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Lane Management in the Era of CAV Deployment

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16. Abstract

The last century has witnessed increased urban sprawl, motorization, and the attendant problems of congestion, safety, and emissions associated with current-day transportation systems. In contemporary literature, researchers suggest that the emerging transportation technologies, including vehicle autonomy and connectivity, offer great promise in helping to address these adversities. As such, highway agencies seek guidance on infrastructure preparations for connected and automated vehicle (CAV) operations. A key area of such preparations is the management of lanes to serve CAVs and human-driven vehicles (HDVs), including the deployment of dedicated lanes for CAVs. There is a need to address the demand and supply perspectives of CAV preparations. On the demand side, agencies need to model reliably the trends and uncertainties of CAV market penetration and level of autonomy during the CAV transition period. On the supply side, agencies need to schedule the CAV-related roadway infrastructure in a way that progressively addresses the growing demand in a strategic and systematic manner. In addressing these research questions, this report first carries out an economics-based lane allocation for CAVs and HDVs in a highway corridor by determining the optimum number of CAVLs by minimizing road user cost. Next, the report carries out such allocation considering the environment (community emissions cost). Third, the report addresses some elements of social and economic sustainability by using a CAV-enabled tradable credit scheme that minimizes user travel time subject to social equity constraints. Further, this report provides guidance on how CAV-dedicated lanes, in conjunction with market-based tradable travel credits, could enable the road agency to achieve maximum efficiency of the existing road infrastructure in the CAV transition period. The key outcome of the framework is an optimal schedule for deploying CAV-dedicated lanes over a given analysis period of several decades in a manner commensurate with CAV demand projections and sustainability-related objectives and constraints. The report also presents guidelines for the implementation of managed lanes in the CAV era. The study framework can serve as a valuable decision-support tool for road agencies in their long-term planning and budgeting in anticipation of the CAV transition period.

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LIST OF ACRONYMS

Acronym	**Meaning**
A&C	Automation and Connectedness
CAV	Connected and Autonomous Vehicle
CAHV	Connected and Autonomous Heavy Vehicle
CANHV	Connected and Autonomous Non-Heavy Vehicle
CAVL	CAV-dedicated Lane
CAVMP	CAV Market Penetration
ICT	Information and Communication Technology
GPL	General Purpose Lane
HDV	Human-Driven Vehicle
LCP	Linear Complementarity Problem
MLCP	Mixed-Linear Complementarity Problem
MPEC	Mathematical Program with Equilibrium Constraints
OCAVLT	Optimal Strategies with CAVLs and Tolling Policy
O-D	Origin-Destination
TCS	Tradable Credit Scheme
TLMCAV	Travel Demand and Lane Management Strategies in the CAV Transition Era
V2V	Vehicle-to-Vehicle
WPS	Worst-case Possible Scenario

COMMONLY USED TERMS

Equity threshold	The lowest acceptable ratio of HDV user benefit to CAV user benefit.
Bi-level model	A decision-making problem where one sub-problem is embedded (nested) within another.
Bottleneck congestion	Congestion at a specific location in a corridor where there is a sudden increase in demand for a fixed capacity or decrease in capacity for given demand.
Deterministic design	Design of a system where the levels of inputs are fixed, not variable.
General-purpose lane	A lane that is accessible to all types or classes of vehicles without restriction.
Lane allocation or assignment	Distribution of a set of lanes (new or existing lanes) to a specific vehicle class such as CAV, EV or heavy vehicles.
Lane appropriation	Reassigning a lane from one vehicle class to another.
Lane capacity	The maximum number of vehicles that a lane can serve per unit of time.
Lane reallocation	Modifying the existing allocation of lanes among the vehicle classes/types.
Lower-level model	A model (nested in a bi-level model) that determines the optimal decision of the secondary class of decision-makers and estimates the resulting outcomes.
Managed lane	A highway lane that functions independently from general-purpose lanes, for which operational strategies such as managing access, restricting eligibility, or employing variable pricing are implemented and managed, often in real time in response to changing conditions.
Mixed stream	Multiple classes of vehicles using a road corridor simultaneously.

Priced managed lane	A type of managed lane that incorporates congestion pricing and lane management. Common examples include express toll lanes, variable-price lanes, and high-occupancy toll lanes.
Queuing delay	Time spent by a vehicle waiting in a queue.
Robust design	A design that makes the infrastructure, operations policies, or performance outcomes less sensitive to variations in uncontrollable variable inputs.
Sustainability	A set of economic, environmental, and social conditions where society has the capacity/opportunity to maintain/improve its quality of life for future generations without degrading the quantity, quality, or the availability of economic, environmental, and social resources.
Sustainable development	Development that meets the needs of the present without compromising the ability of the future generations to meet their own needs, and therefore seeks to minimize the adverse impacts of the infrastructure to the economy, environment, and social sectors.
System optimal	A condition under which the total cost of network usage is minimized by redistributing traffic flow in the network.
Total system cost	The overall cost of system consisting of the costs borne by the owner (agency), users, and the community.
Transport decision-makers	The road agency which makes the managed-lane investment decisions. Typically, this agency and/ or its private sector partner owns and/or operates the roadway infrastructure. In some cases, the lane type provision and/or charging facility type are provided by a private-sector entity through lease, design-build-operate contracting, or as infrastructure owned or operated independently of the road network.
Traditional lane	A lane used by a predefined “basic” type of vehicle, as one without “special” characteristics such as size, toll-paying status, automation level, multiple occupancy status, propulsion energy type and so on.
Special lane	A lane used by a vehicle that is non-basic, that is, has “special” characteristics.

Travel demand	The number of travel units (vehicles, passengers, pedestrians) per unit time that seek to use a given transportation facility at a certain level of service.
Upper-level model	A model (nested in a bi-level model) that addresses the decision structure of the primary decision-maker.
User equilibrium	A condition under which no traveler can improve their travel cost by unilaterally changing their travel choices.

CHAPTER 1 INTRODUCTION

1.1 Study Background

1.1.1 Urban congestion and the promise of emerging transportation technologies

Increased urban development and its attendant problems, such as traffic congestion and emissions, are inevitable due to growing populations worldwide, particularly over the last century. Technology-based solutions offer a great opportunity to address these problems (Alawadhi et al., 2012), and have received increasing interest during the last decade (Federal Highway Administration, 2018; Ong & Hwang, 2019; Volpe Center, 2015). The need for technological solutions is underscored by ever-increasing population growth, urbanization, and motorization. The United Nations estimates that currently 55% of the world's population lives in urban areas and this is projected to increase to 68% by 2050 (United Nations, 2018). In several cities, the existing transportation, water and wastewater, and energy infrastructure systems were designed decades ago to serve far smaller demand, and increasing populations have caused excess demand, and subsequently, poor levels of service (World Bank, 2018).

Unfortunately, such population growth is unfolding at a time when urban areas are already grappling with providing the infrastructure needed to support their populations due to funding inadequacy or lack of skilled managers (Birkmann et al., 2016). According to Grimm et al. (2008) and Alberti (2017), the confluence of structural, functional, and social evolutions has resulted in daunting challenges for city authorities as they struggle to provide critical infrastructure services for their residents. The theme of the 2018 IEEE International Smart Cities Conference included a statement that "as sensors, data, connectivity, networks, and analytics offer opportunities to improve each of these systems independently, the common elements of the technology infrastructure offer more opportunities for interoperability across systems and to reframe how to optimize and make decisions about these systems."

