondia et al. (LaMondia et al., 2016) predicted that AVs can shift demand from personal vehicles and air travel equally for short-distance trips but demonstrates that travelers may prefer air travel for long-distance trips. Perhaps the most insightful study in the context of travel demand impacts of AVs, is that of Harb et al. (Harb et al., 2018) who conducted a naturalistic experiment where travelers were provided with 60 hours of free chauffer services to mimic AV operations, and found that the participants, on average, made up to 58% more trips compared to the no-AV scenario, and the total vehicle-miles traveled increased by 85%. They also found that the increase in travel demand and changes in travel behavior were due to factors including: increased travel demand from participants in the AV era who independently made trips, the emergence of "zero-occupancy trips" where there is no passenger in the vehicle for any reason including making errands, and the eliminated stress of driving that enabled the participants to make leisure-trips more frequently. Levin et al. (Levin and Boyles, 2015) showed that AVs can induce a significant modal shift, decreasing transit ridership increasing personal trips. They demonstrated that the increase in lane capacity due to AV-operations at reduced headways can offset the increase in travel demand thereby mitigating congestion overall.

2.3 AV Impact on Network Capacity and Operations

In a report sponsored by the FHWA, McGuckin et al. (2017) highlighted the need to incorporate CAVs in existing networks in a way that effectively improves network operations overall (McGuckin et al., 2017). The study report also stated that vehicle connectivity and the propagation of corollary traffic-related information can significantly enhance corridor performance and recommended research to maximize AV benefits to transportation network operations. As noted by Mahmassani (2014), changes in travel demand and travel behavior, combined with AV operational capabilities, are expected to significantly influence traffic stream characteristics (Mahmassani, 2014). The researcher added that the performance of the overall network (comprising AV and HDV traffic) can be affected by increases in travel demand and demand patterns, as well as routing and scheduling for individual AVs and shared AVs.

An often-discussed benefit of AVs is the beneficial changes it will bring to network capacity. To understand the impact of AVs on the network capacity, Tientrakool et al. (Tientrakool et al., 2011) demonstrated that a traffic stream composed of vehicles with sensing technology can operate with reduced headways without compromising safety, allowing a 43% increase in lane capacity. Further, they demonstrated that a traffic stream composed of vehicles which additionally possess vehicle-to-vehicle communications can increase lane capacity by up to 273%. A limitation of the Tientrakool et al (2011) study is that it imposed rule-based controls not only to reduce headways between vehicles but also to prevent collision. As such, there may be heterogeneity or time-delay of information in the real world which may prevent lane capacity from reaching such high levels. Nevertheless, the Tientrakool et al. (2011) study suggests that there exists a theoretical maximum capacity benefit that can be earned from a homogeneous traffic stream composed of CAVs only.

Regarding the prospective travel time benefits of AVs, several studies have shown that automation can improve the efficiency of intersections (Dresner and Stone, 2008; Ilgin Guler et al., 2014; Li et al., 2015). These studies primarily employed microsimulations to show that vehicle automation can reduce intersection delays, and therefore, improve throughput in all directions.

2.4 AV Impact on Greenhouse Gas Emissions

The United States Environmental Protection Agency continues to recognize the transportation sector as the largest contributor to GHG emissions (EPA, 2015). For this reason, there have been several initiatives to reduce vehicular emissions by regulating automobile manufacturers and promoting fuel efficient vehicles to consumers (EPA, n.d.; Sinha and Labi, 2007). However, in spite of the recent improvements in vehicle fuel efficiency due to policy, traffic-related factors including congestion and aggressive driving still causes significant fuel consumption and therefore, emissions. It is anticipated that electrically propulsion, and vehicle connectivity and automation can help mitigate such externalities.

Several researchers have investigated the emissions reduction benefits of AVs as a disaggregate, individual vehicle operation or as an aggregate system of connected vehicles (Fagnant and Kockelman, 2014; Greenblatt and Saxena, 2015; Lee and Madanat, 2017; Talebpour et al., 2017). From the perspective of an individual vehicle, AVs are being developed and studied in industry and academia to perform various controller functions to achieve objectives including minimizing travel time (Huegle et al., 2019), mimicking human drivers (Zhu et al., 2018), and stabilizing the neighboring traffic (Cui et al., 2017; Kreidieh et al., 2018; Stern et al., 2018; Wu et al., 2018). The opportunity for emissions mitigation exists with AV controllers focused on stabilizing nearby traffic. As described previously, vehicular string instability is a phenomenon that arises from spontaneous human driver actions, such as hard braking or sudden acceleration (Sugiyamal et al., 2008). The perturbations that occur due to such spontaneous human driver actions can become amplified along a string of vehicles. Thus, the flow of vehicles are disrupted from free flow into stop-and-go flow due to the amplification of the disturbance as it travels downstream (Orosz et al., 2010). String stable traffic refers to when a string of vehicles travel at uniform, free-flow speed. Using an AV controller that can resist the amplification of the disturbances to retain string stability, Stern et al showed the efficacy of AVs in reducing emissions at a disaggregate, vehicular level (Stern et al., 2018). They determined that AVs can increase stability in a short string of vehicles in a lane, thereby reducing the frequency of stop-and-go traffic. Stop-and-go traffic has been thoroughly studied in literature and has been shown to increase vehicular emissions compared to free-flow traffic (Barth and Boriboonsomsin, 2009, 2008b; Veurman et al., 2002); therefore, an individual AV can significantly reduce the emissions of its surrounding vehicles by stabilizing the traffic flow.

At an aggregate level, a system of connected AVs can enhance string stability due to information propagation and joint decision making among the vehicles. Greenblatt and Saxena demonstrated that, notwithstanding a potential increase in travel-miles due to on-demand mobility, an autonomous taxi system can reduce greenhouse-gas emissions by up to 94% below current vehicles through the system-level synergies associated with AV technologies (Greenblatt and Saxena, 2015). Further, Greenblatt and Shaheen (Greenblatt and Shaheen, 2015) suggested that a system of shared AVs can encourage personal-vehicle relinquishment and thus further reduce GHG emissions as well as vehicle miles traveled.

As a result of the increasing efficiency of EV batteries and the increased societal desire to reduce dependence on fossil fuels (Greenblatt and Saxena, 2015), EV technology has evolved quickly as a realistic option for travelers. Further, current versions of electric engine technology are such that these engines, similar to internal combustion engines, now provide nearly instantaneous torque, meaning that vehicle controllers receive immediate feedback from their input signal without a delay for the engine response. For these two reasons, all leading AV manufacturers such as Mercedes-Benz and Tesla select electric engines for their AVs. Tech firms developing AV technology, such as Waymo and Aptiv, partner with vehicle manufacturers to modify hybrid electric vehicles to test their AVs. Therefore, for research purposes, it can be considered appropriate to assume that all AVs will simultaneously be EVs.

The impact of electric vehicles, irrespective of the automation level, is expected to be significant in any transportation system. Several researchers have studied the effects of electric vehicles, including their impact on greenhouse gas emissions (Lee and Madanat, 2017; McCarthy and Yang, 2010; Perujo and Ciuffo, 2010), the energy grid (Clement-Nyns et al., 2010; Perujo and Ciuffo, 2010; Richardson, 2013), and the transportation network design (Chen et al., 2016a; Hess et al., 2012; Lee and Madanat, 2017; Qin and Zhang, 2011; Sarker et al., 2015).

The EV impact of particular importance to this study is the transportation network impact. Lee and Madanat presented a method of locating optimal EV charging stations in an urban grid while considering practical constraints such as peak hour demand and budgetary constraints (Lee and Madanat, 2017). Further, they developed an optimal deployment scheme to simultaneously minimize emissions as well as user costs. While they did not consider AVs in their study, the introduction of AVs adds complexity to the problem as travelers may dispatch their empty AVs to charging stations, which may increase congestion in the network. As such, it seems evident that transportation agencies need to be proactive in preparing the highway infrastructure and policy for optimal operational efficiency of both AVs and HDVs.

2.5 AV Impact on Transportation Infrastructure

Transportation agencies are preparing for safe, seamless entry of AVs (USDOT, 2019). Most of the existing transportation infrastructure is designed to accommodate human drivers and may not be the most effective in receiving AV operations. Infrastructure deficiencies continue to pose one of the biggest challenges to AV implementation (KPMG, 2018; McFarland, 2015). Thus, the agencies may endeavor to address the following critical questions (Saeed, 2019):

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

While human drivers may be able to discern infrastructure deficiencies such as faded lane markings or defective stop signs, AVs may not be able to perform satisfactorily in such adverse situations. For example, it was observed in 2015 that Tesla's autopilot was unable to properly navigate itself where lane markings were in poor condition (McFarland, 2015). Also, Eykholt et al. discovered that simple modifications, as shown in Figure 3, could cause AVs to incorrectly decipher informational infrastructure and conduct inappropriate maneuvers (in this figure, the image was mischaracterized as a 45-mph sign (Eykholt et al., 2017)). In both cases, the safety of the AV and surrounding HDVs are compromised.

Figure 3: Example of stop sign vandalism that causes AV confusion (Eykholt et al., 2017)

Therefore, the transportation agency needs to prepare the infrastructure to be resilient to the forces of damage and destruction, so that AV operations can be facilitated.

2.6 Using Network Design and Managed Lanes Problems to Evaluate AV Impacts on Networks

From research and planning perspectives, the infrastructure preparations can be done through network design and managed lane strategies. The integration of AVs, personal or shared, requires a rethinking of the traditional network design problem (NDP) and managed lane strategies. Traditionally, network design and traffic assignment problems have been addressed using an objective function that minimizes the total system travel time (i.e., system optimal (SO) traffic assignment) or to minimize the individual traveler travel time (i.e., user equilibrium (UE) traffic assignment). To reduce congestion, transportation agencies have implemented congestion pricing strategies such as managed lanes and tolling, thereby driving UE traffic assignment closer to SO traffic assignment. This section presents a review of literature on network design and managed lanes in the context of AVs.

The idea behind NDPs is to identify, evaluate, and implement modifications to the transportation network to serve purposes such as the reduction of system delay. In general, the network modifications include construction of new roads as well as expansion of existing ones to increase the total capacity of the network. One of the first discussions on NDPs is from Beckmann and his team of researchers who discussed the interrelationships between travel demand and changes to network capacity (Beckmann et al., 1956). Subsequently, several studies were carried out both in the problem formulation as well as in solution approaches for these computationally intensive problems (Bell and Iida, 1997; Boyce and Janson, 1980; Chiou, 2005; Lou et al., 2009; Meng et al., 2001; Yang and Bell, 1998).

In literature, NDPs can be classified into two domains: continuous NDPs (CNDP), wherein the capacity changes are continuous; and discrete NDPs (DNDP), wherein the capacity changes are discrete. The difference between DNDPs and CNDPs pose different practical implications and require different approaches in solving the problems A key difference between CNDPs and DNDPs is that CNDPs can be used to determine the optimal link capacities, whereas DNDPs can be used to determine the optimal locations of capacity expansion.

The NDPs are often formulated as a bi-level optimization problem, wherein the upper-level models the decision-making of the transportation agency who modifies the transportation network, and the lower-level models the behavior of the travelers. The upper-level objective is the purpose of the transportation agency, which most commonly, is to minimize total system travel time. The lower-level is typically a UE traffic assignment problem, where the link flows on the network are obtained from a solution of demand/performance function equilibrium (Sheffi, 1984). The performance of a link is typically the Bureau of Public Roads link performance function, which is a nonlinear equation yielding travel time as a function of link capacity and flow. The equilibrium between demand and performance satisfies Wardrop's principles (Wardrop, 1952), which state that equilibrium is reached when no traveler can further reduce their travel time by changing their route.

Solving NDPs is computationally intensive (Yang and Bell, 1998), and the context of the problem can significantly increase the problem complexity. As such, many algorithms have been presented in literature to efficiently obtain optimal solutions. One of the earliest solution approaches is the branch-and-bound technique, presented by Land and Doig (Land and Doig, 2010) and applied to DNDPs by Leblanc (LeBlanc et al., 1975). This approach iteratively constructs a tree structure from a partial solution using branching, that is, selecting a node and creating two new nodes from it. At each iteration, the branch is evaluated against its bounds and is discarded if it does not provide an improvement to the rest of the solution. However, the branch-and-bound algorithm is still computationally intensive and difficult to apply under various uncertainties.

To address uncertainties, specifically with respect to demand, Ukkusuri et al. (Ukkusuri et al., 2007) utilized a heuristic approach via genetic algorithm and solved for a network design which is robust to demand. However, the authors acknowledged that the stopping criteria is difficult to define, and they implemented a predefined number of generations as the stopping criteria. As such, using a genetic algorithm to solve NDPs is often criticized due to the weakness of the stopping criteria. To address the issue of convergence, Lou et al. (Lou et al., 2009) applied the cutting-plane approach to converges to a globally optimal solution in a finite number of iterations. This approach is an application of the active set algorithm presented by Zhang and his team of researchers who implemented UE flow as a variational inequality (VI) and eliminated binary or integer variables by replacing the VI with the corresponding KKT conditions and complementarity constraints (Zhang et al., 2009). The active set algorithm, which is used in this thesis, is discussed in greater depth in Chapter 4.

A few studies have considered NDPs in the context of AVs. Typically, the motivation behind NDPs in relation to AVs is to control the mixed flow of AVs and HDVs by separating the AVs in exclusive lanes. Providing AV-exclusive lanes allows AVs to operate without interactions, uncertainties, and errors from human drivers.

One of the earliest mentions of AV-exclusive lanes is from Shladover (Shladover, 1992), who presented the idea of an automated highways and discussed their potential benefits. To evaluate the benefits and understand the impacts of providing exclusive lanes to smart vehicles, Van Arem et al. simulated vehicles with cooperative-adaptive cruise control (CACC) in exclusive lanes and found that the average speed of the highway was dependent on the market penetration of vehicles with CACC (Van Arem et al., 2006). To extend this work into the domain of CAVs, Talebpour et al. (2017) performed simulations wherein the AVs were modeled with the CACC algorithm (Van Arem et al., 2006) and the HDVs were modeled with the Intelligent Driver Model (IDM) (Treiber et al., 2000). In their simulations, they found that the travel time reliability depends on the market penetration of AVs. Yu et al. presented a similar experiment but also assessed the safety of AVs in the context of managed lanes (Yu et al., 2019). They found in their simulations that the safety and travel time benefits of AV-exclusive lanes also depends on the market penetration.

As such, the need for modeling market penetration is apparent in evaluating the efficacy of AV-exclusive lanes. In a study that considered endogenous market penetration, Chen et al. characterized AV market penetration as a function of the benefits of AV-exclusive lane deployment (Chen et al., 2016b). The approach used by Chen et al. (2016b) to model AV market penetration applies the advanced traveler information systems adoption model in Yang et al.'s study (Yang and Meng, 2001). Further, the Chen et al. (2019b) study solved the AV-exclusive lane location problem with the active set algorithm by minimizing total system travel time. Another recent paper that solved an NDP for AV-exclusive lanes is Liu and Song who claimed that there may exist uncertainty in flow distributions due to AV impacts on road capacity (Liu and Song, 2019). They applied genetic algorithms to the AV-exclusive lane deployment scheme under worst-case traffic flow distributions. Further, they acknowledged that low market penetration of AVs may cause HDVs in the same corridor to face congestion. As such, they assumed that in case of low AV market penetration, HDVs will pay tolls to utilize the AV-exclusive lanes. However, doing so may cause severe public opposition, as tolling HDVs besides the additional travel cost of capacity reduction could further exacerbate the inequity associated with the introduction of AVs.

Lu et al. (2019) addressed the issue of social equity in the interactions between AVs and HDVs (Lu et al., 2019). Their study determined the optimal vehicular trajectory in an AV-exclusive zone. They presented two formulations: trajectory-based traffic management for scheduling (TTMS) and trajectory-based traffic management for scheduling while considering equity (TTMSE). In the former, the objective was to minimize total system travel time, and in the latter, the objective was similar but additionally prevented large variations in travel time of the users. Using dynamic traffic assignment (DTA), their study provided insights towards optimal routing decisions while managing social equity concerns.

Lamotte and his team of researchers considered DTA in the context of AV-exclusive lanes, considering a bottleneck scenario where the central decision maker can vary the corridor capacity for SAV-exclusive use (Lamotte et al., 2017). Their study presented three allocation strategies that the central decision maker can undertake: free market, welfare-maximization, and profit-maximization. Interestingly, the authors incorporated an endogenous demand split between HDVs and AVs based on the cooperation cost distributed in the population and found that, based on a given socially optimal capacity split, the equilibrium demand split is just as effective in reducing social cost as a socially optimal demand split. However, the authors acknowledged that individual users (not on AVs) may face increased costs.

As such, there exists a gap in literature on optimally deploying AV-exclusive lanes over a planning-horizon that adequately considers sustainability. non-consideration of sustainability concepts in AV-exclusive lane deployment may have severe consequences and prove to be costly in taking remedial action in the future. This thesis intends to address this gap.

Table 2 presents a summary of literature on AV-exclusive lanes.

Table 2: Summary of literature on AV-exclusive lanes

Authors (date)	**Economic Impact**	**Emissions**	**Social Equity**	**Market Penetration**	**Methodology**	**Solution Approach**
Van Arem (2006)	Average Speed	No	No	Constant	Simulation	MIXIC
Talebpour (2016)	Throughput; Reliability	No	No	Constant	Simulation	Micro Simulation
Yu (2019)	Average Speed	No	No	Constant	Simulation	AIMSUN
Chen (2017)	Homogeneous Value of Travel Time	No	No	Endogenous	DNDP	Active-set Algorithm
Liu (2019)		No	No	Constant	RNDP	Genetic Algorithm
Lamotte (2017)	Heterogeneous Value of Travel Time	No	Yes	Endogenous	DTA	Various
Lu (2019)		No	Yes	Constant	DTA	Rolling Horizon Algorithm
Our Study		Yes	Yes	Endogenous	DNDP	Active-set Algorithm

2.7 Chapter Summary

Autonomous vehicles are expected to possess intrinsic, individual benefits that provide the AV users with greater benefits compared to HDVs in terms of safety, mobility, and environmental impact. Because of the increased ease of mobility with improved safety, many researchers predict that travel demand will increase due to the incorporation of AVs in the transportation network. However, there are also potential benefits in network capacity due to vehicular communication, enhanced string stability, and operational improvements. Therefore, it remains to be seen if the improved capacity outweighs the improved demand. Some researchers discuss that the ultimate result could be incredibly congested transportation networks.

The impact of AVs on the transportation network depends on the travel patterns and behavior. Due to connectivity and sensing technology, AVs can operate at reduced headways and at increased speeds compared to HDVs. As such, it has been estimated that a traffic stream homogeneously composed of AVs can provide capacity increases up to threefold.

Further, AVs are expected to significantly reduce transportation related GHG emissions. At a disaggregate level, AVs can improve local string stability. Improved string stability leads to reduced stop-and-go traffic, thereby reducing vehicular emissions. At an aggregate level, a system of stable strings of vehicles may provide GHG emissions reduction benefits at a network level. Further, the improvements made to EV batteries, the reduced dependence of the electric grid on fossil fuels, and governmental regulations and incentives have not only motivated automobile manufacturers to develop advanced EVs, but also incentivized consumers to purchase EVs. As a result, leading AV developers have chosen to incorporate AVs with electric engines. If this trend continues, AVs will be expected to be EVs, and tailpipe emissions will be completely negligible in the era of fully autonomous vehicles.

Additionally, AVs present new and significant challenges and opportunities in the domain of network design and congestion pricing. Several simulation-based studies have been conducted to evaluate the efficacy of AV-exclusive lanes. Several of these studies have found that the effectiveness of AV-exclusive lanes depends on the market share of AVs. It has been found that at lower AV market penetration levels, AV-exclusive lanes may lead to a decrease in system efficiency. As such, some researchers have modeled AV market penetration alongside an AV-exclusive lane deployment plan to correspond with the increasing AV market penetration. However, a key gap that remains in literature is the sustainable development of AV-exclusive lanes.

The remaining chapters of this thesis formulates and solves the Sustainable AV-Lane Location (SAVLL) problem, an AV-exclusive lane deployment scheme that can promote AV ownership while addressing the three elements of sustainability, namely, system efficiency, emissions, and social inequity.

CHAPTER 3. RESEARCH METHODOLOGY

3.1 Key Concepts of Autonomous Vehicles

The National Highway Traffic Safety Administration (NHTSA) defines the following levels of automation (NHTSA, 2016):

- Level 0: the human driver does all the driving.
- Level 1: an advanced driver assistance system on the vehicle can sometimes assist the human driver with either steering or braking/accelerating, but not both simultaneously
- Level 2: an advanced driver system on the vehicle can itself actually control both steering and braking/accelerating simultaneously under some circumstances. The human driver must continue to pay full attention at all times and perform the rest of the driving task.
- Level 3: an automated driving system (ADS) on the vehicle can itself perform all aspects of the driving task under some circumstances. In those circumstances, the human driver must be ready to take back control at any time when the ADS requests the human driver to do so. In all other circumstances, the human driver performs the driving task.
- Level 4: an automated driving system (ADS) on the vehicle can itself perform all driving tasks and monitor the driving environment – essentially, do all the driving – in certain circumstances. The human need not pay attention in those circumstances.
- Level 5: an automated driving system (ADS) on the vehicle can do all the driving in all circumstances. The human occupants are just passengers and need never be involved in driving.

For this thesis, the level of automation required to be classified as an AV is Level 4 and Level 5, where the human driver no longer needs to pay attention when the automation is properly and adequately engaged. The motivation behind this assumption is to capture the effects of AVs which require no human input for operations, including environment detection and rapid decision making. Levels 0 – 2 do not have automated driving, and Level 3 still requires a fully engaged driver who may choose not to engage in AV-operations desired for this study. Consequently, vehicles possessing automation levels between 0 and 3 are considered HDVs for the purposes of this thesis.

Further, the transportation network operations can occur at two different conditions:

1. Traffic stream which is homogenously AV (100% market share of AVs)

2. Mixed traffic stream, wherein the roadways are shared between human-driven vehicles (Level 0 – Level 3) and AVs (Level 4 – Level 5).

3.2 Description and Explanation of Assumptions

In order to model the behavior of the travelers with respect to the given transportation network, the road users follow Wardrop's principle, which states that a traveler cannot unilaterally reduce their travel time further by taking another route (Wardrop, 1952). For this principle to hold, three assumptions are made regarding the travelers: (i) they possess perfect knowledge of the travel time of all routes, (ii) the travelers are rational and will choose a route that reduces their travel time, and (iii) the travelers homogeneously value travel time as the only determining factor in choosing their route.

Further, this thesis makes three major assumptions regarding the vehicles:

(1) The environmental, economic, and equity impacts associated with the manufacture of vehicles are disregarded. Therefore, the models applied in this thesis reflects only the consequences that arise from travel behavior and patterns and not from manufacturing.

(2) All AVs possess V2X communication capabilities, while all HDVs are assumed to be ICEVs with no V2X communication capabilities.

(3) All AVs are assumed to be EVs. The rationale behind this assumption is threefold: (i) trends in the automobile industry are leading towards alternative-fuel vehicles; (ii) there exist various governmental initiatives to pursue sustainable automobiles (EPA, 2015, n.d.; United Nations, 2017); and (iii) the instantaneous acceleration and deceleration in EVs absent in ICEVs are allows reduced time delay for the control of the vehicle.

Additionally, this thesis considers only the vehicular emissions from carbon monoxide (CO). The rationale behind this is twofold: CO is primarily emitted by vehicles (Yin and Lawphongpanich, 2006); and CO is one of the most impactful GHG emitted from vehicles (Alexopoulos et al., 1993); Sinha and Labi, 2007). Therefore, a macroscopic CO emission model from Wallace et al. (McTrans, 2008) is utilized in this research.

Lastly, in this thesis, construction of new lanes is not considered. The reason behind this is based on cost constraints; it is assumed that only minimal capital investments are possible in the context of AV lane deployments. Therefore, the network capacity changes in this thesis occur only as a result of AV operations within a fixed total number of lanes in the network. The total number of lanes in the network will remain unchanged throughout the planning horizon.

3.3 Description of the Problem

Table 3 - Table 5 presents a comprehensive list of notations used in this thesis along with a brief explanation of each notation.

Table 3: Set notations

Sets	
T	Set of years
N	Set of nodes
A	Set of links in a segment
$\hat{A}$	Set of links containing AV-exclusive lanes in a segment
W	Set of O-D pairs
$\mathcal{S}$	Set of road user classes
$\mathcal{K}$	Set of all road segments

Table 4: Parameters notations

Parameters		**Units**
θ	Per-lane capacity of a link	$vehs/hr/lane$
q^{w*}	AV market potential for O-D pair $w \in W$	$vehs$
r	Value of travel time for user class $s \in \mathcal{S}$	$\$/hr$
L_{τ}^{w}	Number of trips between O-D pair $w \in W$ at year $\tau \in T$	$trips/year$
Y_{τ}	Additional initial cost of purchase of AVs	$
l_a	Length of link $a \in A$	mi
ϕ	Travel time increase threshold	%
$\ddot{a}, \ddot{b}$	Non-negative parameters for link travel time	
α, β	Non-negative parameters for intrinsic growth function	
$\hat{\alpha}, \hat{\beta}$	Relative weights between the two criteria	
π^k	Total number of lanes in a segment $k \in \mathcal{K}$	
ψ_a	Maximum number of lanes for link $a \in A$	

Table 5: Variable notations

Variables		Units
$t_{w,\tau}^{m}$	Travel time for mode $m \in M$ for O-D pair $w \in W$ at year $\tau \in T$	hrs
$q_{\tau}^{w,m}$	Demand for mode $m \in M$ for O-D pair $w \in W$ at year $\tau \in T$	$vehs$
$x_{a,\tau}^{w,m}$	Flow for mode $m \in M$ on link $a \in A$ between O-D pair $w \in W$ at year $\tau \in T$	$vehs/hr$
n_{τ}^{a}	Number of lanes on link $a \in A$ at year $\tau \in T$	
$\rho_{i,\tau}^{w,m}$	Node potential for node $i \in N$ for mode $m \in M$ associated with O-D pair $w \in W$ at year $\tau \in T$	
$\delta_{a,\tau}^{w,m}$	Auxiliary variable (Karush-Kuhn-Tucker) multiplier	

The problem in this thesis can be described as a Stackleberg leader-follower game. In a Stackleberg game, there exists a leader who makes a decision for the system and a follower who reacts to the decision of the leader. The leader knows how the follower will respond *ex-ante*. In the context of this research, the leader of the game is the transportation planner, who determines when, where, and how many traditional lanes will be converted for AV-exclusive use over a long-term analysis period. The leader's goal will be to promote AV ownership by providing the exclusive lanes, which can have inherent travel time reduction benefits to incentivize AV purchase. However, the leader also possesses other goals: to ensure that the AV-exclusive lane deployment does not infringe on environmental protection and social equity. In the game, the follower is the set of road users, who respond to the AV-exclusive lane deployment by choosing their vehicle mode (AV or HDV) and route.

In the context of the problem addressed in this thesis, the existing transportation network's capacity is prospectively modified. Therefore, the model developed in this research is considered a network design problem (NDP). The conversion of lanes is discrete in nature; therefore, this research is characterized as a discrete NDP or DNDP. In literature, a DNDP in the form of a Stackelberg leader-follower game is expressed as a bi-level optimization problem: the upper level reflects the leader's decisions, and the lower level is the network equilibrium problem which reflects the followers' decisions. As such, this research formulates the DNDP as a bi-level optimization problem, and is denoted the Sustainable AV Lane Location (SAVLL) problem.

To solve the SAVLL problem, the planning horizon is divided into T years. The set of nodes and set of links of the transportation network are denoted N and A, respectively. AV-exclusive links in the network are in the set of $\hat{A}$. Each segment contains two links, $a \in A/\hat{A}$ and $a \in \hat{A}$. In words, each segment has an HDV link and an AV link. Further, the set of OD pairs is denoted W, and $o(w)$ and $d(w)$ correspond to the origin and destination of the OD pair $w \in W$. Additionally, the vehicle modes are denoted $m \in M$ such that $m = 1$ for HDV and $m = 2$ for AV.

Figure 4 presents the schematics of the bi-level optimization problem. The system-level goal of the transportation planner(s) is to minimize travel costs and emissions. Their actions involve locating, quantifying, and timing the AV-exclusive lane deployment. Their actions are restricted to conversion of lanes and not the construction of new lanes. Further, their actions may not cause undesirable levels of inequity, which is discussed in greater detail in the next section. The followers' goal is to minimize their individual travel time, and their actions involve route choice and vehicle type choice. The actions of the transportation planner affect the market penetration of AVs, because the benefit associated with AV ownership changes depending on the AV-exclusive lane deployment. Conversely, the market penetration levels affect the actions of the transportation planner, as AV-exclusive lanes cannot be deployed if the AV market penetration levels are too low for a given year. As such, the market penetration model is considered endogenous, as the AV market share is addressed internally within the framework of the bi-level problem.

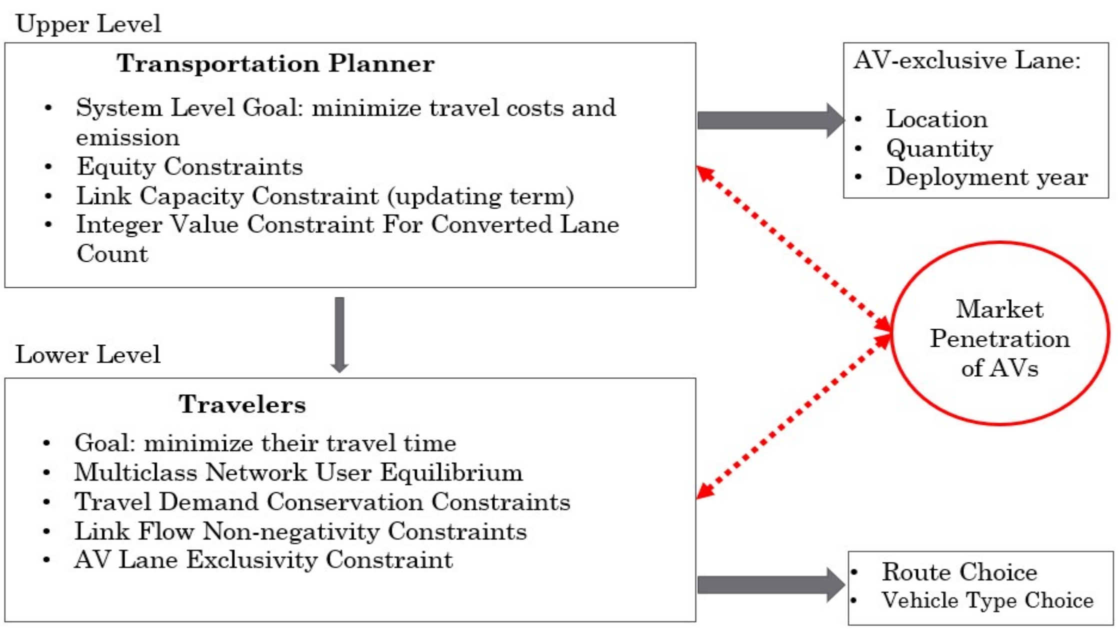

Figure 4. Schematic of the bi-level network optimization problem for the SAVLL problem

3.4 Upper Level Formulation

The upper level solves for an optimal lane deployment scheme that addresses the economic, environmental, and social equity aspects of sustainability. This formulation, for a given year $\tau \in T$ is:

$$\min_{x,q,n,\rho,\delta} Z = \sum_{\tau \in T}\left[\sum_{w \in W} \frac{v}{(1+\sigma_1)^{\tau-1}} \cdot [(\hat{\alpha} \cdot [\gamma_1 t_{w,\tau}^1 d_{w,\tau}^1 + \gamma_2 t_{w,\tau}^2 d_{w,\tau}^2]) + \hat{\beta} \cdot \vartheta \cdot e_\tau]\right] \quad (1)$$

Subject to the following constraints:

$$e_\tau = \sum_{a \in A/\hat{A}} e_{a,\tau}(v_{a,\tau}) \qquad \forall\, \tau \in T \quad (2)$$

$$e_{a,\tau}(v_{a,\tau}) = 0.2038 \cdot t_{a,\tau}(v_{a,\tau}) \cdot e^{0.7962 \cdot \left(\frac{l_a}{t_{a,\tau}(v_{a,\tau})}\right)} \qquad \forall a \in A, \tau \in T \quad (3)$$

$$\frac{t_{w,\tau}^1 - t_{w,(\tau-1)}^1}{t_{w,\tau}^1} \leq \phi \qquad \forall w \in W, \tau \in T \quad (4)$$

$$\boldsymbol{K n_\tau} = \boldsymbol{\pi} \qquad \forall \tau \in T \quad (5)$$

$$n_\tau^a \in \{0,1,\dots,\pi^k\} \qquad \forall a \in A, \tau \in T \quad (6)$$

The objective function shown in Equation (1) minimizes a weighted sum of the monetized cost of AV and HDV travel time and the vehicular emissions from HDVs over the entire network W and planning horizon T. v converts the monetized cost of emissions and travel time from a yearly cost to an hourly cost, and σ_1 is the discount rate. The expression $[\gamma_1 t_{w,\tau}^1 q_{w,\tau}^1 + \gamma_2 t_{w,\tau}^2 q_{w,\tau}^2]$ corresponds to the monetized cost of AV and HDV travel time. In the expression, $t_{w,\tau}^m$ denotes the equilibrium travel time for mode $m \in M$ for OD pair $w \in W$ at year $\tau \in T$ and is solved from the lower level NE problem as $t_{w,\tau}^m = \rho_{i,\tau}^{w,m} - \rho_{j,\tau}^{w,m}$, where $\rho_{(i,j),\tau}^{w,m}$ is the node potential. γ_m denotes the value of time for each vehicle mode $m \in M$, allowing the travel time to be converted into travel cost, and $q_{w,\tau}^{m}$ denotes the market share of vehicle mode $m \in M$ for OD pair $w \in W$ at time $\tau \in T$.

The expression $\vartheta \cdot e_\tau$ corresponds to the monetized vehicular emissions. ϑ denotes the social cost of carbon. e_τ denotes the equilibrium emissions for OD pair $w \in W$ at year $\tau \in T$ and is expanded in Equation (2) and Equation (3). Further, $\hat{\alpha}, \hat{\beta}$ are weights between the two objectives: travel time minimization and network emission minimization. The weights provide the transportation planner with the flexibility to vary the importance of the conflicting objectives.

The VOT of vehicle modes, γ_m, contributes to social equity preservation. Minimizing the marginal system travel time without addressing the vehicle mode VOT heterogeneity indicates that one type of vehicle may benefit more compared to the other. As such, vehicle mode VOT serves as a surrogate weight that provides equal benefits to both AVs and HDVs in terms of travel cost.

The vehicular emissions at the link-level is expressed in Equation (3), which is a non-monotonic carbon monoxide emission function that varies with link travel time and link length (McTrans, 2008). Equation (2) aggregates the link emissions from all links that are not AV-exclusive.

Equation (4) corresponds to the equity preservation constraint. No new construction is considered; therefore, AV-exclusive lanes are provided only through converting an existing traditional lane. As such, deployment of AV-exclusive lanes on a given link takes away capacity from HDVs, potentially increasing the travel time of HDVs. This raises the issue of social equity, because one user class benefits at the expense of the other. To address this, Equation (4) prevents the change in HDV travel time between two consecutive years from exceeding a defined threshold, ϕ. The severity of ϕ depends on the preference of the transportation planner. The concept of placing a threshold to manage equity is prevalent in literature (Yang, 2005) and has also been adopted into the context of AV-exclusive environments (Lu et al., 2019).

Equation (5) and Equation (6) are lane preservation constraints. Again, because new construction of lanes is not considered, the number of lanes in a given segment, n_τ^a, cannot exceed the initial number of lanes in the segment, which is denoted π^k. $\boldsymbol{K}$ is the segment-link incidence matrix with its component value as 1 if the link a is in the segment k, and 0 otherwise. The incidence matrix simply sums the number of AV lanes and traditional lanes in a given segment and ensures that they do not exceed the segment maximum number of lanes. The dimensions of this matrix are $k \times a$, where k is the number of segments in the network and a is the number of links $a \in A$. Further, $\boldsymbol{n_\tau}$ is a vector of dimension a such that each component n_τ^a denotes the number of lanes for link $a \in A$ at time $\tau \in T$. As such, it follows that the sum of lanes in the links composing a given segment equals the total number of lanes in that segment. The set of the total number of lanes in all segments is denoted by the vector $\boldsymbol{\pi}$. Further, Equation (6) ensures that the number of lanes are always discrete and is capped by the segment maximum number of lanes. As such, it follows that the maximum number that a link in a segment can have is, quite simply: $\boldsymbol{\pi^T} \cdot \boldsymbol{K}$, which yields a $1 \times a$ vector corresponding to the maximum number of lanes that link a can have. This vector is denoted by $\boldsymbol{\psi}$ and each element of the vector is ψ_a.

3.5 Lower Level Formulation

The lower level of the problem is a multi-class network equilibrium problem. The road users make two choices in response to the upper-level actions: (1) the mode of transportation, AV vs HDV; and (2) the route that minimizes their travel time. As mentioned previously, the travelers are assumed to follow Wardrop's first principle, such that all routes used for a given OD pair will have the same travel time, and that travel time will be less than or equal to any unused route. Additionally, all users are assumed to have perfect knowledge of the travel times in the network.

The users' travel time follows the Bureau of Public Roads' link performance function:

$$t_{a,\tau}(v_{a,\tau}) = t_a^0 \left[1 + \ddot{a}\left(\frac{v_{a,\tau}}{C_\tau^a}\right)^{\ddot{b}}\right] \qquad \forall a \in A, \tau \in T \qquad (7)$$

In Equation (7), t_a^0 is the free flow travel time for link a. For a given year in the planning horizon for a specific link a, C_τ^a corresponds to the link capacity, and $v_{a,\tau}$ denotes the link flow. $\ddot{a}, \ddot{b}$ are nonnegative parameters.

Since AVs are expected to travel at higher speeds at lower headways, their per-lane capacity is expected to be significantly higher than that of HDVs. Tientrakool et al. (Tientrakool et al., 2011) have shown that AV capacity can exceed 3 times the capacity of HDVs. As such, the capacity C_τ^a is the number of existing lanes multiplied by the per-lane capacity of the link, which will depend only on whether the link is $a \in A/\hat{A}$ or $a \in \hat{A}$.

The multiclass network equilibrium problem is an extension of Beckmann's user equilibrium formulation (Beckmann et al., 1956), which assigns traffic flow on each link given the supply, performance, and demand of the network. The network equilibrium traffic assignment is obtained by solving the following optimization problem:

$$\min_{x} Z(x) = \sum_{a \in A} \int_{0}^{v_{a,\tau}} t_{a,\tau}(x)\, dx \tag{8}$$

Subject to the following constraints:

$$\boldsymbol{\Delta x_{\tau}^{w,m}} = \boldsymbol{\mathcal{N}^{w,m}} q_{\tau}^{w,m} \qquad \forall w \in W, m \in M \tag{9}$$

$$x_{a,\tau}^{w,1} \geq 0 \qquad \forall a \in A, w \in W \tag{10}$$

$$x_{a,\tau}^{w,2} \geq 0 \qquad \forall a \in A/\hat{A}, w \in W \tag{11}$$

$$x_{a,\tau}^{w,1} = 0 \qquad \forall a \in A/\hat{A}, w \in W \tag{12}$$

$$v_{a,\tau} = \sum_{m \in M} \sum_{w \in W} x_{a,\tau}^{w,m} \qquad \forall a \in A \tag{13}$$

The objective function in Equation (8) minimizes sum of the integral of the travel time function. The resulting traffic flow is at equilibrium, where the travel time on all used routes for a given O-D pair are equal to or less than all unused routes for that O-D pair.

Equation (9) ensures flow conservation, where $x_{\tau}^{w,m}$ is the network mapped in an OD-link incidence matrix multiplied by the link flows, and $\boldsymbol{\mathcal{N}^{w,m}}$ is a vector of length N such that its components are either 1 for origin nodes or -1 for destination nodes. Equations (10) and (11) ensure that the flow on all links are nonnegative, and Equation (12) prevents HDVs from accessing AV-exclusive lanes. It may be noted that the converse is not true, meaning that AVs are not restricted from accessing traditional lanes despite the existence of AV-exclusive lanes in the same segment. Equation (13) ensures that the flow on link $a \in A$ for given year $\tau \in T$ is the sum of all O-D pairs at the given link.

The minimization problem can be formulated as a mathematical program with complementarity constraints with the addition of the following constraints, derived from the Karush-Kuhn-Tucker (KKT) conditions for optimality.

$$t_{a,\tau}(v_{a,\tau}) + (\rho_{i,\tau}^{w,m} - \rho_{j,\tau}^{w,m}) = \delta_{ij,\tau}^{w,m} \qquad \forall w \in W, a \in A, (i,j) \in w \qquad (14)$$

$$x_{a,\tau}^{w,1} \cdot \delta_{a,\tau}^{w,m} = 0 \qquad \forall w \in W, a \in A/\hat{A} \qquad (15)$$

$$x_{a,\tau}^{w,2} \cdot \delta_{a,\tau}^{w,m} = 0 \qquad \forall w \in W, a \in A \qquad (16)$$

$$\delta_{a,\tau}^{w,1} \geq 0 \qquad \forall w \in W, a \in A/\hat{A} \qquad (17)$$

$$\delta_{a,\tau}^{w,2} \geq 0 \qquad \forall w \in W, a \in A \qquad (18)$$

The multiplier $\rho_{i,\tau}^{w,m}$ in Equation (14) is the node potential (Smith et al., 1994), and Equations (15) and (16) are the complementarity constraints for the link flow of each link $a \in A/\hat{A}$ or $a \in A$ and for vehicle mode $m \in M$ for O-D pair $w \in W$ at time $\tau \in T$. Satisfying Equations (9) – (18) is equivalent to solving the network equilibrium problem.