The American Society of Civil Engineers (ASCE, 2018a, b) infers that the future urban development will be motivated by the need for intelligent ways to provide quick and reliable information to facilitate operations and other phases of the life cycle development of municipal infrastructure in a manner that is economic, social, and environmentally responsible. This report addresses specific elements of smart transportation as it pertains to the management of a specific class of transportation infrastructure and its operations to mitigate congestion and/or promote social equity and environmental benefits. As part of smart road management, urban road agencies can exploit vehicle automation and connectedness to facilitate efficient use of their road networks.

1.1.2 Connected and automated vehicles (CAVs)

CAVs provide a unique opportunity for urban road agencies to facilitate progress toward achieving smart mobility and safety (FHWA, 2020; Office of the Assistant Secretary for Research and Technology, 2015; Peeta, 2019; Gruyer et al., 2021; USDOT, 2022). This disruptive technology has been well received by transportation and technology agencies and companies. Uber, for example, has stated that it intends to have fully autonomous taxis by 2030 (Goddin, 2015). CAVs are generally controlled by algorithms not humans, and thus can eliminate human error and thereby increase traffic safety. The connectivity feature of CAVs enables the exchange of information to and from other CAVs through vehicle-to-vehicle (V2V) and intelligent roadside units (vehicle-to-infrastructure(V2I)). This allows CAVs to form platoons which increase road capacity and decrease energy consumption (Fernandes & Nunes, 2012). The automation and connectedness of smart city entities, such as their infrastructure, services, and vehicles, can be helpful. In this regard, CAVs and related infrastructure have great potential to reduce congestion from the standpoint of travel demand management and supply increase. This is expected to happen particularly during the anticipated "transition period" that will be characterized by mixed streams (CAVs and human driven vehicles (HDVs)). Two aspects of this potential could be examined: connectivity-enabled travel demand management and transportation infrastructure supply general purpose and CAV-lanes established appropriately through lane management.

1.1.3 Lane management for CAVs

To leverage the capabilities of CAVs for congestion mitigation, urban road agencies need to develop smart governance, including intelligent transportation infrastructure planning and management. During the CAV transition period, traffic flow will comprise both CAVs and HDVs, referred to as a mixed stream. Through connectivity and automation, CAVs can help reduce headways and therefore increase capacity. However, such efficacy could be seriously jeopardized in a mixed fleet. Therefore, the concept of CAV-dedicated lanes (CAVLs) during the transition period is increasingly gaining attention among transportation researchers (Chen et al., 2016; Conceicão et al., 2021; Liu & Song, 2019; L. Ye & Yamamoto, 2018).

1.2 Problem statement

It is needed to address the issue of lane management from the perspectives of three stakeholders involved in transportation infrastructure projects: (i) the urban road agency or municipal infrastructure authorities; (ii) the road users; and (iii) the community. Based on the concerns of these stakeholders, it is needed to propose strategies to address a number of aspects of sustainable development of managed lanes in the CAV era. In this regard, there is a need to: focus on the economically sustainable design of lane management strategies for CAVs and HDVs in a highway corridor; focus on network-level lane management that is environmentally and socially sustainable; capture the forecast uncertainty of potential CAV market size; consider smaller widths for CAVLs that could possibly help to increase the number of lanes in a highway corridor; and address social sustainability by considering equity.

1.3 Study objectives and approaches

The primary objective of this study is to develop a framework for CAVL lane management for a highway road network. First, this report seeks to capture economic sustainability as it determines the number of CAVLs that minimizes the total cost incurred by the road users (travelers). To capture the goal of travelers (total travel time and schedule delay costs), the study seeks to ensure that the framework can help agencies explore the corridor-level design of CAVLs that minimize travelers' costs. Second, this report is intended to capture environmental sustainability (specifically, minimize the worst-case vehicle emissions under the lane reallocation strategy and potential CAV market size). Finally, this report seeks to address social sustainability by reducing social inequity. This is herein sought to use the concept of tradable mobility credits, to minimize the total travel time and to capture equity in terms of excess travel-imposed costs on HDVs due to the allocation of a part of the original road capacity to CAVs. This can address both economic and social sustainability in the system. The study results can help agencies explore the network-wide design of CAVLs while minimizing community cost.

1.4 Organization of the report

This report has eleven (11) chapters. Chapter 2 provides an overview of the definition of sustainability and discusses how different chapters of this report address the different aspects of sustainability. Chapter 3 briefly discusses the effects of CAVs on pavement degradation. Chapter 4 provides a comprehensive literature review of studies related to the design of CAVLs. Then, the gaps between the current literature and the real-world problems are identified. Chapter 5 provides a framework to identify the optimal CAV lane management strategy for a highway corridor. A lane-specific tolling scheme, i.e., different tolls for CAVLs and GPLs, is designed to ensure the minimum total travel cost for users. In this chapter, the equilibrium conditions are formulated as a mixed-linear program with complementarity constraints. The system-optimal condition is formulated as a linear program that determines the optimum number of CAVLs and a lane-specific tolling scheme. The control variable by the urban authorities is the optimal number of CAVLs. CAVs are allowed to use both dedicated and general-purpose lanes (GPLs). Chapter 6 extends this framework to the network level, to identify the optimal CAV lane management strategy at a collection of links, while considering potential CAV market size uncertainty and lateral vehicle positioning control and lane width reduction. Chapter 7 presents a TLMCAV strategy which captures the equity in the implementation of the CAV lane management. It first presents a CAV-enabled tradable credit scheme (TCS) to manage demand where the transportation authority distributes travel credits to travelers directly and instantaneously using the CAVs' automation and connectivity (A&C) features. Travelers use their A&C features to pay these credits for travel to specific locations or times-of-day according to their choices of lane types and links. This part models the expected travel choices based on user equilibrium concepts at different levels of CAV market penetration and demonstrates the existence and uniqueness of an optimal solution in terms of link flows and the prevailing travel credit price. Chapter 8 presents implementation issues associated with lane road management for the new generation transportation technologies of automation and connectivity. Chapter 9 concludes the study with a summary of the research methods and results, the research contributions to existing literature, the study limitations, and future research directions. Chapter 10 presents the levels of performance of this research study in the context of USDOT's research performance indicators, and Chapter 11 presents a synopsis of the study outcomes and outputs. Figure 1.1 presents the structure and main aspects of this report.