3.6 Market Diffusion Modeling

As discussed in Chapter 2, market penetration of AVs plays a critical role in assessing the impact of AVs to the transportation system. For long-term planning purposes, modeling AV penetration based on the actions taken throughout the planning horizon is crucial in making appropriate decisions. Thus, this thesis adopts and modifies the market diffusion model from Yang et al. (Yang and Meng, 2001), wherein the market penetration of advanced traveler information systems (ATIS) is modeled according to the benefits ATIS provides to the users. The market adoption of ATIS is modeled by a modified logistic growth function, where the market share of the next time instance is a function of the current market share of the technology and the benefits accrued from the current time instance. This approach was extended by Chen et al. (Chen et al., 2016b) for AV market diffusion with homogeneous user characteristics. In this thesis, the market diffusion model is extended to incorporate user class heterogeneity in terms of their values of travel time.

The travel demand is differentiated between each vehicle mode $m \in M$, with $m = 1$ corresponding to HDV and $m = 2$ corresponding to AV. Further, the demand sums the benefits obtained by each user class $s \in S$. In essence, the demand at year $\tau + 1 \in T$, denoted $q_{\tau+1}^{w,2}$, depends on the demand at the previous year in conjunction with the benefits gained in the previous year's AV exclusive lane deployment for each user class $s \in S$. The demand at the year $\tau + 1$ is formulated as follows:

$$q_{\tau+1}^{w,2} = q_{\tau}^{w,2} + q_{\tau}^{w,2}\left(1 - \left(\frac{q_{\tau}^{w,2}}{q^{w^*}}\right)\right) \cdot \sum_{i=1}^{S}[P(x = f_i) \cdot f(\boldsymbol{\lambda}_{\boldsymbol{\tau}}^{\boldsymbol{w},\boldsymbol{s}})] \qquad \forall w \in W, \tau \in T, s \in \mathcal{S} \qquad (19)$$

Here, α, β are nonnegative parameters, $\bar{\lambda}^w$ denotes the O-D specific benefit threshold for a given O-D pair, and $\boldsymbol{\lambda}_{\boldsymbol{\tau}}^{\boldsymbol{w}}$ is a vector of dimension S, where its components are the net benefit gained from a specific O-D pair from the previous year for each user class $s \in \mathcal{S}$. The expression $\sum_{i=1}^{S}[P(x = f_i) \cdot f(\boldsymbol{\lambda}_{\boldsymbol{\tau}}^{\boldsymbol{w},\boldsymbol{s}})]$ is the discrete sum of the distribution of the benefits across the user classes 1 to s. This term can be modified to capture a continuous distribution of user classes, in which case the sum would be replaced with an integral. Further, $f(\boldsymbol{\lambda}_{\boldsymbol{\tau}}^{\boldsymbol{w},\boldsymbol{s}})$ denotes the intrinsic growth function, which depends on $\boldsymbol{\lambda}_{\boldsymbol{\tau}}^{\boldsymbol{w}}$. Equations (20) – (22) represent a further expansion as follows:

$$f(\boldsymbol{\lambda}_{\boldsymbol{\tau}}^{\boldsymbol{w},\boldsymbol{s}}) = \alpha e^{\beta(\lambda_{\tau}^{w,s} - \bar{\lambda}^w)} \qquad \forall w \in W, \tau \in T, s \in \mathcal{S} \qquad (20)$$

$$\boldsymbol{\lambda}_{\boldsymbol{\tau}}^{\boldsymbol{w},\boldsymbol{s}} = \boldsymbol{r}\left[\left[C_{\tau}^{w,1} - C_{\tau}^{w,2}\right] \cdot L_{\tau}^{w}\right] - Y \cdot \vec{\mathbf{1}} \qquad \forall w \in W, \tau \in T, s \in \mathcal{S} \qquad (21)$$

$$Y = \frac{y \cdot \sigma_2}{\left(1 - (1 + \sigma_2)\right)^{-(T-\tau)}} \qquad \forall w \in W, a \in A \qquad (22)$$

$\boldsymbol{r}$ is the vector in $R^{\mathcal{S}}$ whose elements are the value of travel time for user class $s \in \mathcal{S}$. $C_{\tau}^{w,m}$ denotes the total travel time for mode $m \in M$ for O-D pair $w \in W$ at year $\tau \in T$. Further, L_{τ}^{w} is the number of trips between each O-D pair for a given year. $Y \cdot \vec{\mathbf{1}}$ is the equivalent annual cost reflecting the additional cost of AV ownership.

Equation (22) denotes the equivalent annual cost reflecting the additional cost of AV purchase, where y is the additional cost of AV ownership at year τ, σ denotes the discount rate, and $(T - \tau)$ denotes the remaining number of years in the analysis period. Therefore, $Y \cdot \vec{\mathbf{1}}$ from constraint (21) is a vector in $R^{\mathcal{S}}$.

Additionally, it is assumed in this analysis that the total demand of the network does not change over the course of the analysis period, such that:

$$\sum_m q_\tau^{w,m} = \sum_m q_0^{w,m} \qquad \forall w \in W, m \in M \qquad (23)$$

Therefore, it trivially follows that the HDV demand is simply $q_0^{w,1} - q_\tau^{w,2}$ for all $\tau > 1$.

3.7 Chapter Summary

The problem described in this thesis is often explained in terms of game theory as a Stackelberg Leader-Follower game. The nature of the game is non-cooperative, but the leader is aware of the followers' decisions prior to taking the leader's actions. In the context of this thesis, the leader is the transportation planner, and the follower is the traveler. Further, AVs are all assumed to be level 4 or level 5 automation, meaning that they can be fully autonomous without requiring any takeover by the human passengers.

The game, modeled mathematically as a bi-level optimization problem, represents a type of network design problem. The upper level reflects the transportation planner, who determines the location, quantity, and deployment year of AV-exclusive lanes. The transportation planner endeavors to minimize vehicular emissions along with the travel costs and is kept from aggressively increasing the travel time of HDVs. The lower level reflects the travelers, who respond to the planner's decisions and make trips accordingly, satisfying Wardrop's first principle. Further, this thesis adopts a modified logistic growth function to model the AV market adoption as a function of the benefits that the user classes obtain from AV ownership in terms of travel costs.

CHAPTER 4. DATA AND SOLUTION APPROACH

In this chapter, the active set method is discussed in detail. In order to solve the SAVLL problem using the active set method, the problem is reformulated as the restricted sustainable AV-exclusive lane location (RSAVLL) problem.

4.1 Description of the Active Set Method Approach

The discrete network design problem formulated in Chapter 3 of this thesis is a mathematical problem with complementarity constraints. It has a non-convex feasible region and the Mangasarian-Fromovitz constraint qualification (MFCQ) does not hold, since there exists no vector $d \in R^n$ to satisfy the conditions: $\nabla g_i(x)^T d < 0 (i \in I(x))$ and $\nabla h_j(x)^T d = 0$, where $g(x)$ is an inequality constraint and $h(x)$ is an equality constraint. The non-convex feasible region entails that the problem possesses several locally optimal solutions. It is possible to search for a globally-optimal solution using branch-and-bound techniques. Nevertheless, it is computationally demanding. Therefore, branch-and-bound algorithms are unrealistic to apply in larger problems. On the other hand, there exist approaches that may be less time consuming but jeopardize the accuracy of the optimal solutions.

Therefore, a compromise can be made using the active set method. It solves for strongly stationary points by solving a sequence of restricted problems. This approach provides a good balance between solution accuracy and computational time and is well-suited for solving DNDPs. Proof of the convergence of the algorithm is presented in Zhang et al. (Zhang et al., 2009).

4.2 Formulation of the Restricted Problem

The bi-level problem can be converted into a single-level problem (Zhang et al., 2009). Satisfying the nonlinear system presented in Equations (14) – (18) is equivalent to solving the lower level. Thus, the upper level problem can be further constrained with Equations (14) – (18) and become a single-level problem which is equivalent to the bi-level problem.

In order to restrict the problem, the integer constraint of the lane count variable are converted into a system of binary variables. This is done by introducing $\mathcal{L}$, which denotes the smallest integer number such that $\psi_a \leq 2^{\mathcal{L}-1}$, where ψ_a is the maximum number of lanes allowable for a given link to possess due to right-of-way restrictions and other constraints. Then, n_τ^a can be expressed as $n_\tau^a = \sum_{\xi=1}^{\mathcal{L}} n_\tau^{a,\xi} \cdot 2^{\xi-1}$, where $n_\tau^{a,\xi}$ is binary for $\xi \in \{1,2,\ldots,\mathcal{L}\}$.

For example, consider a segment with 5 lanes, such that $\pi^k = 5$. Then, $\mathcal{L} = 4$ so that $5 \leq 2^{\mathcal{L}-1}$ holds. Then the number of lanes that can be converted at a given year τ can be expressed as the following:$n^a = 2^0 \cdot n^{a,1} + 2^1 \cdot n^{a,2} + 2^2 \cdot n^{a,3} + 2^3 \cdot n^{a,4} = 5$. This results in $n^{a,1} = n^{a,3} = 1$ and $n^{a,2} = n^{a,4} = 0$, yielding $n^a = 5$, which is equal to the maximum allowable number of lanes converted in that segment, $\pi^k = 5$.

The basic idea behind the algorithm is to restrict the capacity expansion variables into two sets, $\Omega_{\tau,0} = \{(a,\xi): n_\tau^{a,\xi} = 0\}$ and $\Omega_{\tau,1} = \{(a,\xi): n_\tau^{a,\xi} = 1\}, \forall\tau \in T$, where $\xi \in \{1,2,\ldots,\mathcal{L}\}$. These two sets are referred to as the "active sets," because they determine whether $0 \leq n_\tau^{a,\xi}$ or $1 \geq n_\tau^{a,\xi}$ is active.

Since there are $|T|$ analysis years in this study, $|T|$ number of pairs of active sets are created. For each year $\tau \in T$, the pair of active sets are complete, such that $\Omega_0 \cup \Omega_1 = \{(a,\xi): n_\tau^{a,\xi} \in A, \xi = 1,2\}, \forall\tau \in T$ and $\Omega_0 \cap \Omega_1 = \emptyset, \forall\tau \in T$. The decision variables are as follows:

- $q_\tau^{w,m}$ — Demand for mode $m \in M$ for O-D pair $w \in W$ at year $\tau \in T$
- $x_{a,\tau}^{w,m}$ — Flow for mode $m \in M$ on link $a \in A$ between O-D pair $w \in W$ at year $\tau \in T$
- n_τ^a — Number of lanes on link $a \in A$ at year $\tau \in T$
- $\rho_{a,\tau}^{w,m}$ — Node potential for link $a \in A$ at year $\tau \in T$ for O-D pair $w \in W$ and mode $m \in M$
- $\delta_{a,\tau}^{w,m}$ — Auxiliary variable (KKT) multiplier

The RSAVLL problem is then fully formulated as follows:

$$\min_{x,q,n,\rho,\delta} Z = \sum_{\tau \in T}\left[\sum_{w \in W}\left(\hat{\alpha}\cdot\left[\gamma_1 t^1_{w,\tau} d^1_{w,\tau} + \gamma_2 t^2_{w,\tau} d^2_{w,\tau}\right]\right) + \hat{\beta}\cdot\vartheta\cdot e_\tau\right] \tag{24}$$

Subject to constraints (2) – (4), (9) – (27):

$$e_\tau = \sum_{a \in A/\hat{A}} e_{a,\tau}(v_{a,\tau}) \qquad \forall\, \tau \in T \tag{2}$$

$$e_{a,\tau}(v_{a,\tau}) = 0.2038 \cdot t_{a,\tau}(v_{a,\tau}) \cdot e^{0.7962\cdot\left(\frac{l_a}{t_{a,\tau}(v_{a,\tau})}\right)} \qquad \forall a \in A, \tau \in T \tag{3}$$

$$\frac{t^1_{w,\tau} - t^1_{w,(\tau-1)}}{t^1_{w,\tau}} \le \phi \qquad \forall w \in W, \tau \in T \tag{4}$$

$$\boldsymbol{\Delta x^{w,m}_{\tau}} = \boldsymbol{\mathcal{N}^{w,m}} q^{w,m}_\tau \qquad \forall w \in W, m \in M \tag{9}$$

$$x^{w,1}_{a,\tau} \ge 0 \qquad \forall a \in A, w \in W \tag{10}$$

$$x^{w,2}_{a,\tau} \ge 0 \qquad \forall a \in A/\hat{A}, w \in W \tag{11}$$

$$x^{w,1}_{a,\tau} = 0 \qquad \forall a \in A/\hat{A}, w \in W \tag{12}$$

$$v_{a,\tau} = \sum_{m \in M}\sum_{w \in W} x^{w,m}_{a,\tau} \qquad \forall a \in A \tag{13}$$

$$t_{a,\tau}(v_{a,\tau}) + \left(\rho^{w,m}_{i,\tau} - \rho^{w,m}_{j,\tau}\right) = \delta^{w,m}_{ij,\tau} \qquad \forall w \in W, a \in A, (i,j) \in w \tag{14}$$

$$x^{w,1}_{a,\tau} \cdot \delta^{w,m}_{a,\tau} = 0 \qquad \forall w \in W, a \in A/\hat{A} \tag{15}$$

$$x_{a,\tau}^{w,2} \cdot \delta_{a,\tau}^{w,m} = 0 \qquad \forall w \in W, a \in A \qquad (16)$$

$$\delta_{a,\tau}^{w,1} \geq 0 \qquad \forall w \in W, a \in A/\hat{A} \qquad (17)$$

$$\delta_{a,\tau}^{w,2} \geq 0 \qquad \forall w \in W, a \in A \qquad (18)$$

$$q_{\tau+1}^{w,2} = q_{\tau}^{w,2} + q_{\tau}^{w,2}\left(1 - \left(\frac{q_{\tau}^{w,2}}{q^{w^*}}\right)\right) \cdot \sum_{i=1}^{S} [P(x = f_i) \cdot f(\boldsymbol{\lambda}_{\boldsymbol{\tau}}^{\boldsymbol{w},\boldsymbol{s}})] \qquad \forall w \in W, \tau \in T, s \in \mathcal{S} \qquad (19)$$

$$f(\boldsymbol{\lambda}_{\boldsymbol{\tau}}^{\boldsymbol{w},\boldsymbol{s}}) = \alpha e^{\beta(\lambda_{\tau}^{w,s} - \bar{\lambda}^{w})} \qquad \forall w \in W, \tau \in T, s \in \mathcal{S} \qquad (20)$$

$$\boldsymbol{\lambda}_{\boldsymbol{\tau}}^{\boldsymbol{w},\boldsymbol{s}} = \boldsymbol{r}\left[\left[C_{\tau}^{w,1} - C_{\tau}^{w,2}\right] \cdot L_{\tau}^{w}\right] - Y \cdot \vec{\mathbf{1}} \qquad \forall w \in W, \tau \in T, s \in \mathcal{S} \qquad (21)$$

$$Y = \frac{y \cdot \sigma_2}{\left(1 - (1 + \sigma_2)\right)^{-(T-\tau)}} \qquad \forall w \in W, a \in A \qquad (22)$$

$$\sum_{m} q_{\tau}^{w,m} = \sum_{m} q_{0}^{w,m} \qquad \forall w \in W, m \in M \qquad (23)$$

$$\boldsymbol{K}\boldsymbol{n}_{\boldsymbol{\tau}} = \boldsymbol{\pi} \qquad \forall \tau \in T \qquad (25)$$

$$n_{\tau}^{a,\xi} = 0 \qquad \forall (a,\xi) \in \Omega_{\tau,0}, \tau \in T \qquad (26)$$

$$n_{\tau}^{a,\xi} = 1 \qquad \forall (a,\xi) \in \Omega_{\tau,1}, \tau \in T \qquad (27)$$

While the other constraints are identical to the bi-level problem constraints presented in Chapter 3, the RSAVLL problem combines the two levels and performs restriction in Equations (26) and (27). The restriction transforms the capacity variables into a single binary variable, $n_{\tau}^{a,\xi}$.

4.3 Data Descriptions

The SAVLL problem is solved in a real, city-level network. A popular city-level network used in the domain of transportation network design is that of Sioux Falls, SD. The network structure is shown in Figure 6. It consists 76 traditional links and 76 AV links.

Further, Figure 5 below depicts how segments, AV links, and traditional links are defined for the purposes of this thesis. The green, dotted box indicates the segment, which contains both an AV link a traditional link. In practice, the segment can be understood as a corridor, and the AV-links and traditional links in the model can be understood as the AV-lanes and traditional lanes in the corridor.

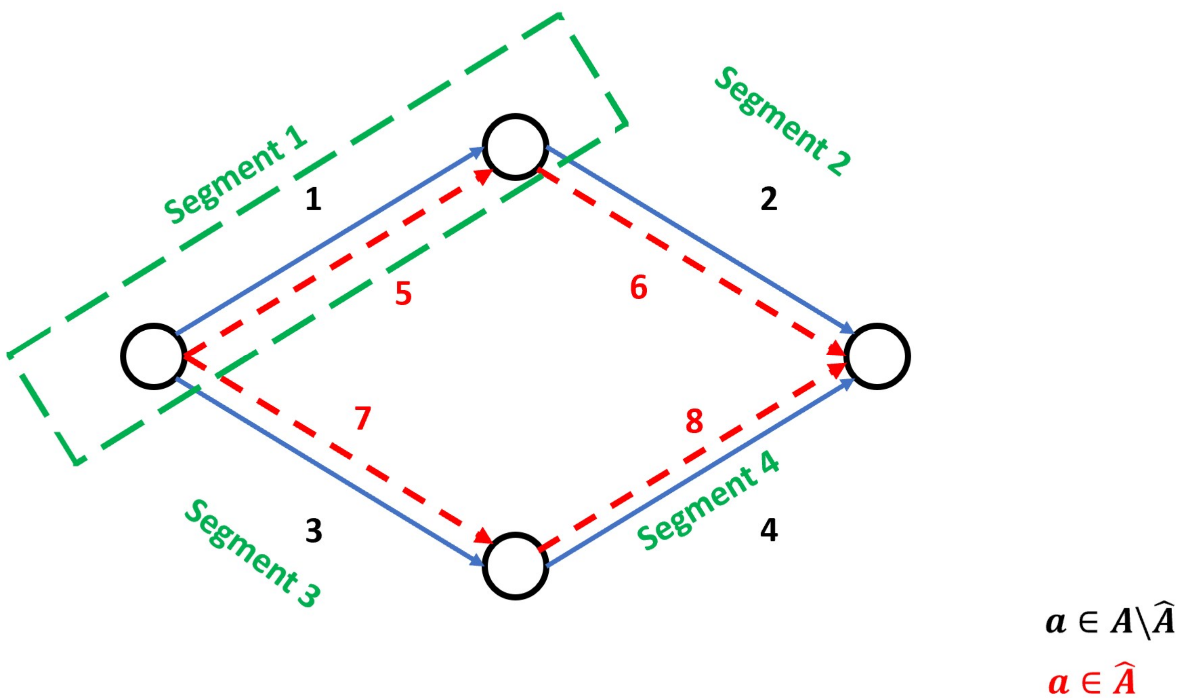

Figure 5. Definition of segments, AV links, and traditional links

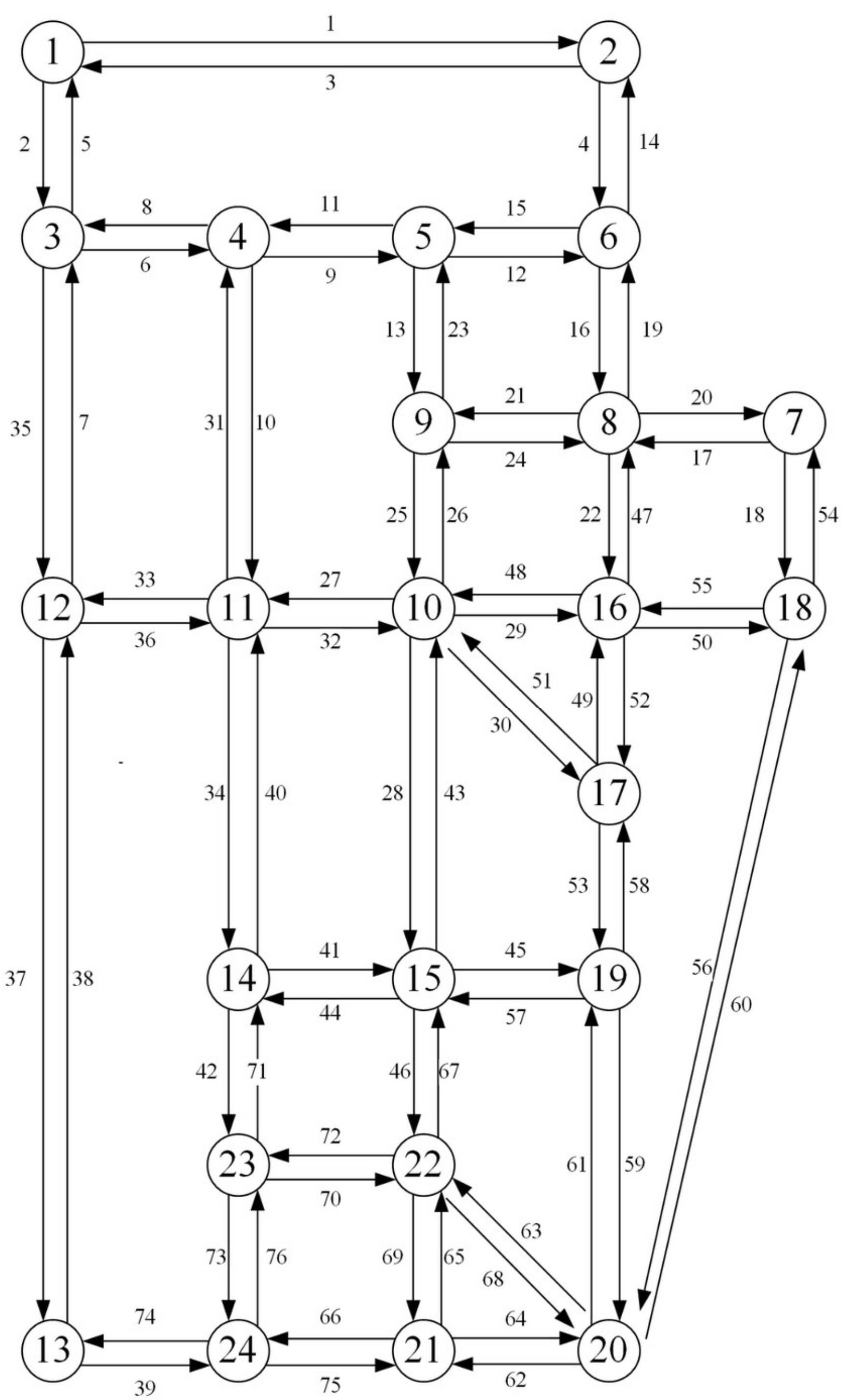

Figure 6: The Sioux Falls network schematics (Source: Transportation Networks for Research Core Team. *Transportation Networks for Research*. https://github.com/bstabler/TransportationNetworks. May, 13, 2019.)