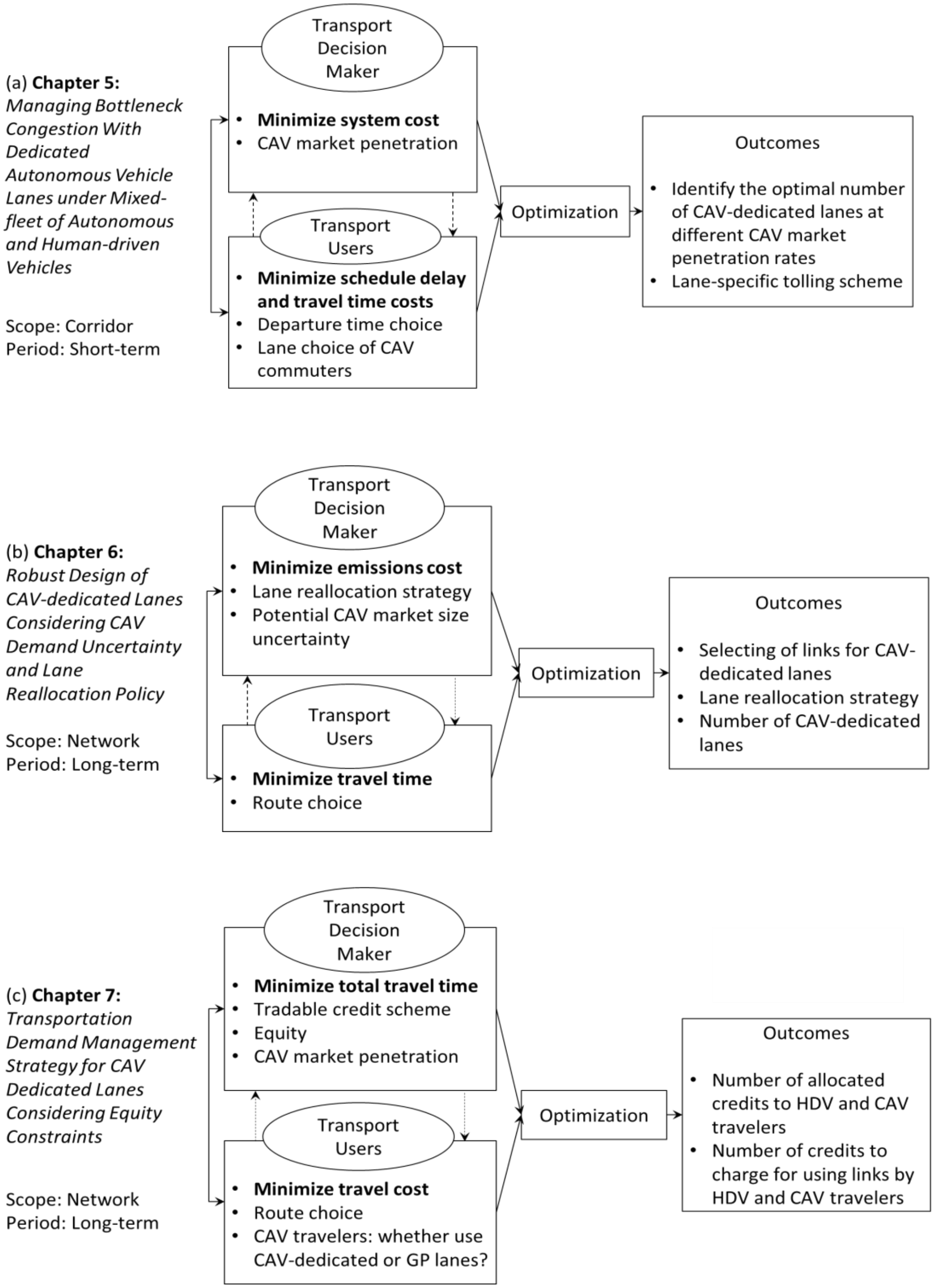


Figure 1.1 Overall structure of the study

CHAPTER 2 CONCEPT OF SUSTAINABLE DEVELOPMENT IN THE CONTEXT OF THE EMERGING TRANSPORTATION TECHNOLOGIES

2.1 Introduction

The concept of sustainability, as stated in the literature, holds that communities are made up of economic, social, and environmental resources and entities that constantly interact with one another and that these interactions must be maintained in a state of harmonious balance, otherwise the community's future survival will be jeopardized. The ASCE Policy Statement 418, on the role of the civil engineer in sustainable development (ASCE, 2018a), defines sustainable development as "supplying people with the energy, food, shelter, transportation, and waste management they require while preserving and safeguarding the environment's quality and the natural resource base necessary for future development." This definition indicates the need for enhanced environmental protection while acknowledging the need for economic growth to meet societal requirements. The importance of sustainable design, construction, and operations has been acknowledged by civil engineering professional organizations all around the world. According to the ASCE policy statement, "civil engineers must commit that before a project is approved, its economic, environmental, and social implications on impacted communities must be evaluated and understood by all stakeholders, and civil engineers must actively engage stakeholders to ensure public knowledge and acceptance of a project's economic, environmental, and social costs and benefits" (ASCE, 2021).

Civil systems developers have a fiduciary responsibility to shape present and future development of civil systems in a manner that is sustainable. ASCE (2021) defined sustainability as: "A set of economic, environmental, and social conditions in which all of society has the capacity and opportunity to maintain and improve its quality of life for future generations without degrading the quantity, quality, or the availability of economic, environmental, and social resources." Also, OECD (1997) defined it as the "(a) use of the biosphere by present generations while maintaining its potential yield (benefit) for future generations; and/or (b) non-declining trends of economic growth and development that might be impaired by natural resource depletion and environmental degradation." Gilman (1992) defined it as "the ability of a society, ecosystem, or any such on-going system to continue functioning into the indefinite future without being forced into decline through the exhaustion or overloading of key resources on which that system depends." Sustainability can play an important role in civil system decision-making processes by serving as a yardstick against which civil systems managers compare proposed or past actions, plans, expenditures, and decisions, which can influence the system's efficacy or longevity (Labi, 2014).

In the period of 1800–1970, the world population tripled, accompanied by a massive economic growth (of 1730 times) (Pisani, 2006), exacerbating social issues such as poverty, hunger, social inequality, and increasing pressure on finite natural resources. The concept of sustainability emerged in early 1970s but attracted more attention following the release of the Brundtland report (Brundtland, 1987) which defines sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." There are several other definitions of sustainable development in the literature.

There is a school of thought that holds the view that the phrase "sustainable development" is a "bad oxymoron" and that the two terms are incompatible; in other words, they believe that sustainability and development cannot coexist (Daly, 2008; Redclift, 2005). Others disagree (Redclift, 2005; Soubbotina, 2004). Traditionally, economic growth generally means growth in gross national product (GNP) which generally consists of both quantitative increase and qualitative improvement. Sustainable growth, however, declares that future growth must be qualitatively different from the past: less output-focused and more environmentally friendly. Given the latter definition of economic growth, society should strive for economic progress that does not come at the expense of its citizens or undue degradation of its natural resources.

Regarding the use of natural resources, there are two basic notions that have been propounded. One notion is that natural resources are utilitarian and exist to sustain humanity; in other words, they are viewed as just another good or service and are therefore, to some extent, interchangeable. The alternative perspective does not support the utilitarian perspective, and instead holds that resources should be used, albeit wisely and sparingly because most of them cannot be replaced. In other words, resources must be used while protecting this capital for future generations. These two perspectives are generally referred to as the two types of sustainable urban development: weak and strong sustainability (Brand, 2009; Dietz & Neumayer, 2007; Ekins et al, 2003; Neumayer, 2013). The definition of weak sustainability which can be found in traditional economics states that the human gain due to economic activities can compensate for the associated environmental degradation. The proponents of weak sustainability postulate that the future generation will have advanced technologies with more resources to address the environmental issues and, hence, fewer efforts need to be made today to avoid future problems. Strong sustainability supports the need to protect resources because they are essential to supporting life itself and because they bring other benefits, in addition to their material utility that are not interchangeable, such as landscapes, the beauty of nature, etc. Therefore, sustainable development can be described as inherently strong rather than weak as it is not possible to substitute natural capital with manmade capital (Munier, 2005).

From the definition of sustainability, there are three main elements or pillars considered for sustainability discussions: economic, environmental, and social (Figure 2.1). Infrastructure development is **viable** when it is sound economically and environmentally, **bearable** when it is sound environmentally and socially, and **equitable** when they are sound economically and socially (Barbier, 1987). The definitions of sustainable development suggest that a set of actions at present are required to maintain a balance between the three pillars of sustainability: economic, environmental, and social, to make it possible for the long-term descendants in the future to achieve their needs. The current sustainability metrics frequently incorporate social, economic, and environmental data. However, determining quantitative metrics for each of the three characteristics is not straightforward. Sociologists still find it difficult to develop metrics for quality-of-life issues since they are intangible, in contrast to economists who find it easy to do so (Braham & Casillas, 2020). On the other hand, due to technological advancements, it is difficult to precisely forecast long-term demands, potential challenges, or the resources that will be available in the distant future. These make it challenging to define distinct objectives. However, these universal goals such as the right to housing, food, accessible education, and healthcare; the right to equal chances and respect for all, regardless of gender, ethnicity, income level, or religion; the right to live in a clean environment, etc., are universal goals that will still be relevant in the future. Hence, evaluation of the future development of engineering systems including CAV related infrastructure, is not possible without considering sustainability.

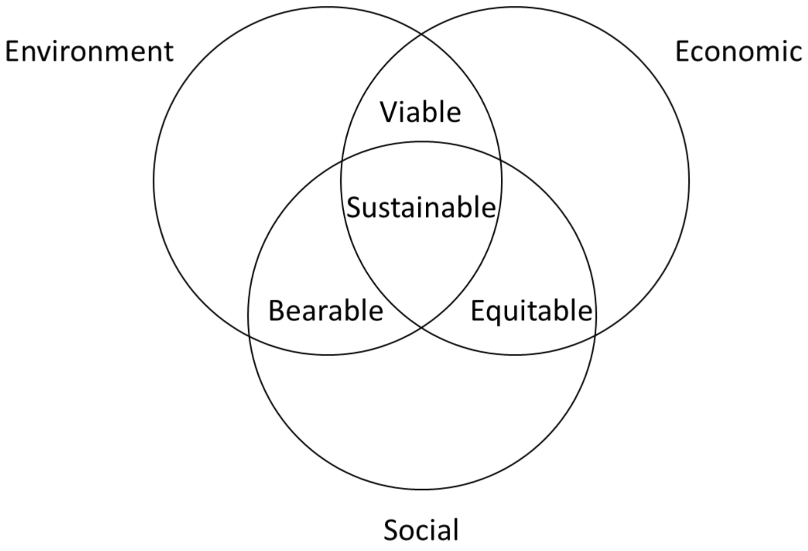


Figure 2.1 The three pillars of sustainability (Barbier, 1987)

2.2 Metrics for sustainability in transportation systems

To evaluate the sustainability of transportation systems development, metrics or quantitative metrics are required. To measure the improvements related to the three pillars of sustainability economic, ecological, and sociological metrics are used in the literature. Besides these one-dimensional metrics, there are others that consider two pillars and are related to the interaction of two aspects of sustainability, for example, socio-ecological, and socio-economic metrics. The metrics obtained from the interaction of all three aspects are the true sustainability metrics (Soubbotina, 2004). Amekudzi et al. (2015) proposed a framework for sustainable development evaluation with composite metrics considering all the three aspects of sustainability. Parris and Kates (2003) compared twelve selected attempts to measure sustainable development with different sets of metrics and highlight that there is no universally accepted metric of progress for sustainable development. Roca and Searcy (2012) compared the metrics in Canadian corporate sustainability reports and concluded that there is a high diversity in the metrics reported. Transportation systems, particularly at urban areas, profoundly influence economic productivity of business entities and the system users, the social wellbeing of the community, safety of pedestrians and drivers, and emissions, air quality, and noise. These are all related to the three pillars of sustainability. As such, in the evaluation of urban transportation systems and any emerging technologies, it is important to identify and apply appropriate metrics of sustainable development.

Jeon and Amekudzi (2005) identified metrics related to 16 initiatives for evaluating sustainable development. Economic efficiency, tax revenues, home-work trip distance and time, total investment in infrastructure maintenance costs, total road expenditures, change in the level of road congestion over time, emission levels, greenhouse gas emissions, fossil fuel consumption, air pollution costs, income inequality, and user benefit inequality are some examples of these metrics. Jeon et al. (2013) pointed out that the essential factors that must be considered in transportation system sustainability are: economic sustainability, including economic efficiency, economic development, and financial affordability; environmental sustainability, including environmental integrity, natural resources, and system resilience; socio-cultural sustainability, including social equity, safety, health, and quality of life; and transportation sustainability, including congestion reduction, mobility, and system performance. While there is no universal definition for transportation sustainability and its metrics, there is a growing agreement that to be effective, the measurements must consider impacts on economic, environmental, and social aspects. Yet still, it is generally difficult to find solutions that result in improvement in all three aspects of sustainability simultaneously. As illustrated by Campbell's planner's triangle in Figure 2.2 (Campbell, 1996), there exist fundamental conflicts between the three aspects, and planners often tend to have a professional bias toward one specific goal.

The concept of trade-off means that, due to the nature of the metrics or the funding being allocated to specific activities or locations, the achievement of high levels of one metric may come at the expense of another. Therefore, trade-off analysis is often required to identify how much of a sustainability metric is being achieved at the cost of another. The concept of trade-off can also be extended in time. For instance, in consideration of sustainability for civil engineering systems, decision-making generally entails a higher initial cost and a reduced overall cost over the life cycle of the system. In the field of transportation asset management, several researchers have identified various types of trade-offs that exist (Bai et al, 2008; Bai et al., 2012; Laumet and Bruun, 2016; Bryce et al., 2018; Parnell et al., 2019; Miralinaghi et al., 2020; Akbar et al, 2020; Seilabi et al., 2022). For example, using CAVs, how much mobility can be gained at the expense of safety, or vice versa? The most effective approach for trade-off analysis is multi-criteria decision making which is beyond the scope of this report. However, trade-offs related to different aspects of the CAV-dedicated lane design are addressed in subsequent chapters of this report.

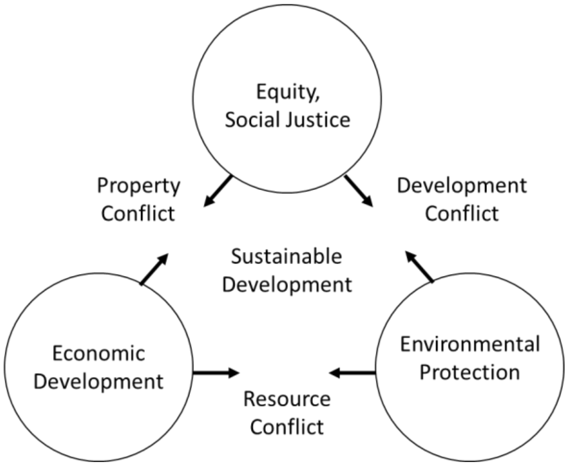


Figure 2.2 Planner's Triangle (adapted from Campbell (1996))

2.3 CAVs and sustainability

Today's urban transportation systems mostly rely on fossil fuels (which are not renewable), and a main cause of air pollution and climate change is the emissions from internal combustion engine vehicles (ICEVs). Further, urban transportation systems are currently impaired by traffic congestion which causes significant economic costs related to not only delays but also, fuel consumption (Sultana et al., 2017). Also, the geographic distribution of transportation infrastructure may result in social inequity as another pillar of sustainability. Technological advancements such as CAVs provide a valuable opportunity for planners to improve sustainable transportation at urban areas. Sustainable transportation is an essential component of sustainable urban development. As discussed in previous sections, in urban transportation development, it is important to reliably measure and strive to achieve elements of the three pillars of sustainability: economic, environmental, and social (ASCE, 2018a; Jeon & Amekudzi, 2005). Urban transportation development needs to look to a future with emerging transportation technology and must be implemented collaboratively with all relevant stakeholders. Also, the process requires significant changes in social perceptions and values toward the environment, as well as in behavior, attitudes, consumption, and spending patterns. In this section, the economic, environmental, and social sustainability prospects of CAVs are discussed.