4.4 Pseudocode

The active set algorithm is presented by Zhang et al. (Zhang et al., 2009) . The pseudocode for solving the SAVLL using the active set algorithm is as follows:

Step 0 Set E = 1

Set $\Omega_{\tau,0} = \left\{(a,\xi): n_{\tau}^{a,\xi} \in A, \xi = 1,2,\dots,\mathcal{L}\right\}$

Set $\Omega_{\tau,1} = \emptyset$ for each year $\tau \in T$

Solve the multiclass network equilibrium with the initial deployment plan

Step 1 Find feasible solution $(\boldsymbol{x},\boldsymbol{q},\boldsymbol{\delta},\boldsymbol{\rho},\boldsymbol{n_a})^T$ to the RSAVLL

Determine largest and smallest KKT multipliers from (26) and (27), denoted $\lambda_{a,\xi,\tau}^{\mathrm{E}}$ and $\mu_{a,\xi,\tau}^{\mathrm{E}}$

Define $TT^{\mathrm{E}} = \sum_{\tau\in T}\left[\sum_{w\in W}\left(\hat{\alpha}\cdot\left[\gamma_1 t_{w,\tau}^1 d_{w,\tau}^1 + \gamma_2 t_{w,\tau}^2 d_{w,\tau}^2\right]\right) + \hat{\beta}\cdot\vartheta\cdot e_\tau\right]$.

Step 2 Set $Q = -\infty$ and adjust the active sets by performing the following:

2.1 Let $(\hat{g},\hat{h})$ solve the following adjustment (knapsack) problem:

$$min\sum_{\tau\in T}\sum_{(a,\xi)\in\Omega_{\tau,0}^{\mathrm{E}}}\lambda_{a,\xi,\tau}^{\mathrm{E}}\cdot g_{a,\xi,\tau} - \sum_{\tau\in T}\sum_{(a,\xi)\in\Omega_{\tau,1}^{\mathrm{E}}}\mu_{a,\xi,\tau}^{\mathrm{E}}\cdot h_{a,\xi,\tau} \tag{28}$$

Subject to the following two constraints:

$$\sum_{\tau\in T}\sum_{(a,\xi)\in\Omega_{\tau,0}^{\mathrm{E}}}\lambda_{a,\xi,\tau}^{\mathrm{E}}\cdot g_{a,\xi,\tau} - \sum_{\tau\in T}\sum_{(a,\xi)\in\Omega_{\tau,1}^{\mathrm{E}}}\mu_{a,\xi,\tau}^{\mathrm{E}}\cdot h_{a,\xi,\tau} \geq Q \tag{29}$$

$$g_{a,\xi,\tau}, h_{a,\xi,\tau} \in (0,1) \tag{30}$$

2.2 If the optimal objective function of the knapsack problem from 2.1 is zero, let $(\boldsymbol{x},\boldsymbol{q},\boldsymbol{\delta},\boldsymbol{\rho},\boldsymbol{n_a})^T$ be the solution to the SAVLL problem. Otherwise, continue to Step 3

Step 3 Shift the restricted sets by defining:

$$\Theta = \sum_{\tau\in T}\sum_{(a,\xi)\in\Omega_{\tau,0}^{\mathrm{E}}}\lambda_{a,\xi,\tau}^{\mathrm{E}}\cdot g_{a,\xi,\tau} - \sum_{\tau\in T}\sum_{(a,\xi)\in\Omega_{\tau,1}^{\mathrm{E}}}\mu_{a,\xi,\tau}^{\mathrm{E}}\cdot h_{a,\xi,\tau} \tag{31}$$

$$\widehat{\Omega}_{\tau,0} = \left(\Omega_{\tau,0}^{\mathrm{E}} - \left\{(a,\xi)\in\Omega_{\tau,0}^{\mathrm{E}}: \hat{g}_{a,\xi,\tau} = 1\right\}\right) \cup \left\{(a,\xi)\in\ \Omega_{\tau,1}^{\mathrm{E}}: \hat{h}_{a,\xi,\tau} = 1\right\} \tag{32}$$

$$\widehat{\Omega}_{\tau,1} = \left(\Omega_{\tau,1}^{\mathrm{E}} - \left\{(a,\xi)\in\Omega_{\tau,1}^{\mathrm{E}}: \hat{h}_{a,\xi,\tau} = 1\right\}\right) \cup \left\{(a,\xi)\in\ \Omega_{\tau,0}^{\mathrm{E}}: \hat{g}_{a,\xi,\tau} = 1\right\} \tag{33}$$

3.1 Solve the multiclass network equilibrium problem with a deployment plan $\hat{\boldsymbol{n}}$ compatible with the restricted set pair, $(\widehat{\Omega}_{\tau,0},\widehat{\Omega}_{\tau,1})$

If the total system costs associated with the multiclass network equilibrium problem is less than TT^{E}, go to step 4. Otherwise, go to step 3.2

3.2 Set $Q = \Theta + \varepsilon$, where $\varepsilon > 0$ is sufficiently small and return to Step 2

Step 4 Set $\Omega_{\tau,0}^{\mathrm{E}+1} = \widehat{\Omega}_{\tau,0}$ and $\Omega_{\tau,1}^{\mathrm{E}+2} = \widehat{\Omega}_{\tau,1}$ and return to step 1

4.5 Explanation of the Pseudocode

In step 0, an initial deployment scheme is set up. Due to the equity constraints, finding a feasible initial deployment plan is challenging. However, starting with no deployment will be feasible regardless of the constraints. Therefore, for this thesis, $\boldsymbol{n_a} = \{\emptyset\}$ will serve as the initial deployment plan. The multiclass network equilibrium problem is solved with this initial plan.

In Step 1, the equilibrium solutions are used to construct a feasible solution for the SAVLL problem, $(\boldsymbol{x}, \boldsymbol{q}, \boldsymbol{n_a}, \boldsymbol{\delta}, \boldsymbol{\rho})^T$. Then, the restricted SAVLL problem is solved to determine the Lagrangian multipliers for the lane conversion constraints, $\lambda^{\mathrm{E}}_{a,\xi,\tau}$ and $\mu^{\mathrm{E}}_{a,\xi,\tau}$. The objective function value is saved as TT^{E} to serve as a benchmark for any other deployment plans investigated in this iteration.

Step 2 – Step 3 are denoted the inner loop, which is iterated until a superior deployment plan compared to that used in Step 1 is found. In Step 2, a binary knapsack problem (KP) is formulated and solved. There are two binary decision variables $g_{a,\xi,\tau}$ and $h_{a,\xi,\tau}$. Here, $g_{a,\xi,\tau} = 1$ means that (a, ξ) is shifted from $\Omega_{\tau,0}$ to $\Omega_{\tau,1}$, and $h_{a,\xi,\tau} = 1$ means a shift in the opposite direction. Essentially, the knapsack problem solves for a deployment scheme by shifting AV lanes to traditional lanes and vice versa so that the system is improved, until there are no more alternatives that further improve the system. Equation (29) constrains the problem so that the objective function never becomes worse at each iteration. Equation (30) ensures that $g_{a,\xi,\tau}$ and $h_{a,\xi,\tau}$ are binary. If the objective function value of the KP is zero, then there are no shifts in the restricted sets that can yield a reduction in the SAVLL objective function value. Therefore, the current solution is the optimal solution and the algorithm can terminate. If the KP objective function is non-zero (i.e., it will always be negative if non-zero), then the restricted sets are shifted in Step 3.

The shifts in restricted sets are conducted according to Equations (31) – (33). Then, the multiclass network equilibrium is solved for given the new deployment plan. Using the equilibrium solutions, the SAVLL objective function is evaluated. If the SAVLL objective function value determined by the equilibrium solutions is less than TT^{E}, then the new current deployment plan yields a SAVLL objective function value that is superior to that of the former. Hence, the current deployment plan is saved in Step 4 and the algorithm restarts. However, if the SAVLL objective function value determined by the equilibrium solutions is greater than or equal to TT^{E}, then the current plan does not present any improvement to the system, and a new deployment plan is solved for again by returning to Step 2 and continuing the algorithm.

4.6 Candidate Links for Lane Conversion

Unlike other studies on optimal AV-exclusive lane deployment, this thesis allows the transportation agency to revert any previously-deployed AV-exclusive lanes. Enabling reversion allows for greater flexibility in the search for optimal deployment plans by rerouting traffic through different paths. Further, as discussed by Lu et al., lower values of ϕ makes it difficult for the solver to find feasible solutions (Lu et al., 2019). The added flexibility of allowing reversion has been observed in this thesis to improve convergence to a feasible solution.

However, allowing all links to be considered for conversion (both traditional to AV-exclusive and vice versa) causes the computation time to increase significantly. In this thesis's Sioux Falls case study, the number of iterations of the inner loop (Step 2 – Step 3) in the algorithm presented in section 0 reached up to 600 iterations before finding an improved deployment plan. To improve the computational time, this thesis presents the following heuristic conditions to determine candidate links for lane conversion:

Condition 1: To convert a traditional lane for AV-exclusive use, at least 12% of the link flows must consist of AVs.

Condition 2: To revert back to traditional lane, the HDV-flow to capacity ratio in a segment containing AV-exclusive lanes must exceed 1.5

Condition 1 prevents the conversion of a traditional lane for AV-exclusive use unless the link flows consist of significant AV penetration. Without Condition 1, the algorithm will iterate the inner loop over links which will not improve total system costs, since those links do not have a sufficient volume of AVs.

Similarly, Condition 2 prevents the reversion of an AV-exclusive lane unless the HDV lanes in the segment are becoming congested. Without Condition 2, the algorithm will also iterate the inner loops to check all AV-exclusive lanes for reversion even though there is no real congestion issue for HDVs in the corresponding segments.

The inclusion of Conditions 1 and 2 allow the algorithm to converge to improved solutions in a much shorter amount of iterations. Though the multiclass network equilibrium problem and the knapsack problem solved in the inner loop are not as computationally intensive as the SAVLL problem, neglecting to implement conditions for candidate links causes the inner loop to iterate hundreds of times.

4.7 Chapter Summary

In this chapter, the sustainable AV-exclusive lane location (SAVLL) problem is restricted so that the integer variables for capacity expansion are replaced with a single binary variable. The problem can then be solved using the active set method. Solving the SAVLL problem is very difficult; therefore, the SAVLL objective function is evaluated using the flow obtained from solving the network equilibrium problem, which is a much easier problem to solve. The SAVLL objective function is calculated from the network equilibrium flow over various feasible deployment plans until a deployment plan produces a superior objective function value. Only then is the SAVLL problem solved. Thus, the computational efficiency greatly increases. Further, in order to improve computational efficiency, this thesis proposes two heuristic conditions to define candidacy for conversion.

CHAPTER 5. RESULTS AND IMPLICATIONS OF RESULTS

5.1 Comparison of Alternative Plans for Deployment

The SAVLL problem was solved using the Sioux Falls (SF) network as a case study. The network characteristics are identical to that used in Leblanc et al. (LeBlanc et al., 1975) and is publicly available. Due to computational constraints, the SF network was reduced to 74 O-D pairs for this thesis. This is a comparable number of O-D pairs as that of the network used in the optimal AV-exclusive lane location problem from Chen et al. (Chen et al., 2016b). However, reducing the network O-D pairs will under-saturate the network and will not result in realistic results. This is because the network capacity remains the same but the number of vehicles travelling in the network is reduced. Therefore, the demand was scaled corresponding to the reduced number of O-D pairs. The initial numerical settings are provided in

Table 7.

Three scenarios were considered in this thesis: the SAVLL deployment, mobility-only consideration (MO) deployment, and no-deployment. Each deployment scenario was performed under user equilibrium (UE) traffic flow conditions. By assessing the impact of the deployment plans given equilibrium flows, the transportation planner can understand the naturalistic effect of the deployment plans.

The SAVLL deployment is formulated in Chapter 4. MO deployment is predominantly used in literature, wherein the total system travel time is minimized with no considerations given to emissions and equity management. In the MO deployment, the objective function removes the emissions term from equation (24), and can be written as the minimization of $\sum_{\tau\in T}\left[\sum_{w\in W}\left(\left[\gamma_1 t^1_{w,\tau} d^1_{w,\tau} + \gamma_2 t^2_{w,\tau} d^2_{w,\tau}\right]\right)\right]$ with the same constraints as SAVLL except for equation (4), the equity constraint. Lastly, in the no-deployment scenario, there is no provision of AV-exclusive lanes. A brief summary can be seen in

Table 6.

While it is not in the scope of this thesis, the transportation planner may want to evaluate the effect of the deployment plans by driving system optimal (SO) traffic flows. If the agency plans to introduce tolling, the deployment effects must be evaluated given the SO traffic flows which would occur due to tolling. To induce SO traffic conditions, the BPR function for link travel time can be modified to include the marginal link travel time. Thus, the link travel time function would be $\widetilde{t_{a,\tau}}(v_{a,\tau}) = t_{a,\tau}(v_{a,\tau}) \times v_{a,\tau} \frac{d}{dx} t_{a,\tau}(v_{a,\tau})$, and the framework for UE traffic flow conditions can be used with the new travel time function.

Table 6: Summary of the actions

	SAVLL	MO	Do Nothing
Lanes deployed	yes	yes	no
Objective	total system travel time and emissions	total system travel time	none
Equity constraint	yes	no	no

Table 7: Initial numerical settings

Parameter	**Description**	**Value**	**Units**
$\hat{\alpha}$	travel cost weight	1	
$\hat{\beta}$	emission cost weight	3	
γ_1	HDV value of travel time	12	$\$/h$
γ_2	AV value of travel time	12	$\$/h$
r_{1-5}	user class value of travel time	8,10,12,14,16	$\$/h$
$\ddot{\alpha}$	BPR Parameter	0.2	
$\ddot{\beta}$	BPR Parameter	4	
s	number of user classes	5	
α	market share parameter	0.3	$1/year$
β	market share parameter	0	$year/\$$
σ_1	discount rate for upper level objective function	5	%
σ_2	Discount rate for equivalent annual cost of AV ownership	5	%
ϕ	equity constraint	2.50	
$q_0^{w,2}$	Initial AV Demand	10	%

5.2 AV-exclusive Lane Deployment

The AV-exclusive lanes in the network at the final year of analysis, $\tau = T = 10$, for the SAVLL and MO deployments are found in Table 12 and Table 13, respectively. Further, the raw result of the AV-exclusive lane deployment, which includes the timing of the deployment, is found in Table 14 and Table 15.

The total number of AV-exclusive lanes deployed for SAVLL and MO are presented in Table 8 below. Given UE flow, 48 segments had AV-exclusive lanes in the SAVLL deployment, and a total of 69 segments had AV-exclusive lanes in the MO deployment. The actual number of AV-exclusive lanes is 54 for the SAVLL deployment and 84 for the MO deployment.

Table 8: Total number of AV-exclusive lanes recommended for deployment

	User Equilibrium	
	SAVLL	**MO**
# of AV-exclusive Lanes	54	84
# of segments with AV-exclusive Lanes	48	69

It can be observed that, given UE flow patterns, the MO deployment provides more AV-exclusive lanes compared to the SAVLL deployment and affects more segments than the SAVLL deployment. This is an expected result, since SAVLL deployment is more restricted in its approach to ensure that the HDV travel times do not increase beyond ϕ due to deployment.

5.3 Social Equity Results

As discussed in previous chapters, the issue of social equity arises from the deployment of AV-exclusive lanes. The SAVLL deployment is restrictive in allowing the travel time of HDV owners from increasing dramatically from year to year, while the MO deployment relaxes this condition and allows the HDV travel time to increase unboundedly if a feasible path exists.

Given equilibrium flow conditions, the MO deployment plan resulted in a 3.08% average increase in HDV travel time. On the other hand, the SAVLL deployment resulted in a 1.63% average increase in HDV travel time. Further, without placing a constraint on HDV travel time increase, the MO deployment plan causes 7 link-time pairs to exceed 250% increase in HDV travel time. The largest increase in HDV travel time occurs on link 6.5 (starting node at 6 and ending node at 5) at time $\tau = 2$ with 409.55% increase in HDV travel time. The reason behind this sharp increase is primarily due to the sudden reduction in HDV capacity. According to Table 15, two lanes are converted from traditional lanes to AV-exclusive use at this link-time pair, leaving a single lane for HDV use, thereby violating the equity threshold.

The SAVLL deployment, which was defined to prevent deployment if HDV travel time is set to increase by more than 250%, yielded in both a more conservative number of deployment as well as a smaller average increase in HDV travel time. The largest increase in HDV travel time occurs on link 17.16 (starting node at 17 and ending node at 16) at time $\tau = 4$ with 236.84% increase in HDV travel time. According to Table 14, two lanes are converted from traditional lanes to AV-exclusive use at this link-time pair, leaving a single lane for HDV use, thus resulting in the sharp increase in HDV travel time. As shown in Table 10, there is only one link-time pair which exceeds 200% increase in HDV travel time, and there is only 4 link-time pairs which exceeds 100% increase in HDV travel time.

While an equity threshold constraint only reduces the feasible region and does not mitigate inequity, it gives direct control for the agency to define a limit on how much travel cost increase they want to allow for HDVs. The alternative could be to involve congestion pricing, so that the increased travel cost of HDVs are tolled to AVs in the AV-exclusive lane. However, doing so raises the question of AV promotion and may rather negate the benefit of AV-exclusive lane deployment.

Lastly, it must be mentioned that the SAVLL deployment is more difficult to solve than the MO deployment. The equity constraints on each link and time forces a restriction on lane deployment, which alters the paths taken by the travelers. As discussed by Lu et al, who utilize a similar equity constraint in AV-exclusive zones, the equity constraints can cause the solver to fail to find an optimal solution within a reasonable amount of time (Lu et al., 2019). From the computational experiments of this thesis, for $\phi < 2.5$, GAMS was unable to find a feasible solution after 63 hours of searching.

Table 9: HDV travel time effects due to MO deployment given UE flow

MO Deployment Given UE Flow	
Average change	3.08%
Maximum increase	409.55%
>250% increase	7
>200% increase	7
>100% increase	8
>50% increase	22

Table 10: HDV travel time effects due to SAVLL deployment given UE flow

SAVLL Deployment Given UE Flow	
Average change	1.63%
Maximum increase	236.84%
>250% increase	0
>200% increase	1
>100% increase	4
>50% increase	16

5.4 Environmental Protection and Economic Impact Results

The total system costs of each scenario are presented in Figure 7 below. The results show that taking either deployment plan can reduce the total costs by $363 million compared to the scenario where AV-exclusive lanes are not deployed.

While the total system costs of SAVLL and MO deployment are similar, the SAVLL deployment has a lower emissions cost and higher travel cost. Depending on the objective of the agency, the weight of emissions cost can be further increased to achieve a deployment plan that will further reduce emissions. Likewise, if the primary objective of the agency is to reduce the system travel cost, the weights can be adjusted to reflect the agency objective.

5.5 Impact of Plans on AV Market Adoption

Due to the improvements in travel cost, the benefit of AV ownership is greater under the MO deployment than in the SAVLL deployment. Figure 8 shows the deployment effects on AV market penetration. Given an initial 10% AV market share, the adoption of AVs under the MO deployment plan outperforms that of the SAVLL deployment. At the end of the analysis period, the MO deployment results in close to 50% AV market share, whereas the SAVLL deployment results in only about 30% of AV market share.