2.3.1 Economic sustainability

It is widely discussed in the literature that CAVs improve mobility due to reduced headways and the elimination of human error. However, besides the positive effects on travel time and fuel consumption reduction, CAVs could have negative economic effects, such as increased employment, at least in the short term. According to the U.S. Bureau of Labor Statistics, 1,951,500 heavy and tractor-trailer truck drivers and 872,600 passenger vehicle drivers were employed in 2020 (Office of Occupational Statistics and Employment Projections, 2022). Therefore, appropriate policies must be considered to prevent such economic instability.

It is expected that energy consumption will be influenced by several CAV technology features, including advancements in route optimization, eco-driving, crash avoidance, and vehicle right-sizing, among others. Many of these changes will reduce energy use, but some may have the opposite effect. The marginal cost of driving, which is anticipated to decrease dramatically with CAV technology, is one of the main factors that will put increasing pressure on energy demand. The per-mile cost of fuel will decrease as CAV fuel efficiency increases. Consequently, there will be an increase in travel demand which will partially offset the fuel savings from increased energy efficiency. Additionally, the per-mile cost of travel time will decrease due to improved comfort and reduced value of time, leading to even more additional travel demand (Taiebat et al., 2019).

Deploying CAVs has the potential to significantly reduce the detrimental effects of car ownership's dominance in land use and transportation, thus promoting urban sustainability. The opportunities can be divided into three collateral actions: making cities more compact; ridesharing; and improving and digitalizing public transportation. CAVs have the potential to reduce inefficient land use in urban areas through reducing the required space for parking and roads and by reducing the number of vehicles through increasing the occupancy of the vehicles. Another effect of CAV deployment is the reduction of agency revenues due to a decrease in parking charges and traffic fines. Although this effect could be beneficial from social and environmental standpoints, it is expected to be adverse from an agency's standpoint of economic sustainability. On the other hand, from a general societal perspective, CAV deployment may result in higher economic efficiency due to reduction in labor cost because human driver input is reduced.

2.3.2 Environmental sustainability

To fully consider the sustainability prospects of CAVs, it is useful to carry out a life cycle assessment (LCA) and examine the impacts at the different phases of the CAV life cycle, from resourcing of materials to manufacturing and assembling, to operation on the roads, and finally, end of life. Transportation facilities and vehicles generally have significant environmental footprint in all phases of their life cycle (Orsato & Wells, 2007). However, emissions at the operational phase have the highest impact (37% of all human-caused emissions). Therefore, an important opportunity for improving the environmental sustainability of transportation vehicles is to reduce their greenhouse gas emissions which has significant implications for climate change.

CAVs, even where they have internal combustion engines, can increase fuel efficiency due to their more fuel-efficient driving behavior. Studies show that the eco-driving feature of AVs alone could yield additional fuel savings (Brown et al., 2014; Wu, Zhao, & Ou, 2011). The V2V and V2I connectivity could reduce deceleration and acceleration which could in turn reduce fuel use and emissions (Li et al., 2015). Although heavy trucks constitute only 4% of the vehicles in the US, they account for 25% of fuel consumption (Wang, 2015). Truck platooning reduces wind resistance to track movements and hence, increase fuel savings (Herrmann et al., 2018). Furthermore, reduced headways of the CAVs will increase the capacity of the roadway and reduce traffic congestion and emissions. The use of zero-emission and renewable energy sources show great promise in emission reduction, as automobile manufacturers are increasing their electric vehicle production. There exist several studies on electric and automated vehicles (Azin et al., 2021; Zhuge & Wang, 2021). The stated plans of several automakers, such as Waymo, Apple, and Tesla, involve an intention to adopt electricity as the power source for future autonomous vehicles (Gurman, 2021; Tesla, 2021; Valdes-Dapena, 2018).

2.3.3 Social sustainability

Regarding the social impacts of sustainability, CAVs could contribute to the health and well-being of society through the reduction of air pollution and increased road traffic safety. CAVs also have the prospects of reducing inequality and increasing accessibility. The contribution of CAVs to emissions reduction and traffic congestion (discussed in the previous section) is also related to the public health element of social sustainability. In as much as congestion is considered mostly from an economic perspective (congestion increases travel time and fuel consumption), it also has attendant ills of air pollution, noise, and driver stress and therefore impacts public health. High levels of air pollution can have several negative health effects as it raises the risk of lung cancer, heart problems, and respiratory infections. Air pollution exposure, both short-term and long-term, has been linked to negative health effects, particularly among the vulnerable, elderly, children, and the impoverished (World Health Organization, 2019). Besides the direct health-threatening effects, emissions contribute to climate change which causes rise in global temperatures, increased heat of the oceans and shrinking of the ice sheets, a rise in the sea level, and a higher frequency of extreme events (Global Climate Change, 2022). It must be noted that adoption of CAVs will have a significant effect on air pollution and noise reduction only if they are electrically (or gasoline) propelled. The most touted benefit of CAVs is the prospective improvement in traffic safety. According to the National Highway Traffic Safety Administration (NHTSA), approximately 42,000 people died in motor vehicle accidents in the United States in 2021 (NHTSA, 2022), and CAVs could prospectively eliminate 90-95% of crashes because it reduces human driver error.

Traffic crash fatalities are disproportionately distributed between higher-income and lower-income populations. Meanwhile, it is expected that the high price of CAVs (at least, at the inception of the CAV transition period) will mean that the safety benefits of CAVs will be enjoyed mostly by the higher income persons, and thereby increase social inequity. Also, CAVs could benefit very young and very old demographic groups, as well as people with medical conditions who depend on others for vehicle travel. The accessibility and mobility problem of these groups are not only limited to using a personal vehicle, but also using crowded and complex public transit systems is challenging for them. CAV deployment can increase accessibility for people of all ages, genders, and income levels. However, CAV ownership may be difficult for low-income groups. Therefore, it is to develop strategies to deploy CAVs in ways that improve equitable mobility cost-effectively to form a part of overall public transportation.

2.3.4 Summary of literature on transportation sustainability

This section synthesizes the existing literature on sustainability considerations in the design of transportation systems. Table 2.1 presents some of the studies that explore the effects of CAVs on transportation system sustainability. These studies consider various metrics to investigate the sustainability contributions of CAVs. Table 2.2 presents sustainability-related metric used in road network design studies. Economic performance measures are typically total travel time, consumer surplus, and schedule delay penalties. For the environmental aspect, CO_2 and CO emissions, and greenhouse gas emissions are generally used as performance measures. Regarding the social aspect of sustainability, studies have used the equity performance measure (which considers the effects of the proposed decisions on the costs of the travelers) with different values of time.

Table 2.1 Summary of studies on CAVs and sustainability

Study	**Sustainability metrics**	**Sustainability aspect**
Ma et al. (2019)	Fuel consumption	Environmental; Economic
Chehri and Mouftah (2019)	Number of vehicles Travel time Emissions Safety Parking spaces	Environmental Economic
Gruyer (2021)	Safety Energy consumption Travel time Comfort-health	Environmental Economic; Social
Balasubramaniam et al. (2017)	Number of vehicles Safety	Environmental Economic
Gungor and Al-Qadi (2020)	Fuel consumption Pavement rehabilitation cost	Economic
Gungor et al. (2020)	Fuel consumption Pavement rehabilitation cost	Economic

Table 2.2 Summary of studies on sustainability considerations for transportation systems

Study	**Sustainability metrics**	**Sustainability aspect**	**decision**
Wismans et al. (2011)	System CO2 emissions Noise System travel time	Environmental, Social, Economic	Time-varying travel management strategies
Sharma and Mathew (2011)	System emissions System travel cost	Environmental, Economic	Road-capacity improvement
Chen and Yang (2012)	System CO emissions System travel time	Environmental, Economic	Rebate and toll
Sharma and Mishra (2013)	System greenhouse gas emissions System travel time	Environmental, Economic	Emission-based tolling strategy
Friesz et al. (2013)	System emissions System travel cost	Environmental, Economic	Time-varying tolling strategy
Li et al. (2014)	System emissions cost Elastic demand	Environmental, Economic	Road-capacity improvement
Yin et al. (2014)	System CO emissions System travel cost Equity	Environmental, Economic, Social	Road-capacity improvement Toll
Amirgholy et al. (2015)	System CO emissions System travel time Elastic demand	Environmental, Economic	Cordon-base congestion pricing
Miandoabchi et al. (2015)	System CO emissions System travel time	Environmental, Economic	Road construction
Szeto et al. (2015)	System CO emissions Elastic demand Equity	Environmental, Economic, Social	Road-capacity improvement Toll
Chen et al. (2016)	System accident cost System travel time	Social, Economic	CAVL subnetwork design
Madadi et al. (2020)	CAV infrastructure installation cost System travel time	Economic	CAVL subnetwork design
Lin et al. (2021)	System CO emissions System travel time	Environmental, Economic	CAVL subnetwork design
This report (Chapter 5)	System travel cost	Economic	CAVL deployment
This report (Chapter 6)	System CO emissions	Environmental	CAVL subnetwork design
This report (Chapter 7)	System travel time Equity	Economic, Social	CAVL subnetwork design

2.4 Discussion on sustainability of the proposed CAVL designs in this report

Automated transportation systems are still in their early stages of development. Therefore, there exists an opportunity to plan and design these systems in a manner that considers various aspects of sustainability. In this report, an effort is made to investigate the deployment of CAVLs in the HDV-CAV transition horizon, considering aspects of transportation system efficiency and equity. With an ever-increasing population, limited resources, and finite resilience of natural resources, it is critical that alternative solutions are found rather than focus on expanding infrastructure to meet the increasing demand. The adoption of CAVLs will enable CAVs to minimize their headways and increase the capacity of the roadway. In this report, the optimal designs of CAVLs are determined at the corridor and network levels. Lane additions to the network are not considered; only reallocation of the current lanes to CAVs is considered.

In Chapter 5 of this report, bottleneck congestion mitigation is investigated using CAVLs for a mixed stream of HDVs and CAVs. The objective is to minimize the travel cost of the travelers which consists of costs due to the queuing delay, schedule penalty, and tolls. The resulting design provides the required number of CAVLs for different shares of CAVs in the traffic stream to improve efficiency at the bottleneck. In this study, a constant total travel demand at the bottleneck is assumed and a solution using CAV technology for congestion mitigation is proposed. The solution involves a tolling policy which imposes higher tolls on HDV users, which has a decreasing trend over time while CAV demand grows. This could lead to inequity at the beginning of the transition horizon. In Chapter 6, the selection and scheduling of CAVLs for a road network are established. The possibility of allocating reduced lane widths to CAVs due to the zero-lateral wander (which leads to an increased number of lanes) is considered. A constant growth rate is assumed for the overall demand during the planning horizon, and a demand diffusion model is used to estimate the demand for CAVs. The objective is to minimize the total vehicle emissions of the entire road network. Chapter 7 proposes a framework to capture the equity in the implementation of the CAV lane management strategy. The objective is to minimize total travel time.

Each chapter of this report assumes either a constant travel demand or a constant growth rate for the total demand. However, it is also important to consider the effects of the growing travel demand over time and the effects of the induced travel demand on the roadway system due to this improvement. Figure 2.3 illustrates the consumer surplus with an increase in transportation supply, such as allocation of CAVLs with higher capacity, and elastic demand. This implies that proper travel demand management strategies may be required alongside the proposed designs and policies.

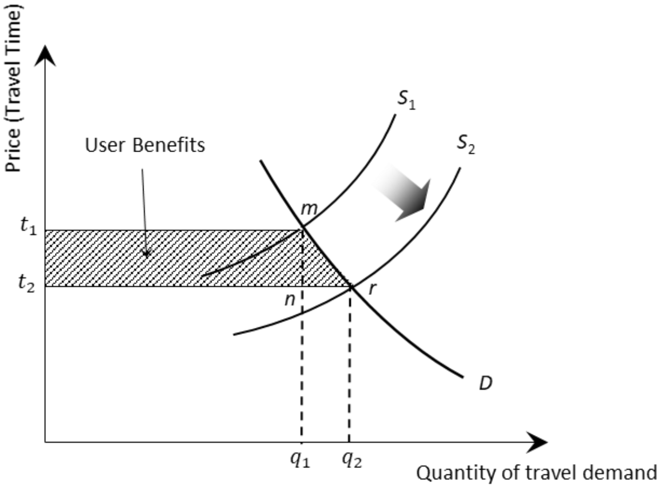


Figure 2.3 User benefits (consumer surplus) due to an increase in transportation supply assuming elastic demand

Figure 2.4 depicts the demand and supply equilibrium states for two possible scenarios of CAVLs. In this figure, the supply has changed from S_1 to S_2 due to the increased capacity of CAVLs. The increased capacity of the roadway will result in reduced travel time which in turn will induce additional demand over time. Therefore, the demand curve will change from D_1 to D_2. Initially the increased demand uses the available capacity of the roadway that will result in reduced travel time of the system (Figure 2.4 (a)). However, since the available capacity of the roadway is limited after some point, the additional induced demand will result in congestion and increased travel time of the system (Figure 2.4 (b)). Hence, it is essential to consider the effect of the induced demand over time in decision making process.