Figure 7: Cost comparison across three scenarios considered

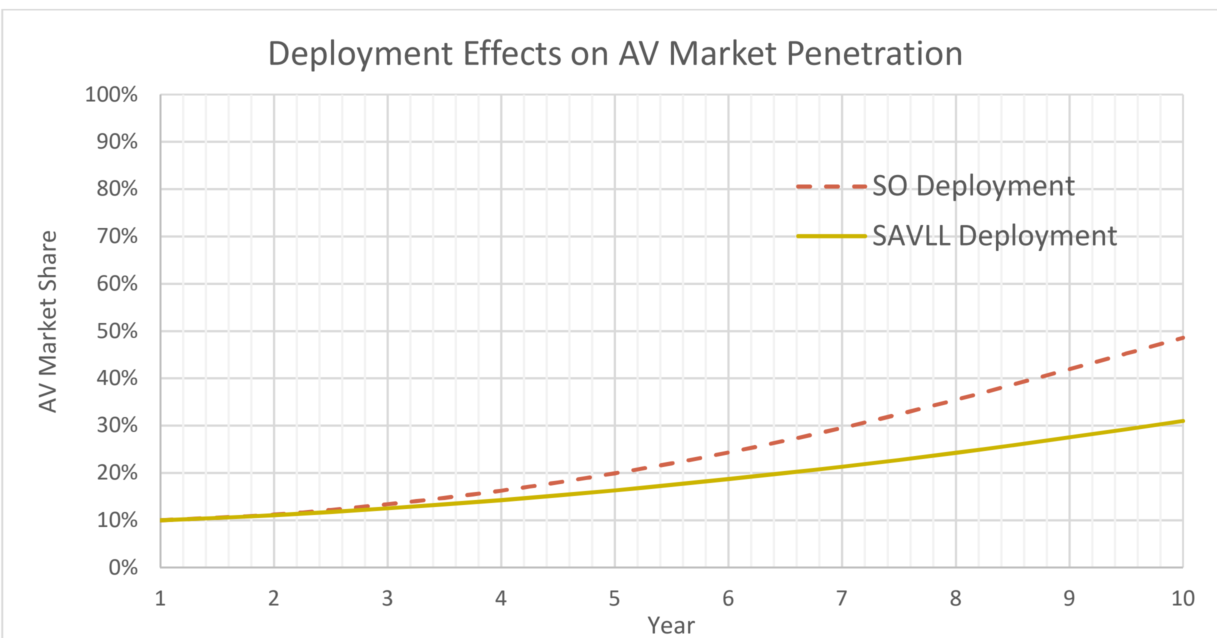

Figure 8: Effects of alternative deployment strategies on AV market penetration

5.6 Sensitivity of Equity Threshold

The most critical parameter that influences the analysis in this thesis is the equity threshold parameter. Tightness of this parameter will likely result in the following: infeasibility, highly conservative deployment, or complete non-consideration of equity. Therefore, this section presents an analysis of the sensitivity of the optimal solution to the equity threshold parameter.

Table 11 presents the effect of the equity threshold on the total system costs for the SAVLL problem. Four levels of the equity threshold were analyzed. It is observed that as the value of ϕ becomes relaxed, the total system travel time decreases. Therefore, it can be inferred that having a strict equity threshold causes the AV-exclusive lane deployment to deviate further away from system optimality. Thus, the inclusion of the equity threshold necessitates that the SAVLL deployment and MO deployment are mutually exclusive.

However, in the case of CO emissions, the lowest value is obtained when $\phi = 7.5$. Even though the total system travel time is lower when $\phi = 10$, the system emissions is not the lowest at $\phi = 10$. This result is corroborated by Yin et al. (Yin and Lawphongpanich, 2006), who found that a system optimal traffic assignment does not necessarily yield the minimal emissions.

Table 11: Sensitivity analysis with respect to the equity threshold parameter

	values of ϕ			
	2.5	5	7.5	10
emissions (gCO/y)	151,393,241	152,185,363	141,080,847	150,688,511
total travel time (h/y)	17,745	17,677	17,519	16,957

5.7 Impact of Findings on Future Practice of Infrastructure Planning

The case study presented in this chapter provides various insights for future practices in infrastructure planning, especially in the context of AV accommodation. The key questions for transportation agencies to address for infrastructure preparedness of AVs, which is discussed in Section 2.5 of this thesis, can be answered based on the findings of this thesis:

- Which highway infrastructure changes are required to support AV operations and when are these investments needed?

- AV-exclusive lanes can serve as an effective infrastructural change to support AV operations, and they can be provided on a rolling basis over a planning horizon.

- Will market penetration drive the infrastructure preparedness?
    - The market penetration and infrastructure provision may endogenously affect each other. Namely, high penetration drives more provision of AV-exclusive lanes, and provision of AV-exclusive lanes increases AV penetration.
- What will be the market penetration trends in the future?
    - The market penetration trends in the future depend heavily on the benefits of AV ownership. These benefits will come as a result of both AV capabilities as well as the agency's provision of infrastructure.
- Which infrastructure management practices including the minimum levels of regular roadway maintenance, will be required to promote AV operations?
    - This thesis evaluated the effect of AV-exclusive lanes on AV operations and found that it allows operations of the system to improve significantly.
- To what extent, should human-driven and autonomous vehicles be allowed in the same or different lanes?
    - The complete separation of AVs and HDVs, as long as there exists significant share of AVs in the traffic stream, proves to be the most efficient. The no-deployment strategy resulted in the highest emissions cost and travel cost.
- How will agency expenditures and revenues change, and what will AV-related infrastructure retrofitting mean in terms of public investment?
    - In the context of AV-exclusive lanes, very little agency expenditures will occur. No new construction is required to improve the system.

5.8 Study Limitations

The traffic assignment model used in this thesis is both deterministic and static, i.e., no stochasticity is considered, and time-of-day dynamics are not captured. Modeling the transportation network to be deterministic can be inaccurate, since it leaves out any margin of errors (Shao et al., 2006). Researchers have pointed out the shortcomings of a deterministic model due to the oversimplifications inherent in them, especially given that the reality is rarely deterministic (Pasik-Duncan, 2019). Further, static traffic assignment is unable to capture day-to-day operations and can only provide an average performance of the transportation network. The deployment of AV-exclusive lanes via conversion of traditional lanes requires no construction. Therefore, in practice, the transportation agency is not constrained to only make deployment decisions once per year, as is the case in the scenario presented in this thesis. The frequency of deployment can become reduced to meet peak-hour AV demand. For example, knowing that peak hour AV demand is very high, the transportation agency can provide more AV-exclusive lanes, only to revert them back to traditional lanes when the AV demand reduces later in the day. Thus, dynamically providing AV-exclusive lanes can be more effective.

Further, the market penetration model utilized in this thesis is a modified logistic growth function to capture diffusion as an effect of growth and cost. While a few researchers have used this approach to model market adoption of AVs, it is difficult to argue that it provides a fully reliable relationship between market adoption of AVs and benefits from AV-exclusive lane deployment. Additionally, in this thesis, an explicit awareness by the AV traveler, of the reduction in emissions cost did not play a role in the travelers' mode choice. The only factor which was considered to affect the travelers' mode choice is the travel cost. This is an oversimplification of traveler behavior, as more and more people are becoming increasingly invested in environmental protection and social justice. In future consideration of model choice in this analysis, researchers may refer to Stephen et al. who provided guidance that will be useful for selecting appropriate mode choice models (Stephens et al., 2017)s.

This thesis presents sustainability considerations in AV-exclusive lane deployment to facilitate mitigation of risk by the transportation agency in the future; however, it does not consider safety explicitly. There exists an implicit assumption that safety is improved due to increasing market adoption of AVs; however, at the current time, it is rather difficult to model safety benefits of AV-exclusive lanes at the network level without grossly oversimplifying the safety costs. Therefore, in future research, safety impacts could be consider after evaluating reliably, net safety costs or benefits (associated with vehicles or pedestrians) of AV-exclusive lanes can be done more accurately through more microscopic approaches, as done by Yu et al (Yu et al., 2019) and Chen et al (Chen et al., 2019) and after assessing the capabilities of pedestrian detection by AVs in a more reliable manner as suggested by Combs et al. (Combs et al., 2019).

5.9 Chapter Summary

This chapter presented the result of a case study using the Sioux Falls road network. A comparison was drawn between the SAVLL deployment, MO deployment, and no deployment. The three elements of sustainability were utilized as the performance criteria in comparing the three plans. The SAVLL deployment addresses each of the three elements, whereas the MO deployment only considers total system travel time.

With regard to equity management, the SAVLL deployment prevented any increase in HDV travel time from exceeding the threshold, ϕ. The average increase in HDV link travel time was 1.64%. No link-time pairs exceeded 250% increase in HDV travel time, and only one link-time pair exceeded 200% increase in HDV travel time due to AV-exclusive lane deployment.

On the other hand, the MO deployment caused the HDV travel time to increase from the previous year by an average of 3.08% among the affect link-time pairs. Further, the highest increase in HDV travel time was 409.55%. 7 link-time pairs exceeded 250% increase in HDV travel time due to AV-exclusive lane deployment. If the transportation agency implements an AV-exclusive lane deployment scheme by only considering total system travel time, it will cause HDV owners to experience sharp increase in travel time, and therefore may lead to public opposition.

Further, this thesis shows the costs associated with the remaining two elements of sustainability: environmental protection and economic impact. The total system travel cost is understood as the economic impact by incorporating heterogenous user and vehicle class values of travel time. A macroscopic model for modeling vehicular CO emissions, in conjunction with the social cost of carbon emission, is utilized in assessing and addressing the environmental impact of the AV-exclusive lane deployment.

The performance measure used for this thesis was the monetized cost of travel time and vehicular emissions. In terms of travel cost, the MO deployment strategy resulted in the lowest costs. On the other hand, providing no AV-exclusive lanes resulted in the highest travel costs from the system. In terms of emissions cost, the SAVLL deployment resulted in the lowest cost, and no deployment of AV-exclusive lanes resulted in the highest emissions cost. A relative weight of 3:1 between emissions cost and travel costs results in equal total system costs between the SAVLL and MO deployment plans. The weighted sum bi-criteria optimization in the SAVLL deployment serves to provide flexibility to the transportation agency to address their goals. If the agency believes that the emissions cost should have an even higher weight, they can easily implement them.

Further, the results of this case study show that the MO deployment outperforms the SAVLL model in AV promotion. This is an expected outcome, since the market diffusion model only considers travel costs. Thus, the lower travel costs incurred in the MO deployment results in improved market adoption of AVs compared to the SAVLL deployment. It is evident that there exists a trade-off between meeting system level goals of sustainability and AV promotion. The transportation agency and practitioners can tune the critical parameters to improve AV market adoption or improve system-level goals of sustainability.

CHAPTER 6. CONCLUDING REMARKS

6.1 Summary, Discussion, and Conclusion

This thesis presented the formulation of the Sustainable AV-exclusive Lane Location (SAVLL) problem. The SAVLL deployment addresses the three elements of sustainable development in planning, as defined by the UN: economic impact, environmental protection, and social equity. The economic impact is addressed by total system travel costs; environmental protection is addressed by the total system emissions cost; and social equity is addressed using an equity threshold constraint, which prevents AV-exclusive lane deployments that cause steep increases in HDV travel time.

The SAVLL problem is considered a Stackelberg leader-follower game, which is modeled as a bi-level optimization problem: the upper level reflects the transportation agency and the AV-exclusive lane deployment, and the lower level reflects the travelers who respond to the deployment. As shown by several researchers (Talebpour et al., 2017; Van Arem et al., 2006; Yu et al., 2019), the AV-exclusive lane deployment policy should be strongly influenced by the AV market penetration. However, the market penetration will also depend on the deployment, as the increased benefit of AV ownership will further propagate AV adoption. Therefore, this thesis implements a modified logistic growth function that models the AV adoption while also considering the benefits of AV ownership due to the AV-exclusive lane deployment. Further, this thesis also implements varying user and vehicle class heterogeneity in value of travel time. While the VOTs are parametrized, sourcing data from survey-based studies can help increase the reliability of the VOTs to further increase the realism and applicability of the SAVLL problem.

Solving the SAVLL problem is challenging, as the problem is both nonlinear and nonconvex. Consequently, there exists multiple local optima in the feasible region. Further, the SAVLL problem violates the Mangasarian-Fromovitz constraint qualification (MFCQ). Therefore, the Karush-Kuhn-Tucker (KKT) conditions cannot be used to verify solution optimality as they may not hold. This leaves very few options for solving the SAVLL problem. In this thesis, the active-set method (ASM) proposed by Zhang et al. (Zhang et al., 2009) was adapted and utilized. This approach has been used for optimal AV-exclusive lane location problems by Chen et al. (Chen et al., 2016b). For improved computational efficiency, this thesis also proposes two conditions for link conversion and reversion. These heuristic conditions allow the algorithm to ignore links that have little or no impact on the SAVLL objective function.

A case study was conducted using the Sioux Falls network. Over a ten-year planning horizon, three deployment strategies were compared: the SAVLL deployment, the MO deployment, and no-deployment of AV-exclusive lanes. The results showed that the SAVLL and MO deployments outperform the no-deployment in travel costs and emission costs. Additionally, the SAVLL deployment incurs higher travel costs than MO deployment but results in a lower emissions cost compared to the MO deployment. In this numerical experiment, weighing the emissions cost to be three times the weight of the travel costs entails the SAVLL and MO deployments to have equal total costs. The weighted sum approach to the bicriteria optimization allows the transportation agency the flexibility to implement their goals in the model. Further, in terms of equity, the MO deployment caused up to 409.55% increase in HDV travel time due to AV-exclusive lane deployment. The total number of affected link-time pairs over the analysis period was 7. Thus, while the MO deployment strategy is commonly prescribed in the literature, doing this in the context of AV lane deployment would significantly benefit the AV owners at the expense of HDV owners. Given the expectation that AVs will be less affordable compared to HDVs, deploying AV-exclusive lanes to attain system optimal traffic will induce public criticism that the government is making infrastructure planning policies that benefit higher-income individuals at the expense of the lower-income individuals.

From the perspective of AVs only, the analysis carried out in this thesis indicate that MO deployment outperforms the SAVLL deployment. This is largely due to the fact that the logistic growth model for AV adoption only considers travel cost differences between AV and HDV as the benefit for AV ownership. In reality, as people are becoming increasingly engaged in activist causes including environmental protection and social justice, their concerns are expected to have greater influence on agency decision making. Thus, the gap between the AV market share under MO and SAVLL deployment plans can be expected to reduce.

In conclusion, this thesis makes a strong argument for considering all three elements of sustainability for AV-exclusive lane deployment. The objective of the thesis was to present a mathematical model to be used by the transportation agency to meet the following goals:

- AV promotion: both the MO deployment and the SAVLL deployment propagated AV market adoption, with MO deployment outperforming SAVLL deployment (Figure 8).
- Meeting sustainability goals: the SAVLL formulation addresses economic impact through the monetized minimization of the total system travel time, environmental protection through the monetized minimization of the total system emissions, and equity management through the prevention of AV-exclusive lane deployment which causes dramatic increases (more than 7 links experiencing greater than 250% increase) HDV travel time.
- Low implementation costs: the AV-exclusive lane deployment presented in this thesis requires conversion of traditional lanes, thereby avoiding construction costs.
- Flexibility: the formulation is structured so that the transportation agency can change the decision criteria, weights, and parameters in a manner that ensures greater consistency with their current mission or overall goals.

In effect, transportation agencies can use the framework of this thesis to help promote AV ownership in contexts that not only avoid incurrence of new-lane construction costs but also minimize public opposition and social unrest associated with user inequity.

6.2 Future Work

As discussed in Section 5.7, there are a number of limitations in this thesis that are associated with the planning and operations contexts of the AV-lane deployment problem. Many of these limitations present opportunities for future work. A potential research direction is to identify dynamic AV-exclusive lane deployment over peak hours in a day. In a situation of perfect connectivity between vehicles and infrastructure, the real-time O-D demand of AVs can be known. This information can be leveraged to allow dynamically-assigned exclusive lanes in a network by converting both exclusivity and directionality of lanes to optimize the network operations. Another potential research direction is to address equity by implementing congestion pricing strategies. There are several research opportunities including tolling and tradable credit schemes to address the increased travel time of HDVs. In this case, it will be essential to determine the effect of system optimal traffic flows to ensure that the appropriate AV-exclusive lane deployment strategy is considered. Lastly, the current model for AV adoption depends only on the travel cost benefits. To improve the market adoption model, a survey-based study can be conducted to understand and model the travelers' attitudes towards AV ownership given its environmental and social equity impacts.

APPENDIX A: LANE DEPLOYMENT

Table 12: AV-exclusive lane deployment under SAVLL at year 10

Link	# of AV-exclusive lanes	Link	# of AV-exclusive lanes
1 .2	1	14.15	2
2 .1	1	15.14	1
2 .6	1	15.19	1
3 .4	1	15.22	1
3 .12	1	16.8	1
4 .3	2	16.10	1
4 .5	1	16.17	1
4 .11	1	16.18	1
5 .4	1	17.10	1
6 .2	1	17.16	2
6 .5	2	17.19	1
6 .8	1	18.16	1
7 .18	2	18.20	1
8 .6	1	19.15	1
8 .16	1	20.22	1
9 .5	1	21.22	1
9 .10	1	21.24	1
10.9	1	22.15	1
10.11	1	22.21	1
11.10	1	22.23	1
11.12	1	23.22	1
11.14	2	24.13	1
12.13	1	24.21	1
13.24	1	24.23	1

Table 13: AV-exclusive lane deployment under MO at year 10

Link	# of AV-exclusive Lanes	Link	# of AV-exclusive Lanes	Link	# of AV-exclusive Lanes
1 .3	1	10.9	1	17.10	1
2 .1	1	10.11	1	17.16	1
3 .1	1	10.15	2	17.19	1
3 .4	1	10.16	1	18.7	1
3 .12	1	11.10	1	18.16	2
4 .3	1	11.12	1	18.20	2
4 .5	1	11.14	1	19.15	1
4 .11	1	12.3	1	19.17	1
5 .4	1	12.11	1	19.20	1
5 .6	2	12.13	1	20.18	2
5 .9	1	13.12	1	20.21	1
6 .2	1	13.24	1	20.22	1
6 .5	1	14.11	2	21.20	1
6 .8	1	14.15	2	21.22	1
7 .8	2	14.23	1	21.24	2
7 .18	1	15.10	1	22.15	1
8 .6	2	15.14	2	22.20	1
8 .7	1	15.19	1	22.21	1
8 .9	1	15.22	1	22.23	2
8 .16	1	16.8	1	23.22	2
9 .5	1	16.10	1	24.13	2
9 .8	1	16.17	1	24.21	1
9 .10	2	16.18	1	24.23	1

APPENDIX B: LANE DEPLOYMENT RAW RESULTS

Table 14: Total SAVLL deployment

link	time	# of AV-exclusive lanes	link	time	# of AV-exclusive lanes
1 .2	t8	1	13.24	t6	1
1 .2	t9	1	13.24	t7	2
1 .2	t10	1	13.24	t10	1
1 .3	t3	1	14.15	t2	1
2 .1	t4	1	14.15	t3	1
2 .1	t5	1	14.15	t4	1
2 .1	t6	1	14.15	t5	1
2 .1	t7	1	14.15	t6	2
2 .1	t8	1	14.15	t7	1
2 .1	t9	1	14.15	t8	1
2 .1	t10	1	14.15	t9	1
2 .6	t8	1	14.15	t10	2
2 .6	t9	1	15.14	t2	1
2 .6	t10	1	15.14	t3	1
3 .4	t2	1	15.14	t4	1
3 .4	t3	1	15.14	t5	1
3 .4	t4	1	15.14	t6	1
3 .4	t5	1	15.14	t7	1
3 .4	t6	1	15.14	t8	1
3 .4	t7	1	15.14	t9	1
3 .4	t8	1	15.14	t10	1
3 .4	t9	1	15.19	t2	1
3 .4	t10	1	15.19	t3	2
3 .12	t4	1	15.19	t4	1
3 .12	t5	1	15.19	t5	1
3 .12	t6	1	15.19	t6	1
3 .12	t7	1	15.19	t7	1
3 .12	t8	1	15.19	t8	1
3 .12	t9	1	15.19	t9	1
3 .12	t10	1	15.19	t10	1
4 .3	t3	2	15.22	t2	1
4 .3	t4	2	15.22	t3	1
4 .3	t5	2	15.22	t4	1
4 .3	t6	2	15.22	t5	1