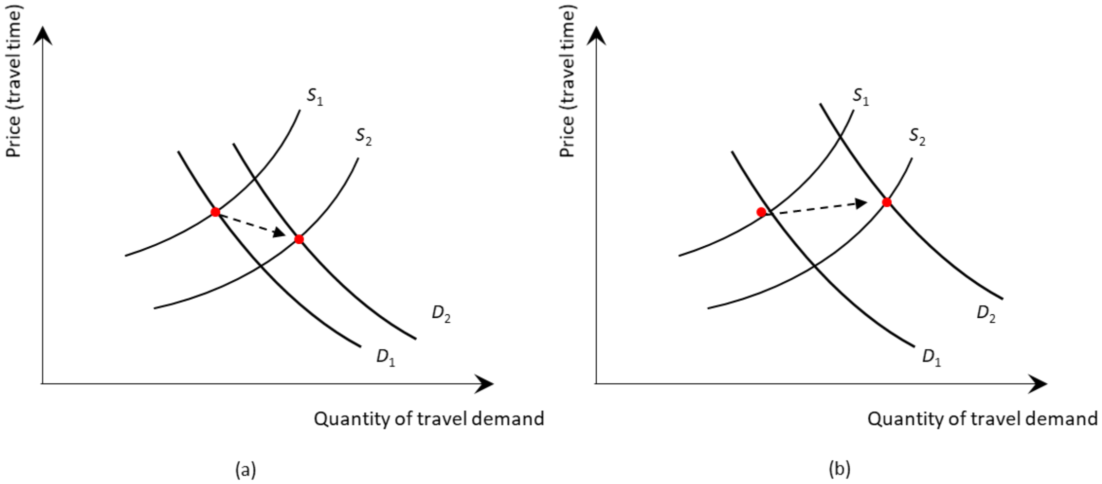


Figure 2.4 Demand and supply equilibrium

From the transportation infrastructure viewpoint, this study is predicated on the assumption that the transition from GPLs to CAVLs causes no significant change in basic infrastructure costs, in other words, no new lanes will be constructed to serve CAVs. In addition, studies in literature have investigated the effects of CAVs on pavement degradation. Channelized traffic due to platooning and zero lateral wander of CAVs will increase the pavement deterioration and the rehabilitation and maintenance costs of the pavement. There exist studies in the literature that consider these effects and propose methodologies for relocating CAVs within the lanes to reduce (or even, reverse) these adverse effects, as discussed in Chapter 4. It is necessary to consider these effects in the infrastructure planning for the CAV era. This discussion highlights the importance of considering the effects of plans and policies not just on different aspects of sustainability for that system, but also their impact on other systems over a period of time. Although it is necessary to address issues such as bottleneck congestion, it is also necessary to examine the impacts that local decisions might have on the entire system. Further, it is important to consider the impacts of current decisions in the future. For example, future road improvements could result in induced demand and thereby reduce the sustainability of the intended investment.

3 RELATIONSHIPS BETWEEN CAVS AND HIGHWAY INFRASTRUCTURE

3.1 Introduction

For over 100 years or more, road infrastructure has been designed to accommodate evolving changes in vehicle design and technology. The motivation has been the need to modify the physical configuration of operational policies for highway infrastructure to ensure not only more durable roads, but also safer and more efficient road operations. Such practice is consistent with the highway infrastructure management principles (AASHTO, 2011; FHWA, 1999) (FHWA 1999; AASHTO 2011) where highway asset managers need to upgrade and operate highway assets in a manner that duly accounts for changes in vehicle technology. With the advent of CAV operations, highway agencies are realizing that their current infrastructure design and operational policies will need to be adjusted to accommodate CAVs adequately (AASHTO 2017; FHWA 2018). For this reason, agencies seek guidance on the changes that are needed to prepare the roadways for this technology.

Researchers have recognized that critical considerations in CAV-related infrastructure planning include the start year of Levels 4 and 5 CAV operations (that is, the year of their commercial introduction and initiation of operations on public roads), and their market penetration growth with time (Labi, 2019; Saeed et al., 2021). It has been argued that these attributes of CAV market penetration and timing of their operations will impact the schedule and scope of the needed infrastructure changes, and the new CAV-related policies for road design, lane management, and vehicle operations (FHWA, 2018; Ha, 2019). For a given level of market penetration, the timing, scope, and intensity of infrastructure preparations will be affected by the prevailing or anticipated dominant level (or, more likely, the lowest level) of vehicle automation in the traffic: generally, higher levels of market penetration and the level of vehicle automation will generally translate into higher levels of infrastructure preparation (AASHTO, 2017).

Saeed et al. (2021) provided a suggested classification of CAV infrastructure needs, and discussed the challenges and opportunities associated with the provision of appropriate infrastructure to support CAV operations. The challenges include uncertainties associated with the initial year of operations and market penetration of each level of autonomy (LOA), identifying design changes, and adequacy of funds for infrastructure retrofits. The opportunities discussed by the authors, include analytical techniques for addressing uncertainties, funding via public–private partnerships, and a chance to redesign certain design elements of road infrastructure, giving agencies a stronger case for legislative approval for increased infrastructure funding.

The Saeed et al. Classification involves four categories of CAV-related infrastructure. Class 1 is the base infrastructure used currently in the human-driven vehicle (HDV) environment; Class 2 are the new types of physical roadway infrastructure due to design and management/operations changes needed to support CAV operations, and includes dedicated lanes; Class 3 is the set of cyber infrastructure types dedicated to highly automated vehicles (AVs) (for example, sign-mounted sensors in-pavement and) and connected vehicles (CVs) [for example, dedicated short-range communication facilities, fiber optic cables and conduits for 5G connectivity]; and electric vehicle (EV) infrastructure (charging stations and guideways) needed to support CAV operations (Miralinaghi et al., 2020). Class 4 infrastructure is that for which there will be changes in dimensions of their design features such as thicker pavements. Furthermore, in the post-transition period of 100% CAV market penetration and level of autonomy of 5, certain HDV-supporting infrastructures will be retired due to obsolescence.

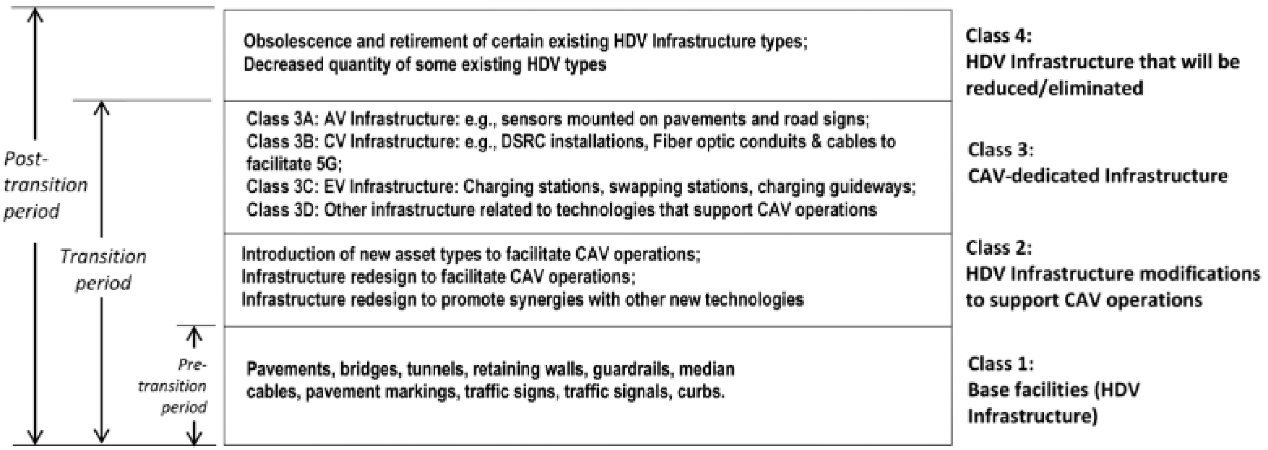


Figure 3.1 CAV-related infrastructure classes in various eras related to the AV transition period (Saeed et al., 2021)

This chapter of the report focuses on Class 2 and Class 4 types of infrastructure. In subsequent chapters, the report addresses roadway design and operations changes needed to support CAV operations, specifically, dedicated lanes and toll policies, respectively. In subsequent sections of the present chapter, the report addresses increased thickness of pavements in the wheel tracks to account for reduced lateral wheel wander associated with connected and automated trucks.

3.2 General impacts in terms of user cost and agency cost

For a roadway infrastructure, the stakeholders are the road agency, road users, and the community that will be affected by the road infrastructure. Poor quality of transportation infrastructure has implications for road users. For example, Schrank et al. (2009) project that the user costs of transportation infrastructure will grow from $179 billion in 2017 to $237 billion in 2025 (a 32% increase). The road user costs are related to delay, crash costs, and vehicle operating costs (VOCs) such as fuel consumption, tire wear, maintenance, and devaluation. Hence, road user costs should be considered in developing the investment strategies related to new transportation strategies.