Table 14 continued

4 .3	t7	2	15.22	t6	1
4 .3	t8	2	15.22	t7	1
4 .3	t9	2	15.22	t8	1
4 .3	t10	2	15.22	t9	1
4 .5	t2	1	15.22	t10	1
4 .5	t3	1	16.8	t4	1
4 .5	t4	1	16.8	t5	1
4 .5	t5	1	16.8	t6	1
4 .5	t6	1	16.8	t7	1
4 .5	t7	1	16.8	t8	1
4 .5	t8	1	16.8	t9	1
4 .5	t9	1	16.8	t10	1
4 .5	t10	1	16.10	t2	1
4 .11	t2	1	16.10	t4	2
4 .11	t3	1	16.10	t10	1
4 .11	t4	1	16.17	t4	1
4 .11	t5	1	16.17	t6	1
4 .11	t6	1	16.17	t7	1
4 .11	t7	1	16.17	t8	1
4 .11	t8	1	16.17	t9	1
4 .11	t9	1	16.17	t10	1
4 .11	t10	1	16.18	t2	2
5 .4	t3	2	16.18	t3	2
5 .4	t4	2	16.18	t4	1
5 .4	t5	1	16.18	t5	1
5 .4	t6	1	16.18	t6	1
5 .4	t7	1	16.18	t7	1
5 .4	t8	1	16.18	t8	1
5 .4	t9	1	16.18	t9	1
5 .4	t10	1	16.18	t10	1
5 .6	t2	2	17.10	t4	1
5 .6	t3	2	17.10	t5	1
5 .6	t4	2	17.10	t6	1
5 .6	t5	1	17.10	t7	1
5 .6	t6	2	17.10	t8	1
5 .6	t7	2	17.10	t9	1
5 .9	t5	1	17.10	t10	1
6 .2	t3	1	17.16	t4	2
6 .2	t4	1	17.16	t5	1
6 .2	t5	1	17.16	t7	1

Table 14 continued

6 .2	t6	1	17.16	t8	1
6 .2	t7	1	17.16	t9	1
6 .2	t8	1	17.16	t10	2
6 .2	t9	1	17.19	t2	1
6 .2	t10	1	17.19	t3	1
6 .5	t5	1	17.19	t4	1
6 .5	t6	1	17.19	t5	1
6 .5	t8	2	17.19	t6	2
6 .5	t10	2	17.19	t7	1
6 .8	t4	1	17.19	t8	2
6 .8	t8	1	17.19	t9	1
6 .8	t9	1	17.19	t10	1
6 .8	t10	1	18.7	t2	2
7 .18	t2	2	18.7	t3	2
7 .18	t3	2	18.7	t4	2
7 .18	t4	2	18.7	t5	2
7 .18	t5	2	18.7	t6	2
7 .18	t6	1	18.7	t7	2
7 .18	t7	1	18.16	t2	2
7 .18	t8	2	18.16	t6	2
7 .18	t9	2	18.16	t7	2
7 .18	t10	2	18.16	t8	1
8 .6	t3	1	18.16	t9	2
8 .6	t4	1	18.16	t10	1
8 .6	t5	1	18.20	t2	2
8 .6	t6	1	18.20	t3	2
8 .6	t7	1	18.20	t4	2
8 .6	t8	1	18.20	t6	2
8 .6	t9	1	18.20	t7	2
8 .6	t10	1	18.20	t8	2
8 .7	t2	1	18.20	t9	1
8 .7	t3	1	18.20	t10	1
8 .7	t4	1	19.15	t2	1
8 .7	t5	1	19.15	t3	1
8 .7	t6	1	19.15	t4	1
8 .7	t7	1	19.15	t5	1
8 .7	t8	1	19.15	t6	1
8 .9	t4	1	19.15	t7	1
8 .16	t4	1	19.15	t8	1
8 .16	t7	1	19.15	t9	1

Table 14 continued

8 .16	t8	1	19.15	t10	1
8 .16	t9	1	20.22	t2	1
8 .16	t10	1	20.22	t3	1
9 .5	t3	2	20.22	t4	1
9 .5	t4	2	20.22	t5	1
9 .5	t5	2	20.22	t6	1
9 .5	t6	2	20.22	t7	1
9 .5	t7	2	20.22	t8	1
9 .5	t8	2	20.22	t9	1
9 .5	t9	2	20.22	t10	1
9 .5	t10	1	21.20	t4	1
9 .8	t2	1	21.22	t5	1
9 .8	t3	1	21.22	t6	1
9 .8	t4	1	21.22	t7	1
9 .8	t5	1	21.22	t10	1
9 .8	t6	1	21.24	t2	1
9 .8	t7	1	21.24	t3	1
9 .10	t3	1	21.24	t4	1
9 .10	t4	1	21.24	t5	1
9 .10	t5	1	21.24	t6	1
9 .10	t6	1	21.24	t7	1
9 .10	t7	1	21.24	t8	1
9 .10	t8	1	21.24	t9	1
9 .10	t9	1	21.24	t10	1
9 .10	t10	1	22.15	t2	1
10.9	t3	2	22.15	t3	1
10.9	t4	1	22.15	t4	1
10.9	t5	1	22.15	t5	1
10.9	t6	1	22.15	t6	1
10.9	t7	1	22.15	t7	1
10.9	t8	1	22.15	t8	1
10.9	t9	1	22.15	t9	1
10.9	t10	1	22.15	t10	1
10.11	t4	1	22.21	t2	1
10.11	t5	1	22.21	t3	1
10.11	t6	1	22.21	t4	1
10.11	t7	1	22.21	t5	1
10.11	t8	1	22.21	t6	1
10.11	t9	1	22.21	t7	1
10.11	t10	1	22.21	t8	1

Table 14 continued

10.15	t5	1	22.21	t9	1
10.16	t2	1	22.21	t10	1
10.16	t3	1	22.23	t2	1
10.16	t4	1	22.23	t3	1
10.16	t5	1	22.23	t4	1
10.16	t6	2	22.23	t5	1
10.16	t7	1	22.23	t6	1
10.17	t4	1	22.23	t7	1
10.17	t5	1	22.23	t8	1
10.17	t6	1	22.23	t9	1
11.10	t2	1	22.23	t10	1
11.10	t3	1	23.22	t2	1
11.10	t4	1	23.22	t3	1
11.10	t5	1	23.22	t4	1
11.10	t6	1	23.22	t5	1
11.10	t7	1	23.22	t6	1
11.10	t8	1	23.22	t7	1
11.10	t9	2	23.22	t8	1
11.10	t10	1	23.22	t9	1
11.12	t4	1	23.22	t10	1
11.12	t5	1	24.13	t2	1
11.12	t6	1	24.13	t3	1
11.12	t7	1	24.13	t4	1
11.12	t8	1	24.13	t5	1
11.12	t9	1	24.13	t6	1
11.12	t10	1	24.13	t7	1
11.14	t2	2	24.13	t8	1
11.14	t3	2	24.13	t9	1
11.14	t4	1	24.13	t10	1
11.14	t5	1	24.21	t5	1
11.14	t6	1	24.21	t6	1
11.14	t7	2	24.21	t7	1
11.14	t8	2	24.21	t10	1
11.14	t9	1	24.23	t2	1
11.14	t10	2	24.23	t3	1
12.13	t4	2	24.23	t4	1
12.13	t5	1	24.23	t5	1
12.13	t6	1	24.23	t6	1
12.13	t7	1	24.23	t7	1
12.13	t8	1	24.23	t8	1

Table 14 continued

12.13	t9	1	24.23	t9	1
12.13	t10	1	24.23	t10	1
13.24	t5	1			

Table 15: Total MO deployment

Link	**time**	**total**	**Link**	**time**	**total**	**Link**	**time**	**total**
1 .2	t3	1	9 .10	t3	1	16.18	t10	1
1 .2	t4	1	9 .10	t4	1	17.10	t5	1
1 .2	t5	1	9 .10	t5	1	17.10	t6	1
1 .2	t6	1	9 .10	t6	1	17.10	t7	1
1 .2	t7	1	9 .10	t7	1	17.10	t8	1
1 .2	t8	1	9 .10	t8	1	17.10	t9	1
1 .2	t9	1	9 .10	t9	1	17.10	t10	1
1 .3	t5	1	9 .10	t10	2	17.16	t2	2
1 .3	t9	1	10.9	t2	2	17.16	t3	1
1 .3	t10	1	10.9	t3	1	17.16	t4	1
2 .1	t5	1	10.9	t4	1	17.16	t5	1
2 .1	t6	1	10.9	t5	1	17.16	t6	1
2 .1	t7	1	10.9	t6	1	17.16	t7	1
2 .1	t8	1	10.9	t7	1	17.16	t8	1
2 .1	t9	1	10.9	t8	1	17.16	t9	1
2 .1	t10	1	10.9	t9	1	17.16	t10	1
2 .6	t3	1	10.9	t10	1	17.19	t2	1
2 .6	t4	1	10.11	t2	2	17.19	t3	1
2 .6	t5	1	10.11	t3	1	17.19	t4	1
2 .6	t6	1	10.11	t4	1	17.19	t5	1
2 .6	t7	1	10.11	t5	1	17.19	t6	1
2 .6	t8	1	10.11	t6	1	17.19	t7	1
2 .6	t9	1	10.11	t7	1	17.19	t8	1
3 .1	t2	1	10.11	t8	1	17.19	t9	1
3 .1	t4	1	10.11	t9	1	17.19	t10	1
3 .1	t5	1	10.11	t10	1	18.7	t2	2
3 .1	t8	1	10.15	t2	2	18.7	t3	2
3 .1	t10	1	10.15	t3	2	18.7	t4	2
3 .4	t2	1	10.15	t4	2	18.7	t5	2
3 .4	t3	1	10.15	t5	2	18.7	t6	2
3 .4	t4	1	10.15	t6	2	18.7	t7	2
3 .4	t5	1	10.15	t7	2	18.7	t8	2
3 .4	t6	1	10.15	t8	2	18.7	t9	2

Table 15 continued

3 .4	t7	1	10.15	t9	2	18.7	t10	1
3 .4	t8	1	10.15	t10	2	18.16	t2	2
3 .4	t9	1	10.16	t3	1	18.16	t3	1
3 .4	t10	1	10.16	t4	1	18.16	t4	2
3 .12	t3	1	10.16	t5	1	18.16	t5	2
3 .12	t4	1	10.16	t6	1	18.16	t6	2
3 .12	t5	2	10.16	t7	1	18.16	t7	2
3 .12	t6	1	10.16	t8	1	18.16	t8	2
3 .12	t7	1	10.16	t9	1	18.16	t9	2
3 .12	t8	1	10.16	t10	1	18.16	t10	2
3 .12	t9	1	10.17	t2	1	18.20	t2	2
3 .12	t10	1	11.10	t7	2	18.20	t8	2
4 .3	t3	1	11.10	t9	2	18.20	t9	2
4 .3	t4	1	11.10	t10	1	18.20	t10	2
4 .3	t5	1	11.12	t3	1	19.15	t2	1
4 .3	t6	1	11.12	t4	1	19.15	t3	1
4 .3	t7	1	11.12	t5	1	19.15	t4	1
4 .3	t8	1	11.12	t6	1	19.15	t5	1
4 .3	t9	1	11.12	t7	1	19.15	t6	1
4 .3	t10	1	11.12	t8	1	19.15	t7	1
4 .5	t2	1	11.12	t9	1	19.15	t8	1
4 .5	t3	1	11.12	t10	1	19.15	t9	1
4 .5	t4	1	11.14	t2	2	19.15	t10	1
4 .5	t5	1	11.14	t4	1	19.17	t2	1
4 .5	t6	1	11.14	t5	1	19.17	t3	1
4 .5	t7	1	11.14	t6	1	19.17	t5	1
4 .5	t8	1	11.14	t7	1	19.17	t10	1
4 .5	t9	1	11.14	t8	1	19.20	t2	1
4 .5	t10	1	11.14	t9	1	19.20	t3	1
4 .11	t2	1	11.14	t10	1	19.20	t5	1
4 .11	t9	1	12.3	t2	2	19.20	t6	1
4 .11	t10	1	12.3	t3	2	19.20	t7	1
5 .4	t3	1	12.3	t4	2	19.20	t8	1
5 .4	t4	1	12.3	t8	1	19.20	t9	1
5 .4	t5	1	12.3	t9	1	19.20	t10	1
5 .4	t6	1	12.3	t10	1	20.18	t8	2
5 .4	t7	1	12.11	t5	1	20.18	t10	2
5 .4	t8	2	12.11	t6	1	20.21	t3	1
5 .4	t9	1	12.11	t7	1	20.21	t4	1
5 .4	t10	1	12.11	t8	1	20.21	t10	1

Table 15 continued

5 .6	t2	2	12.11	t9	1	20.22	t2	1
5 .6	t3	2	12.11	t10	1	20.22	t3	1
5 .6	t4	2	12.13	t3	1	20.22	t4	1
5 .6	t5	2	12.13	t4	1	20.22	t5	1
5 .6	t6	2	12.13	t5	1	20.22	t6	1
5 .6	t7	2	12.13	t6	1	20.22	t7	1
5 .6	t8	2	12.13	t7	1	20.22	t8	1
5 .6	t9	2	12.13	t8	1	20.22	t9	1
5 .6	t10	2	12.13	t9	1	20.22	t10	1
5 .9	t2	2	12.13	t10	1	21.20	t5	1
5 .9	t3	1	13.12	t10	1	21.20	t6	1
5 .9	t4	1	13.24	t3	1	21.20	t7	1
5 .9	t5	1	13.24	t4	1	21.20	t8	1
5 .9	t6	1	13.24	t5	1	21.20	t9	1
5 .9	t7	1	13.24	t6	1	21.20	t10	1
5 .9	t8	1	13.24	t7	1	21.22	t4	1
5 .9	t9	1	13.24	t8	1	21.22	t5	1
5 .9	t10	1	13.24	t9	1	21.22	t6	1
6 .2	t5	1	13.24	t10	1	21.22	t7	1
6 .2	t6	1	14.11	t2	2	21.22	t8	1
6 .2	t7	1	14.11	t3	2	21.22	t9	1
6 .2	t8	1	14.11	t4	2	21.22	t10	1
6 .2	t9	1	14.11	t5	2	21.24	t2	1
6 .2	t10	1	14.11	t6	2	21.24	t3	2
6 .5	t2	2	14.11	t7	2	21.24	t4	1
6 .5	t3	1	14.11	t8	2	21.24	t5	1
6 .5	t4	1	14.11	t9	2	21.24	t6	1
6 .5	t5	1	14.11	t10	2	21.24	t7	1
6 .5	t6	1	14.15	t2	2	21.24	t8	1
6 .5	t7	1	14.15	t6	1	21.24	t9	2
6 .5	t8	1	14.15	t7	1	21.24	t10	2
6 .5	t9	1	14.15	t8	1	22.15	t3	1
6 .5	t10	1	14.15	t9	1	22.15	t4	1
6 .8	t3	1	14.15	t10	2	22.15	t5	1
6 .8	t4	2	14.23	t2	1	22.15	t6	1
6 .8	t5	1	14.23	t4	1	22.15	t7	1
6 .8	t6	1	14.23	t5	1	22.15	t9	1
6 .8	t7	1	14.23	t10	1	22.15	t10	1
6 .8	t8	1	15.10	t2	2	22.20	t3	1
6 .8	t9	1	15.10	t3	1	22.20	t4	1

Table 15 continued

6 .8	t10	1	15.10	t4	2	22.20	t5	1
7 .8	t10	2	15.10	t5	2	22.20	t7	1
7 .18	t2	1	15.10	t6	1	22.20	t8	1
7 .18	t3	1	15.10	t7	2	22.20	t9	1
7 .18	t4	1	15.10	t9	1	22.20	t10	1
7 .18	t5	1	15.10	t10	1	22.21	t2	1
7 .18	t6	1	15.14	t2	2	22.21	t3	1
7 .18	t7	1	15.14	t3	1	22.21	t4	1
7 .18	t8	1	15.14	t4	2	22.21	t5	1
7 .18	t9	1	15.14	t5	1	22.21	t6	1
7 .18	t10	1	15.14	t6	1	22.21	t7	1
8 .6	t3	1	15.14	t7	1	22.21	t8	1
8 .6	t4	1	15.14	t8	1	22.21	t9	1
8 .6	t5	1	15.14	t9	2	22.21	t10	1
8 .6	t6	1	15.14	t10	2	22.23	t2	1
8 .6	t7	1	15.19	t2	1	22.23	t3	2
8 .6	t8	1	15.19	t3	1	22.23	t4	2
8 .6	t9	1	15.19	t4	1	22.23	t5	2
8 .6	t10	2	15.19	t5	1	22.23	t6	2
8 .7	t2	1	15.19	t6	1	22.23	t7	2
8 .7	t3	1	15.19	t7	1	22.23	t8	2
8 .7	t4	1	15.19	t8	1	22.23	t9	2
8 .7	t5	1	15.19	t9	1	22.23	t10	2
8 .7	t6	1	15.19	t10	1	23.14	t3	1
8 .7	t7	1	15.22	t2	1	23.14	t8	1
8 .7	t8	1	15.22	t3	1	23.22	t2	2
8 .7	t9	1	15.22	t4	1	23.22	t3	2
8 .7	t10	1	15.22	t5	1	23.22	t4	1
8 .9	t2	1	15.22	t6	1	23.22	t5	1
8 .9	t3	1	15.22	t7	1	23.22	t6	1
8 .9	t4	1	15.22	t8	1	23.22	t7	1
8 .9	t5	1	15.22	t9	1	23.22	t8	2
8 .9	t6	1	15.22	t10	1	23.22	t9	2
8 .9	t7	1	16.8	t3	1	23.22	t10	2
8 .9	t8	1	16.8	t4	1	23.24	t3	1
8 .9	t9	1	16.8	t5	1	23.24	t7	1
8 .9	t10	1	16.8	t6	1	23.24	t8	1
8 .16	t2	1	16.8	t7	1	24.13	t2	1
8 .16	t4	1	16.8	t8	1	24.13	t3	1
8 .16	t5	1	16.8	t9	1	24.13	t4	1

Table 15 continued

8 .16	t6	1	16.8	t10	1	24.13	t5	1
8 .16	t7	1	16.10	t2	1	24.13	t6	1
8 .16	t8	1	16.10	t3	1	24.13	t7	1
8 .16	t9	1	16.10	t4	1	24.13	t8	1
8 .16	t10	1	16.10	t5	1	24.13	t9	2
9 .5	t3	1	16.10	t6	1	24.13	t10	2
9 .5	t4	1	16.10	t7	1	24.21	t4	1
9 .5	t5	1	16.10	t8	1	24.21	t5	1
9 .5	t6	1	16.10	t9	1	24.21	t6	1
9 .5	t7	1	16.10	t10	1	24.21	t7	1
9 .5	t8	1	16.17	t4	1	24.21	t8	1
9 .5	t9	1	16.17	t5	1	24.21	t9	1
9 .5	t10	1	16.17	t8	1	24.21	t10	1
9 .8	t2	1	16.17	t9	1	24.23	t2	1
9 .8	t3	1	16.17	t10	1	24.23	t3	1
9 .8	t4	1	16.18	t2	1	24.23	t4	1
9 .8	t5	1	16.18	t3	1	24.23	t5	1
9 .8	t6	1	16.18	t4	1	24.23	t6	1
9 .8	t7	1	16.18	t5	1	24.23	t7	1
9 .8	t8	1	16.18	t6	1	24.23	t8	1
9 .8	t9	1	16.18	t7	1	24.23	t9	1
9 .8	t10	1	16.18	t8	1	24.23	t10	1
9 .10	t2	2	16.18	t9	1			

APPENDIX C: AV MARKET ADOPTION RAW RESULTS

Table 16: Raw Results of AV Demand for Each O-D Pair

		AV Demand				AV Demand	
O-D	**Time**	**MO**	**SAVLL**	**OD**	**Time**	**MO**	**SAVLL**
1 .2	t1	0.15	0.15	6 .9	t1	0.3	0.3
1 .2	t2	0.168	0.166	6 .9	t2	0.337	0.331
1 .2	t3	0.201	0.188	6 .9	t3	0.401	0.375
1 .2	t4	0.244	0.214	6 .9	t4	0.488	0.429
1 .2	t5	0.299	0.245	6 .9	t5	0.598	0.491
1 .2	t6	0.365	0.281	6 .9	t6	0.731	0.561
1 .2	t7	0.443	0.32	6 .9	t7	0.887	0.641
1 .2	t8	0.532	0.364	6 .9	t8	1.064	0.729
1 .2	t9	0.629	0.413	6 .9	t9	1.257	0.825
1 .2	t10	0.729	0.465	6 .9	t10	1.458	0.93
1 .3	t1	0.15	0.15	6 .10	t1	0.9	0.9
1 .3	t2	0.168	0.166	6 .10	t2	1.01	0.994
1 .3	t3	0.201	0.188	6 .10	t3	1.204	1.126
1 .3	t4	0.244	0.214	6 .10	t4	1.465	1.286
1 .3	t5	0.299	0.245	6 .10	t5	1.793	1.472
1 .3	t6	0.365	0.281	6 .10	t6	2.192	1.684
1 .3	t7	0.444	0.32	6 .10	t7	2.661	1.923
1 .3	t8	0.532	0.364	6 .10	t8	3.193	2.187
1 .3	t9	0.629	0.413	6 .10	t9	3.772	2.476
1 .3	t10	0.729	0.465	6 .10	t10	4.375	2.789
1 .4	t1	0.75	0.75	6 .11	t1	0.3	0.3
1 .4	t2	0.842	0.828	6 .11	t2	0.337	0.331
1 .4	t3	1.003	0.939	6 .11	t3	0.401	0.375
1 .4	t4	1.22	1.072	6 .11	t4	0.488	0.429
1 .4	t5	1.494	1.227	6 .11	t5	0.598	0.491
1 .4	t6	1.827	1.404	6 .11	t6	0.731	0.561
1 .4	t7	2.218	1.602	6 .11	t7	0.887	0.641
1 .4	t8	2.66	1.822	6 .11	t8	1.064	0.729
1 .4	t9	3.143	2.063	6 .11	t9	1.257	0.825
1 .4	t10	3.645	2.324	6 .11	t10	1.458	0.93
1 .5	t1	0.3	0.3	6 .12	t1	0.15	0.15
1 .5	t2	0.337	0.331	6 .12	t2	0.168	0.166
1 .5	t3	0.401	0.375	6 .12	t3	0.201	0.188
1 .5	t4	0.488	0.429	6 .12	t4	0.244	0.214
1 .5	t5	0.598	0.491	6 .12	t5	0.299	0.245
1 .5	t6	0.731	0.561	6 .12	t6	0.365	0.281

Table 16 continued

1 .5	t7	0.887	0.641	6 .12	t7	0.444	0.32
1 .5	t8	1.064	0.729	6 .12	t8	0.532	0.364
1 .5	t9	1.257	0.825	6 .12	t9	0.629	0.413
1 .5	t10	1.458	0.93	6 .12	t10	0.729	0.465
1 .6	t1	0.45	0.45	6 .13	t1	0.45	0.45
1 .6	t2	0.505	0.497	6 .13	t2	0.505	0.497
1 .6	t3	0.602	0.563	6 .13	t3	0.602	0.563
1 .6	t4	0.732	0.643	6 .13	t4	0.732	0.643
1 .6	t5	0.897	0.736	6 .13	t5	0.897	0.736
1 .6	t6	1.096	0.842	6 .13	t6	1.096	0.842
1 .6	t7	1.331	0.961	6 .13	t7	1.331	0.961
1 .6	t8	1.596	1.093	6 .13	t8	1.596	1.093
1 .6	t9	1.886	1.238	6 .13	t9	1.886	1.238
1 .6	t10	2.187	1.394	6 .13	t10	2.187	1.394
1 .7	t1	0.75	0.75	6 .14	t1	0.15	0.15
1 .7	t2	0.842	0.828	6 .14	t2	0.168	0.166
1 .7	t3	1.003	0.939	6 .14	t3	0.201	0.188
1 .7	t4	1.221	1.072	6 .14	t4	0.244	0.214
1 .7	t5	1.494	1.227	6 .14	t5	0.299	0.245
1 .7	t6	1.827	1.404	6 .14	t6	0.365	0.281
1 .7	t7	2.218	1.602	6 .14	t7	0.444	0.32
1 .7	t8	2.661	1.822	6 .14	t8	0.532	0.364
1 .7	t9	3.143	2.063	6 .14	t9	0.629	0.413
1 .7	t10	3.646	2.324	6 .14	t10	0.729	0.465
1 .8	t1	1.2	1.2	6 .15	t1	0.15	0.15
1 .8	t2	1.347	1.325	6 .15	t2	0.168	0.166
1 .8	t3	1.605	1.502	6 .15	t3	0.201	0.188
1 .8	t4	1.953	1.715	6 .15	t4	0.244	0.214
1 .8	t5	2.391	1.963	6 .15	t5	0.299	0.245
1 .8	t6	2.923	2.246	6 .15	t6	0.365	0.281
1 .8	t7	3.548	2.563	6 .15	t7	0.444	0.32
1 .8	t8	4.257	2.916	6 .15	t8	0.532	0.364
1 .8	t9	5.029	3.302	6 .15	t9	0.629	0.413
1 .8	t10	5.833	3.718	6 .15	t10	0.729	0.465
1 .9	t1	0.75	0.75	6 .16	t1	0.6	0.6
1 .9	t2	0.842	0.828	6 .16	t2	0.674	0.663
1 .9	t3	1.003	0.939	6 .16	t3	0.803	0.751
1 .9	t4	1.221	1.072	6 .16	t4	0.976	0.858
1 .9	t5	1.494	1.227	6 .16	t5	1.196	0.982
1 .9	t6	1.827	1.404	6 .16	t6	1.462	1.123
1 .9	t7	2.218	1.602	6 .16	t7	1.774	1.282
1 .9	t8	2.661	1.822	6 .16	t8	2.128	1.458

Table 16 continued

1 .9	t9	3.143	2.063	6 .16	t9	2.514	1.651
1 .9	t10	3.645	2.324	6 .16	t10	2.916	1.859
1 .10	t1	1.95	1.95	6 .17	t1	0.3	0.3
1 .10	t2	2.189	2.154	6 .17	t2	0.337	0.331
1 .10	t3	2.608	2.44	6 .17	t3	0.401	0.375
1 .10	t4	3.173	2.787	6 .17	t4	0.488	0.429
1 .10	t5	3.886	3.19	6 .17	t5	0.598	0.491
1 .10	t6	4.75	3.649	6 .17	t6	0.731	0.561
1 .10	t7	5.766	4.166	6 .17	t7	0.887	0.641
1 .10	t8	6.917	4.738	6 .17	t8	1.064	0.729
1 .10	t9	8.172	5.365	6 .17	t9	1.257	0.825
1 .10	t10	9.478	6.042	6 .17	t10	1.458	0.93
1 .11	t1	0.75	0.75	6 .19	t1	0.15	0.15
1 .11	t2	0.842	0.828	6 .19	t2	0.168	0.166
1 .11	t3	1.003	0.939	6 .19	t3	0.201	0.188
1 .11	t4	1.221	1.072	6 .19	t4	0.244	0.214
1 .11	t5	1.494	1.227	6 .19	t5	0.299	0.245
1 .11	t6	1.827	1.404	6 .19	t6	0.365	0.281
1 .11	t7	2.218	1.602	6 .19	t7	0.444	0.32
1 .11	t8	2.66	1.822	6 .19	t8	0.532	0.364
1 .11	t9	3.143	2.063	6 .19	t9	0.629	0.413
1 .11	t10	3.645	2.324	6 .19	t10	0.729	0.465
1 .12	t1	0.3	0.3	6 .20	t1	0.15	0.15
1 .12	t2	0.337	0.331	6 .20	t2	0.168	0.166
1 .12	t3	0.401	0.375	6 .20	t3	0.201	0.188
1 .12	t4	0.488	0.429	6 .20	t4	0.244	0.214
1 .12	t5	0.598	0.491	6 .20	t5	0.299	0.245
1 .12	t6	0.731	0.561	6 .20	t6	0.365	0.281
1 .12	t7	0.887	0.641	6 .20	t7	0.444	0.32
1 .12	t8	1.064	0.729	6 .20	t8	0.532	0.364
1 .12	t9	1.257	0.825	6 .20	t9	0.629	0.413
1 .12	t10	1.458	0.93	6 .20	t10	0.729	0.465
1 .13	t1	0.75	0.75	6 .22	t1	0.15	0.15
1 .13	t2	0.842	0.828	6 .22	t2	0.168	0.166
1 .13	t3	1.003	0.939	6 .22	t3	0.201	0.188
1 .13	t4	1.22	1.072	6 .22	t4	0.244	0.214
1 .13	t5	1.494	1.227	6 .22	t5	0.299	0.245
1 .13	t6	1.827	1.404	6 .22	t6	0.365	0.281
1 .13	t7	2.218	1.602	6 .22	t7	0.444	0.32
1 .13	t8	2.66	1.822	6 .22	t8	0.532	0.364
1 .13	t9	3.143	2.063	6 .22	t9	0.629	0.413
1 .13	t10	3.645	2.324	6 .22	t10	0.729	0.465

Table 16 continued

1 .14	t1	0.45	0.45	17.1	t1	0.15	0.15
1 .14	t2	0.505	0.497	17.1	t2	0.168	0.166
1 .14	t3	0.602	0.563	17.1	t3	0.201	0.188
1 .14	t4	0.732	0.643	17.1	t4	0.244	0.214
1 .14	t5	0.897	0.736	17.1	t5	0.299	0.245
1 .14	t6	1.096	0.842	17.1	t6	0.365	0.281
1 .14	t7	1.331	0.961	17.1	t7	0.444	0.32
1 .14	t8	1.596	1.093	17.1	t8	0.532	0.364
1 .14	t9	1.886	1.238	17.1	t9	0.629	0.413
1 .14	t10	2.187	1.394	17.1	t10	0.729	0.465
1 .15	t1	0.75	0.75	17.2	t1	0.15	0.15
1 .15	t2	0.842	0.828	17.2	t2	0.168	0.166
1 .15	t3	1.003	0.939	17.2	t3	0.201	0.188
1 .15	t4	1.221	1.072	17.2	t4	0.244	0.214
1 .15	t5	1.494	1.227	17.2	t5	0.299	0.245
1 .15	t6	1.827	1.404	17.2	t6	0.365	0.281
1 .15	t7	2.218	1.602	17.2	t7	0.444	0.32
1 .15	t8	2.661	1.822	17.2	t8	0.532	0.364
1 .15	t9	3.143	2.063	17.2	t9	0.629	0.413
1 .15	t10	3.645	2.324	17.2	t10	0.729	0.465
1 .16	t1	0.75	0.75	17.4	t1	0.3	0.3
1 .16	t2	0.842	0.828	17.4	t2	0.337	0.331
1 .16	t3	1.003	0.939	17.4	t3	0.401	0.375
1 .16	t4	1.221	1.072	17.4	t4	0.488	0.429
1 .16	t5	1.494	1.227	17.4	t5	0.598	0.491
1 .16	t6	1.827	1.404	17.4	t6	0.731	0.561
1 .16	t7	2.218	1.602	17.4	t7	0.887	0.641
1 .16	t8	2.661	1.822	17.4	t8	1.064	0.729
1 .16	t9	3.143	2.063	17.4	t9	1.257	0.825
1 .16	t10	3.645	2.324	17.4	t10	1.458	0.93
1 .17	t1	0.6	0.6	17.5	t1	0.15	0.15
1 .17	t2	0.674	0.663	17.5	t2	0.168	0.166
1 .17	t3	0.803	0.751	17.5	t3	0.201	0.188
1 .17	t4	0.976	0.858	17.5	t4	0.244	0.214
1 .17	t5	1.196	0.982	17.5	t5	0.299	0.245
1 .17	t6	1.462	1.123	17.5	t6	0.365	0.281
1 .17	t7	1.774	1.282	17.5	t7	0.444	0.32
1 .17	t8	2.128	1.458	17.5	t8	0.532	0.364
1 .17	t9	2.514	1.651	17.5	t9	0.629	0.413
1 .17	t10	2.916	1.859	17.5	t10	0.729	0.465
1 .18	t1	0.15	0.15	17.6	t1	0.45	0.45
1 .18	t2	0.168	0.166	17.6	t2	0.505	0.497

Table 16 continued

1 .18	t3	0.201	0.188	17.6	t3	0.602	0.563
1 .18	t4	0.244	0.214	17.6	t4	0.732	0.643
1 .18	t5	0.299	0.245	17.6	t5	0.897	0.736
1 .18	t6	0.365	0.281	17.6	t6	1.096	0.842
1 .18	t7	0.444	0.32	17.6	t7	1.33	0.961
1 .18	t8	0.532	0.364	17.6	t8	1.596	1.093
1 .18	t9	0.629	0.413	17.6	t9	1.886	1.238
1 .18	t10	0.729	0.465	17.6	t10	2.187	1.394
1 .19	t1	0.45	0.45	17.7	t1	0.15	0.15
1 .19	t2	0.505	0.497	17.7	t2	0.168	0.166
1 .19	t3	0.602	0.563	17.7	t3	0.201	0.188
1 .19	t4	0.732	0.643	17.7	t4	0.244	0.214
1 .19	t5	0.897	0.736	17.7	t5	0.299	0.245
1 .19	t6	1.096	0.842	17.7	t6	0.365	0.281
1 .19	t7	1.331	0.961	17.7	t7	0.443	0.32
1 .19	t8	1.596	1.093	17.7	t8	0.532	0.364
1 .19	t9	1.886	1.238	17.7	t9	0.629	0.413
1 .19	t10	2.187	1.394	17.7	t10	0.729	0.465
1 .20	t1	0.45	0.45	17.8	t1	0.3	0.3
1 .20	t2	0.505	0.497	17.8	t2	0.337	0.331
1 .20	t3	0.602	0.563	17.8	t3	0.401	0.375
1 .20	t4	0.732	0.643	17.8	t4	0.488	0.429
1 .20	t5	0.897	0.736	17.8	t5	0.598	0.491
1 .20	t6	1.096	0.842	17.8	t6	0.731	0.561
1 .20	t7	1.331	0.961	17.8	t7	0.887	0.641
1 .20	t8	1.596	1.093	17.8	t8	1.064	0.729
1 .20	t9	1.886	1.238	17.8	t9	1.257	0.825
1 .20	t10	2.187	1.394	17.8	t10	1.458	0.93
1 .21	t1	0.15	0.15	17.9	t1	0.15	0.15
1 .21	t2	0.168	0.166	17.9	t2	0.168	0.166
1 .21	t3	0.201	0.188	17.9	t3	0.201	0.188
1 .21	t4	0.244	0.214	17.9	t4	0.244	0.214
1 .21	t5	0.299	0.245	17.9	t5	0.299	0.245
1 .21	t6	0.365	0.281	17.9	t6	0.365	0.281
1 .21	t7	0.444	0.32	17.9	t7	0.443	0.32
1 .21	t8	0.532	0.364	17.9	t8	0.532	0.364
1 .21	t9	0.629	0.413	17.9	t9	0.629	0.413
1 .21	t10	0.729	0.465	17.9	t10	0.729	0.465
1 .22	t1	0.6	0.6	17.10	t1	0.45	0.45
1 .22	t2	0.674	0.663	17.10	t2	0.505	0.497
1 .22	t3	0.803	0.751	17.10	t3	0.602	0.563
1 .22	t4	0.976	0.858	17.10	t4	0.732	0.643

Table 16 continued

1 .22	t5	1.196	0.982	17.10	t5	0.897	0.736
1 .22	t6	1.462	1.123	17.10	t6	1.096	0.842
1 .22	t7	1.774	1.282	17.10	t7	1.33	0.961
1 .22	t8	2.128	1.458	17.10	t8	1.596	1.093
1 .22	t9	2.514	1.651	17.10	t9	1.886	1.238
1 .22	t10	2.916	1.859	17.10	t10	2.187	1.394
1 .23	t1	0.45	0.45	17.11	t1	0.45	0.45
1 .23	t2	0.505	0.497	17.11	t2	0.505	0.497
1 .23	t3	0.602	0.563	17.11	t3	0.602	0.563
1 .23	t4	0.732	0.643	17.11	t4	0.732	0.643
1 .23	t5	0.897	0.736	17.11	t5	0.897	0.736
1 .23	t6	1.096	0.842	17.11	t6	1.096	0.842
1 .23	t7	1.331	0.961	17.11	t7	1.33	0.961
1 .23	t8	1.596	1.093	17.11	t8	1.596	1.093
1 .23	t9	1.886	1.238	17.11	t9	1.886	1.238
1 .23	t10	2.187	1.394	17.11	t10	2.187	1.394
1 .24	t1	0.15	0.15	17.12	t1	0.3	0.3
1 .24	t2	0.168	0.166	17.12	t2	0.337	0.331
1 .24	t3	0.201	0.188	17.12	t3	0.401	0.375
1 .24	t4	0.244	0.214	17.12	t4	0.488	0.429
1 .24	t5	0.299	0.245	17.12	t5	0.598	0.491
1 .24	t6	0.365	0.281	17.12	t6	0.731	0.561
1 .24	t7	0.444	0.32	17.12	t7	0.887	0.641
1 .24	t8	0.532	0.364	17.12	t8	1.064	0.729
1 .24	t9	0.629	0.413	17.12	t9	1.257	0.825
1 .24	t10	0.729	0.465	17.12	t10	1.458	0.93
6 .1	t1	0.15	0.15	17.13	t1	0.15	0.15
6 .1	t2	0.168	0.166	17.13	t2	0.168	0.166
6 .1	t3	0.201	0.188	17.13	t3	0.201	0.188
6 .1	t4	0.244	0.214	17.13	t4	0.244	0.214
6 .1	t5	0.299	0.245	17.13	t5	0.299	0.245
6 .1	t6	0.365	0.281	17.13	t6	0.365	0.281
6 .1	t7	0.443	0.32	17.13	t7	0.443	0.32
6 .1	t8	0.532	0.364	17.13	t8	0.532	0.364
6 .1	t9	0.629	0.413	17.13	t9	0.629	0.413
6 .1	t10	0.729	0.465	17.13	t10	0.729	0.465
6 .3	t1	0.15	0.15	17.14	t1	0.15	0.15
6 .3	t2	0.168	0.166	17.14	t2	0.168	0.166
6 .3	t3	0.201	0.188	17.14	t3	0.201	0.188
6 .3	t4	0.244	0.214	17.14	t4	0.244	0.214
6 .3	t5	0.299	0.245	17.14	t5	0.299	0.245
6 .3	t6	0.365	0.281	17.14	t6	0.365	0.281

Table 16 continued

6 .3	t7	0.444	0.32	17.14	t7	0.443	0.32
6 .3	t8	0.532	0.364	17.14	t8	0.532	0.364
6 .3	t9	0.629	0.413	17.14	t9	0.629	0.413
6 .3	t10	0.729	0.465	17.14	t10	0.729	0.465
6 .4	t1	0.3	0.3	17.15	t1	0.15	0.15
6 .4	t2	0.337	0.331	17.15	t2	0.168	0.166
6 .4	t3	0.401	0.375	17.15	t3	0.201	0.188
6 .4	t4	0.488	0.429	17.15	t4	0.244	0.214
6 .4	t5	0.598	0.491	17.15	t5	0.299	0.245
6 .4	t6	0.731	0.561	17.15	t6	0.365	0.281
6 .4	t7	0.887	0.641	17.15	t7	0.443	0.32
6 .4	t8	1.064	0.729	17.15	t8	0.532	0.364
6 .4	t9	1.257	0.825	17.15	t9	0.629	0.413
6 .4	t10	1.458	0.93	17.15	t10	0.729	0.465
6 .5	t1	0.15	0.15	17.16	t1	0.3	0.3
6 .5	t2	0.168	0.166	17.16	t2	0.337	0.331
6 .5	t3	0.201	0.188	17.16	t3	0.401	0.375
6 .5	t4	0.244	0.214	17.16	t4	0.488	0.429
6 .5	t5	0.299	0.245	17.16	t5	0.598	0.491
6 .5	t6	0.365	0.281	17.16	t6	0.731	0.561
6 .5	t7	0.444	0.32	17.16	t7	0.887	0.641
6 .5	t8	0.532	0.364	17.16	t8	1.064	0.729
6 .5	t9	0.629	0.413	17.16	t9	1.257	0.825
6 .5	t10	0.729	0.465	17.16	t10	1.458	0.93
6 .6	t1	0.6	0.6	17.17	t1	0.15	0.15
6 .6	t2	0.674	0.663	17.17	t2	0.168	0.166
6 .6	t3	0.803	0.751	17.17	t3	0.201	0.188
6 .6	t4	0.976	0.858	17.17	t4	0.244	0.214
6 .6	t5	1.196	0.982	17.17	t5	0.299	0.245
6 .6	t6	1.462	1.123	17.17	t6	0.365	0.281
6 .6	t7	1.774	1.282	17.17	t7	0.443	0.32
6 .6	t8	2.128	1.458	17.17	t8	0.532	0.364
6 .6	t9	2.514	1.651	17.17	t9	0.629	0.413
6 .6	t10	2.916	1.859	17.17	t10	0.729	0.465
6 .7	t1	0.3	0.3	17.22	t1	0.15	0.15
6 .7	t2	0.337	0.331	17.22	t2	0.168	0.166
6 .7	t3	0.401	0.375	17.22	t3	0.201	0.188
6 .7	t4	0.488	0.429	17.22	t4	0.244	0.214
6 .7	t5	0.598	0.491	17.22	t5	0.299	0.245
6 .7	t6	0.731	0.561	17.22	t6	0.365	0.281
6 .7	t7	0.887	0.641	17.22	t7	0.443	0.32
6 .7	t8	1.064	0.729	17.22	t8	0.532	0.364

Table 16 continued

6 .7	t9	1.257	0.825	17.22	t9	0.629	0.413
6 .7	t10	1.458	0.93	17.22	t10	0.729	0.465
6 .8	t1	0.6	0.6	17.23	t1	0.15	0.15
6 .8	t2	0.674	0.663	17.23	t2	0.168	0.166
6 .8	t3	0.803	0.751	17.23	t3	0.201	0.188
6 .8	t4	0.976	0.858	17.23	t4	0.244	0.214
6 .8	t5	1.196	0.982	17.23	t5	0.299	0.245
6 .8	t6	1.462	1.123	17.23	t6	0.365	0.281
6 .8	t7	1.774	1.282	17.23	t7	0.443	0.32
6 .8	t8	2.128	1.458	17.23	t8	0.532	0.364
6 .8	t9	2.514	1.651	17.23	t9	0.629	0.413
6 .8	t10	2.916	1.859	17.23	t10	0.729	0.465

REFERENCES

AASHTO, 2018. Infrastructure Needs for Autonomous Vehicles [WWW Document]. URL https://www.tam-portal.com/project/infrastructure-needs-for-autonomous-vehicles/ (accessed 10.11.19).

Abraham, H., Lee, C., Brady, S., Fitzgerald, C., Mehler, B., Reimer, B., Coughlin, J.F., 2016. Autonomous Vehicles, Trust, and Driving Alternatives: A survey of consumer preferences. Massachusetts Inst. Technol. AgeLab White Pap. 2016-6.

Alexopoulos, A., Assimacopoulos, D., Mitsoulis, E., 1993. Model for traffic emissions estimation. Atmos. Environ. Part B, Urban Atmos. https://doi.org/10.1016/0957-1272(93)90020-7

Azevedo, C.L., Marczuk, K., Raveau, S., Soh, H., Adnan, M., Basak, K., Loganathan, H., Deshmunkh, N., Lee, D.H., Frazzoli, E., Ben-Akiva, M., 2016. Microsimulation of demand and supply of autonomous mobility on demand. Transp. Res. Rec. https://doi.org/10.3141/2564-03

Barbier, E.B., 1987. The concept of sustainable economic development. Environ. Conserv. 14, 101–110.

Barth, M., Boriboonsomsin, K., 2009. Traffic Congestion and Greenhouse Gases. Access.

Barth, M., Boriboonsomsin, K., 2008a. Real-World CO2 Impacts of Traffic Congestion. Transp. Res. Rec.

Barth, M., Boriboonsomsin, K., 2008b. Real-world carbon dioxide impacts of traffic congestion. Transp. Res. Rec. https://doi.org/10.3141/2058-20

Beckmann, M., McGuire, C.B., Winsten, C.B., 1956. Studies in the Economics of Transportation.

Bell, M.G.H., Iida, Y., 1997. Transportation network analysis, Transportation network analysis. https://doi.org/10.1002/9781118903032

Bergenhem, C., Pettersson, H., Coelingh, E., Englund, C., Shladover, S., Tsugawa, S., 2012. Overview of platooning systems, in: 19th Intelligent Transport Systems World Congress, ITS 2012.

Boyce, D.E., Janson, B.N., 1980. A discrete transportation network design problem with combined trip distribution and assignment. Transp. Res. Part B. https://doi.org/10.1016/0191-2615(80)90040-5

Brundtland, G.H., Khalid, M., Agnelli, S., Al-Athel, S., Chidzero, B., 1987. Our common future. New York.

Chen, S., Saeed, T.U., Alqadhi, S.D., Labi, S., 2019. Safety impacts of pavement surface roughness at two-lane and multi-lane highways: accounting for heterogeneity and seemingly unrelated correlation across crash severities. Transp. A Transp. Sci. https://doi.org/10.1080/23249935.2017.1378281

Chen, Z., He, F., Yin, Y., 2016a. Optimal deployment of charging lanes for electric vehicles in transportation networks. Transp. Res. Part B Methodol. https://doi.org/10.1016/j.trb.2016.05.018

Chen, Z., He, F., Zhang, L., Yin, Y., 2016b. Optimal deployment of autonomous vehicle lanes with endogenous market penetration. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2016.09.013

Childress, S., Nichols, B., Charlton, B., Coe, S., 2015. Using an activity-based model to explore the potential impacts of automated vehicles. Transp. Res. Rec. https://doi.org/10.3141/2493-11

Chiou, S.W., 2005. Bilevel programming for the continuous transport network design problem. Transp. Res. Part B Methodol. https://doi.org/10.1016/j.trb.2004.05.001

Clement-Nyns, K., Haesen, E., Driesen, J., 2010. The impact of Charging plug-in hybrid electric vehicles on a residential distribution grid. IEEE Trans. Power Syst. https://doi.org/10.1109/TPWRS.2009.2036481

Combs, T.S., Sandt, L.S., Clamann, M.P., McDonald, N.C., 2019. Automated Vehicles and Pedestrian Safety: Exploring the Promise and Limits of Pedestrian Detection. Am. J. Prev. Med. https://doi.org/10.1016/j.amepre.2018.06.024

Connolly, R., Pierce, G., Zhu, Y., Gattaciecca, J., 2018. Estimating Public Health Benefits, Cost-Effectiveness, and Distributional Equity from California's Vehicle Emission Reduction Initiatives: Lessons from the San Joaquin Valley's Tune In & Tune Up Program, in: APHA's 2018 Annual Meeting & Expo (Nov. 10-Nov. 14). American Public Health Association.

Cordera, R., dell'Olio, L., Ibeas, A., Ortúzar, J. de D., 2019. Demand for environmentally friendly vehicles: A review and new evidence. Int. J. Sustain. Transp. https://doi.org/10.1080/15568318.2018.1459969

Cui, S., Seibold, B., Stern, R., Work, D.B., 2017. Stabilizing traffic flow via a single autonomous vehicle: Possibilities and limitations, in: IEEE Intelligent Vehicles Symposium, Proceedings. https://doi.org/10.1109/IVS.2017.7995897

Dresner, K., Stone, P., 2008. A multiagent approach to autonomous intersection management. J. Artif. Intell. Res. https://doi.org/10.1613/jair.2502

Elfar, A., Xavier, C., Talebpour, A., Mahmassani, H.S., 2018. Traffic shockwave detection in a connected environment using the speed distribution of individual vehicles. Transp. Res. Rec. https://doi.org/10.1177/0361198118794717

EPA, 2015. Sources of Greenhouse Gas Emissions. Clim. Chang.

EPA, n.d. Carbon Pollution from Transportation [WWW Document]. URL https://www.epa.gov/transportation-air-pollution-and-climate-change/carbon-pollution-transportation

Eykholt, K., Evtimov, I., Fernandes, E., Li, B., Rahmati, A., Xiao, C., Prakash, A., Kohno, T., Song, D., 2017. Robust Physical-World Attacks on Deep Learning Models.

Fagnant, D.J., Kockelman, K., 2015. Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. Transp. Res. Part A Policy Pract. https://doi.org/10.1016/j.tra.2015.04.003

Fagnant, D.J., Kockelman, K.M., 2014. The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2013.12.001

Ferranti, P., 2019. The United Nations Sustainable Development Goals, in: Encyclopedia of Food Security and Sustainability. https://doi.org/10.1016/b978-0-08-100596-5.22063-5

FHWA, 2018. FHWA National Dialogue on Highway Automation. Federal Highway Administration [WWW Document]. URL https://ops.fhwa.dot.gov/automationdialogue/ (accessed 10.11.19).

Gao, P., Kaas, H.-W., Mohr, D., Wee, D., 2016. Disruptive Trends That Will Transform the Auto Industry, McKinsey & Company.

Gkartzonikas, C., Gkritza, K., 2019. What have we learned? A review of stated preference and choice studies on autonomous vehicles. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2018.12.003

Goodman, A., Hastak, M., 2015. Infrastructure Planning, Engineering, and Economics, in: Infrastructure Planning, Engineering, and Economics.

Goodman, A.S., Hastak, M., 2006. Infrastructure planning handbook: planning, engineering, and economics. ASCE Press New York.

Greenblatt, J.B., Saxena, S., 2015. Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles. Nat. Clim. Chang. https://doi.org/10.1038/nclimate2685

Greenblatt, J.B., Shaheen, S., 2015. Automated Vehicles, On-Demand Mobility, and Environmental Impacts. Curr. Sustain. Energy Reports. https://doi.org/10.1007/s40518-015-0038-5

Harb, M., Xiao, Y., Circella, G., Mokhtarian, P.L., Walker, J.L., 2018. Projecting travelers into a world of self-driving vehicles: estimating travel behavior implications via a naturalistic experiment. Transportation (Amst). https://doi.org/10.1007/s11116-018-9937-9

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. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2016.09.003

Hedrick, J.K., Tomizuka, I.M., Varaiya, P., 1994. Control Issues in Automated Highway Systems. IEEE Control Syst. https://doi.org/10.1109/37.334412

Hess, A., Malandrino, F., Reinhardt, M.B., Casetti, C., Hummel, K.A., Barceló-Ordinas, J.M., 2012. Optimal deployment of charging stations for electric vehicular networks, in: CoNEXT UrbaNe 2012 - Proceedings of the ACM Conference on the 1st Workshop on Urban Networking. https://doi.org/10.1145/2413236.2413238

Hill, C.J., Garrett, K., 2011. AASHTO Connected Vehicle Infrastructure Deployment Analysis. Intell. Transp. Syst. Jt. Progr. Off.

Huegle, M., Kalweit, G., Mirchevska, B., Werling, M., Boedecker, J., 2019. Dynamic Input for Deep Reinforcement Learning in Autonomous Driving.

Ilgin Guler, S., Menendez, M., Meier, L., 2014. Using connected vehicle technology to improve the efficiency of intersections. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2014.05.008

Keeble, B.R., 1988. The Brundtland Report: "Our Common Future." Med. War. https://doi.org/10.1080/07488008808408783

Kim, S.W., Liu, W., Ang, M.H., Frazzoli, E., Rus, D., 2015. The Impact of Cooperative Perception on Decision Making and Planning of Autonomous Vehicles. IEEE Intell. Transp. Syst. Mag. https://doi.org/10.1109/MITS.2015.2409883

KPMG, 2018. Autonomous Vehicles Readiness Index: Assessing Countries' Openness and Preparedness for Autonomous Vehicles.

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

Labi, S., Saeed, T.U., Volovski, M., Alqadhi, S.D., 2015. An Exploratory Discussion of the Impacts of Driverless Vehicle Operations on the Man-Made Environment, in: 1st International Conference on Mechanical and Transportation Engineering. Kuala Lumpur, Malaysia.

LaMondia, J.J., Fagnant, D.J., Qu, H., Barrett, J., Kockelman, K., 2016. Shifts in long-distance travel mode due to automated vehicles: Statewide mode-shift simulation experiment and travel survey analysis. Transp. Res. Rec. https://doi.org/10.3141/2566-01

Lamotte, R., De Palma, A., Geroliminis, N., 2017. On the use of reservation-based autonomous vehicles for demand management. Transp. Res. Part B Methodol. 99, 205–227.

Land, A.H., Doig, A.G., 2010. An automatic method for solving discrete programming problems, in: 50 Years of Integer Programming 1958-2008: From the Early Years to the State-of-the-Art. https://doi.org/10.1007/978-3-540-68279-0_5

LeBlanc, L.J., Morlok, E.K., Pierskalla, W.P., 1975. An efficient approach to solving the road network equilibrium traffic assignment problem. Transp. Res. https://doi.org/10.1016/0041-1647(75)90030-1

Lee, J., Madanat, S., 2017. Optimal design of electric vehicle public charging system in an urban network for Greenhouse Gas Emission and cost minimization. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2017.10.008

Levin, M.W., Boyles, S.D., 2015. Effects of autonomous vehicle ownership on trip, mode, and route choice. Transp. Res. Rec. https://doi.org/10.3141/2493-04

Li, Z., Chitturi, M. V., Yu, L., Bill, A.R., Noyce, D.A., 2015. Sustainability effects of next-generation intersection control for autonomous vehicles. Transport. https://doi.org/10.3846/16484142.2015.1080760

Litman, T., 2014. Autonomous Vehicle Implementation Predictions: Implications for Transport Planning. Transp. Res. Board Annu. Meet. https://doi.org/10.1613/jair.301

Liu, Z., Song, Z., 2019. Strategic planning of dedicated autonomous vehicle lanes and autonomous vehicle/toll lanes in transportation networks. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2019.07.022

Lou, Y., Yin, Y., Lawphongpanich, S., 2009. Robust approach to discrete network designs with demand uncertainty. Transp. Res. Rec. https://doi.org/10.3141/2090-10

Lu, G., Nie, Y.M., Liu, X., Li, D., 2019. Trajectory-based traffic management inside an autonomous vehicle zone. Transp. Res. Part B Methodol. 120, 76–98.

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.

McCarthy, R., Yang, C., 2010. Determining marginal electricity for near-term plug-in and fuel cell vehicle demands in California: Impacts on vehicle greenhouse gas emissions. J. Power Sources. https://doi.org/10.1016/j.jpowsour.2009.10.024

McFarland, M., 2015. Elon Musk vents about California's lane markings confusing Tesla's autopilot. Washington Post.

McGuckin, T., Lambert, J., Newton, D., Pearmine, A., Hubbard, E., Sheehan, R., 2017. Leveraging the Promise of Connected and Autonomous Vehicles to Improve Integrated Corridor Management and Operations: A Primer. United States. Federal Highway Administration.

McTrans, 2008. TRANSYT-7F Users Guide, Canadian journal of surgery. Journal canadien de chirurgie.

Meng, Q., Yang, H., Bell, M.G.H., 2001. An equivalent continuously differentiable model and a locally convergent algorithm for the continuous network design problem. Transp. Res. Part B Methodol. https://doi.org/10.1016/S0191-2615(00)00016-3

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

Miralinaghi, M., Peeta, S., 2019. Promoting zero-emissions vehicles using robust multi-period tradable credit scheme. Transp. Res. Part D Transp. Environ. https://doi.org/10.1016/j.trd.2019.08.012

Miralinaghi, M., Peeta, S., 2016. Multi-period equilibrium modeling planning framework for tradable credit schemes. Transp. Res. Part E Logist. Transp. Rev. https://doi.org/10.1016/j.tre.2016.05.013

Miralinaghi, S., 2018. Multi-Period Tradable Credit Schemes for Transportation and Environmental Applications.

NHTSA, 2016. Federal Automated Vehicles Policy: Accelerating the Next Revolution In Roadway Safety. U.S. Dep. Transp. https://doi.org/12507-091216-v9

Orosz, G., Wilson, R.E., Stépán, G., 2010. Traffic jams: dynamics and control. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 368, 4455–4479. https://doi.org/10.1098/rsta.2010.0205

Parkin, J., Sharma, D., 1999. Infrastructure planning. Thomas Telford.

Pasik-Duncan, B., 2019. Advances in noise modeling in stochastic systems and control.

Perujo, A., Ciuffo, B., 2010. The introduction of electric vehicles in the private fleet: Potential impact on the electric supply system and on the environment. A case study for the Province of Milan, Italy. Energy Policy. https://doi.org/10.1016/j.enpol.2010.04.010

Polzin, S.E., Chu, X., Toole-Holt, L., 2004. Forecasts of future vehicle miles of travel in the United States, in: Transportation Research Record. https://doi.org/10.3141/1895-19

Qin, H., Zhang, W., 2011. Charging scheduling with minimal waiting in a network of electric vehicles and charging stations, in: Proceedings of the Annual International Conference on Mobile Computing and Networking, MOBICOM. https://doi.org/10.1145/2030698.2030706

R., D.J., Beckman, M., McGuire, C.B., Winsten, C.B., Koopmans, T.C., 1956. Studies in the Economics of Transportation. OR. https://doi.org/10.2307/3007560

Ramasubramanian, L., Albrecht, J., 2018. Planning Challenges and the Challenges of Planning, in: Essential Methods for Planning Practitioners. Springer, pp. 15–37.

Richardson, D.B., 2013. Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2012.11.042

Riggs, W., Larco, N., Tierney, G., Ruhl, M., Karlin-Resnick, J., Rodier, C., 2019. Autonomous Vehicles and the Built Environment: Exploring the Impacts on Different Urban Contexts. https://doi.org/10.1007/978-3-319-94896-6_19

Saeed, T.U., 2019. Road Infrastructure Readiness for Autonomous Vehicles. Purdue University. https://doi.org/10.25394/PGS.8949011.v1

Sarker, M.R., Pandžić, H., Ortega-Vazquez, M.A., 2015. Optimal operation and services scheduling for an electric vehicle battery swapping station. IEEE Trans. Power Syst. https://doi.org/10.1109/TPWRS.2014.2331560

Shao, H., Lam, W.H.K., Tam, M.L., 2006. A reliability-based stochastic traffic assignment model for network with multiple user classes under uncertainty in demand. Networks Spat. Econ. https://doi.org/10.1007/s11067-006-9279-6

Sheffi, Y., 1984. Urban Transportation Networks. Prentice-Hall.

Shladover, S.E., 1992. The California PATH Program of IVHS research and its approach to vehicle-highway automation, in: IEEE Intelligent Vehicles Symposium, Proceedings. https://doi.org/10.1109/IVS.1992.252284

Sinha, K.C., Labi, S., 2007. Transportation Decision Making: Principles of Project Evaluation and Programming, Transportation Decision Making: Principles of Project Evaluation and Programming. https://doi.org/10.1002/9780470168073

Smith, D.K., Ahuja, R.K., Magnanti, T.L., Orlin, J.B., 1994. Network Flows: Theory, Algorithms, and Applications. J. Oper. Res. Soc. https://doi.org/10.2307/2583863

Stephens, T.S., Levinson, R.S., Brooker, A., Liu, C., Lin, Z., Birky, A., Kontou, E., 2017. Comparison of Vehicle Choice Models. Argonne National Lab.(ANL), Argonne, IL (United States).

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

Sugiyamal, Y., Fukui, M., Kikuchi, M., Hasebe, K., Nakayama, A., Nishinari, K., Tadaki, S.I., Yukawa, S., 2008. Traffic jams without bottlenecks-experimental evidence for the physical mechanism of the formation of a jam. New J. Phys. https://doi.org/10.1088/1367-2630/10/3/033001

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

Talebpour, A., Mahmassani, H.S., Elfar, A., 2017. Investigating the effects of reserved lanes for autonomous vehicles on congestion and travel time reliability. Transp. Res. Rec. https://doi.org/10.3141/2622-01

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

Treiber, M., Hennecke, A., Helbing, D., 2000. Congested traffic states in empirical observations and microscopic simulations. Phys. Rev. E - Stat. Physics, Plasmas, Fluids, Relat. Interdiscip. Top. https://doi.org/10.1103/PhysRevE.62.1805

Triggs, T.J., Harris, W.G., 1982. REACTION TIME OF DRIVERS TO ROAD STIMULI. Hum. Factors Rep. HFR.

Ukkusuri, S. V., Mathew, T. V., Waller, S.T., 2007. Robust transportation network design under demand uncertainty. Comput. Civ. Infrastruct. Eng. https://doi.org/10.1111/j.1467-8667.2006.00465.x

United Nations, 2017. The Sustainable Development Goals Report. United Nations Publ. https://doi.org/10.18356/3405d09f-en

United Nations, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. United Nations Sustainable knowledge platform. Sustain. Dev. Goals. https://doi.org/https://sustainabledevelopment.un.org/post2015/transformingourworld

United Nations, 2007. Indicators of Sustainable Development : Guidelines and Methodologies, New York. https://doi.org/10.1016/j.cirpj.2010.03.002

USDOT, 2019. Preparing for the Future of Transportation: Automated Vehicles 3.0.

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 Brummelen, J., O'Brien, M., Gruyer, D., Najjaran, H., 2018. Autonomous vehicle perception: The technology of today and tomorrow. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2018.02.012

Veurman, J., Gense, N.L.J., Wilmink, I.R., Baarbé, H.I., 2002. Emissions at different conditions of traffic flow, in: Advances in Transport.

Wardrop, J.G., 1952. Some Theoretical Aspects of Road Traffic Research. ICE Proc. Eng. Div. https://doi.org/10.1680/ipeds.1952.11260

Weinstein, A., Sciara, G.C., 2006. Unraveling equity in HOT lane planning: A view from practice. J. Plan. Educ. Res. https://doi.org/10.1177/0739456X06288093

Wu, C., Bayen, A.M., Mehta, A., 2018. Stabilizing Traffic with Autonomous Vehicles, in: Proceedings - IEEE International Conference on Robotics and Automation. https://doi.org/10.1109/ICRA.2018.8460567

Yang, H., 2005. Mathematical and Economic Theory of Road Pricing, Mathematical and Economic Theory of Road Pricing. https://doi.org/10.1108/9780080456713

Yang, H., Bell, M.G.H., 1998. Models and algorithms for road network design: A review and some new developments. Transp. Rev. https://doi.org/10.1080/01441649808717016

Yang, H., Meng, Q., 2001. Modeling user adoption of advanced traveler information systems: Dynamic evolution and stationary equilibrium. Transp. Res. Part A Policy Pract. https://doi.org/10.1016/S0965-8564(00)00030-6

Yin, Y., Lawphongpanich, S., 2006. Internalizing emission externality on road networks. Transp. Res. Part D Transp. Environ. https://doi.org/10.1016/j.trd.2006.05.003

Yu, H., Tak, S., Park, M., Yeo, H., 2019. Impact of Autonomous-Vehicle-Only Lanes in Mixed Traffic Conditions. Transp. Res. Rec. https://doi.org/10.1177/0361198119847475

Zhang, K., Batterman, S., Dion, F., 2011. Vehicle emissions in congestion: Comparison of work zone, rush hour and free-flow conditions. Atmos. Environ. https://doi.org/10.1016/j.atmosenv.2011.01.030

Zhang, L., Lawphongpanich, S., Yin, Y., 2009. An Active-set Algorithm for Discrete Network Design Problems, in: Transportation and Traffic Theory 2009: Golden Jubilee. https://doi.org/10.1007/978-1-4419-0820-9_14

Zhang, W., Guhathakurta, S., Khalil, E.B., 2018. The impact of private autonomous vehicles on vehicle ownership and unoccupied VMT generation. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2018.03.005

Zhu, M., Wang, X., Wang, Y., 2018. Human-like autonomous car-following model with deep reinforcement learning. Transp. Res. Part C Emerg. Technol. https://doi.org/10.1016/j.trc.2018.10.024