Pavement conditions, generally described in terms of the international roughness index (IRI) proposed by the World Bank (Sayers et al., 1986), can affect fuel consumption, maintenance and repair, and tire wear costs. For example, HDM-4 VOC model has been used in several studies to evaluate the effect of roughness (IRI) on user costs (Islam & Buttlar, 2012; Chatti & Zaabar, 2012; Ziyadi et al., 2018). These studies reported that for an IRI increase of 1 m/km, the fuel consumption increases by about 2% for passenger cars irrespective of their speeds. For heavy trucks at 96 and 56 km/h, the fuel consumption increases by 1% and 2%, respectively. For maintenance, at an IRI of 4 m/km, the total cost increases by 10% for all vehicles. For IRI of 5 m/km, the maintenance costs reported to grow by 40% for passenger cars and 50% for heavy trucks.

The tire wear cost, for a 1 m/km increase of IRI, showed 1% increase for all vehicles at 88 km/h (Chatti and Zaabar, 2012). Barnes and Langworthy (2004) reported a $200 increase (1.67 cents/vehicle-mile assuming 12,000 annual mileage) in vehicle maintenance and repair costs. It is anticipated that CAV operations will impact the user cost in an indirect manner.

The major agency costs over the pavement life cycle include maintenance and rehabilitation costs. Rehabilitation of a system means a major retrofit or replacement of a component of that system. Maintenance is the repair of localized damage or reduction of damage propagation. According to the FHWA (2022), national highway travels have increased by about 14 percent between 2000 and 2019. In addition, truck loading is becoming heavier due to increasingly less restrictive overweight policies in efforts to boost productivity. Therefore, it is essential to develop appropriate performance metrics for cost-effective and timely maintenance and rehabilitation of pavements. Qiao et al. (2017) developed a framework to determine optimal IRI triggers for scheduling different types of pavement treatments. According to FHWA pavement condition thresholds, pavements with an IRI of less than 95 (in/mi) can be in good condition, and pavements with an IRI of more than 170 correspond to poor condition. Over pavement life cycle, preservation and rehabilitation treatments must be carried out continually to preserve the pavement in state of good repair (FHWA, 2017). The pavement condition declines over time because of the accumulated and synergistic effect of traffic load and environmental conditions. In the CAV era, particularly with respect to trucking operations, it can be expected that there will be increased rutting on highway pavements. This is discussed in the subsequent section of this chapter.

3.2.1 Effect of wheel wander on pavement degradation

On a road pavement, the wheels of the vehicles do not always follow the same line. Wheel wander, also known as a random wheel path, is influenced by a variety of factors, including the kind of vehicle, driver, wind, and mechanical alignment of trailers. Lateral wander of the vehicles changes the number of axle load applications over a point in pavement performance prediction. Increased lateral wander has significant effects on pavement degradation and can increase the performance life of the pavement (Siddharthan et al., 2016). Considering the lateral wander characteristics of heavy nonautonomous trucks, Erlingsson et al. (2012) measured the rutting depth of flexible pavements with different lane widths. Their results showed a 40% reduction in rutting as the standard deviation of the lateral wander increased from 0 to 40 cm for wider lanes.

Generally, a normal distribution is assumed for lateral positioning of the vehicles inside a lane, where the standard deviation of the normal distribution represents the lateral wander of the vehicle. Although, lateral wander of the wheels on the pavement is expected to affect both fatigue and rutting damage propagation, different methods are used to account for wander in each case. Fatigue damage is determined using the following equation:

$$D = \sum_{i=1}^{T} \frac{n_i}{N_i} \tag{3.1}$$

where, D is fatigue damage, T is the total number of periods, n_i is the actual traffic in the i^{th} period, and N_i is the traffic allowed under conditions in the i^{th} period (AASHTO, 2020). As this equation is linear, the total fatigue damage with wander can be estimated from the damage profile with zero lateral wander. However, the permanent deformation (rutting) is not linearly related to the traffic and lateral wander must be directly applied to the response, not the damage. Figure 3.2

illustrates the Mechanistic-Empirical Pavement Design Guide's (MEPDG) considerations for the effect of lateral wander on fatigue damage profile resulting from dual wheels (AASHTO, 2020). Figure 3.2(a) and (b) show a dual wheel with zero lateral wander and the resulting damage profile, respectively. In this case, the maximum value from the damage profile is used to predict the fatigue life of the pavement. However, using the maximum value could lead to excessively conservative predictions for the pavement performance life.

Figure 3.2 presents the normal distribution assumption for lateral wander, where the standard deviation is dependent on the lateral wander of the wheels under consideration. The area under the curve is subdivided into five quantiles, each of which represents 20% of the traffic distribution. Next, the points along the x coordinate are found by multiplying the standard normal value z, related to the midpoint of these areas, by the standard deviation. It is assumed that 20% of the traffic, and thus the related damage profiles (D_1, D_2, D_3, D_4, and D_5), are centered at each of these points. To determine the total damage, 11 points within the wheel wander region are considered, and the damage for each of these points is determined as follows:

$$D(x) = 0.2 \sum_{i=1}^{5} D_i\,(x) \tag{3.2}$$

The resulting damage profiles for fatigue and rutting are used to compute the roughness (IRI) of the pavement.

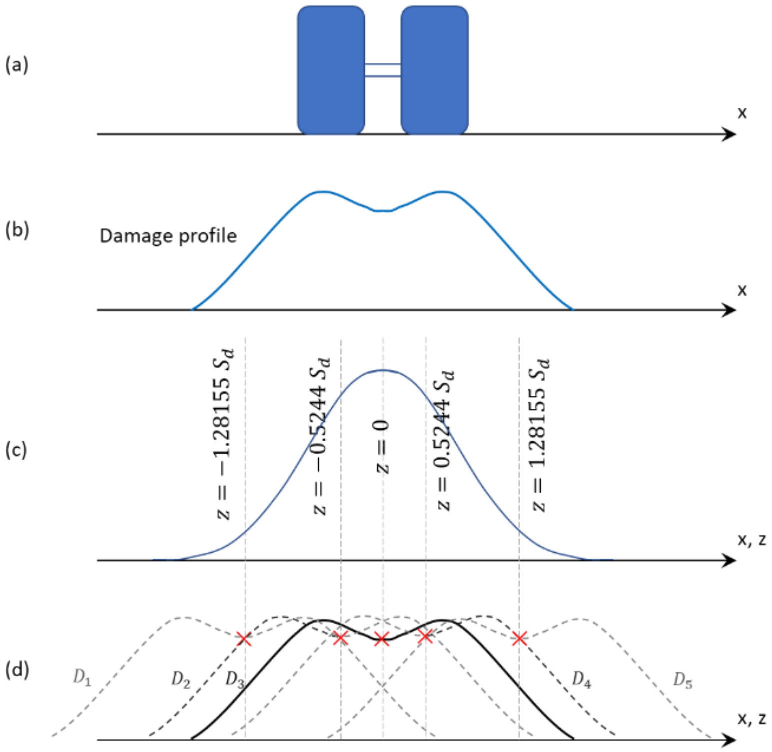


Figure 3.2 MEPDG's considerations for predicting damage profile of a dual wheel

3.3 Pavement degradation in the CAV era

The prospect of controlling lateral vehicle wander to improve pavement performance has received significant attention. A number of studies have proposed that while a normal lateral distribution is usually assumed for HDVs, CAVs can be constrained to follow specific lateral distribution patterns. Noorvand et al. (2017) studied the effect of autonomous truck lateral positioning and their market penetration on the asphalt layer thickness design, considering mixed stream of vehicles and CAV-dedicated lanes. Figure 3.3 depicts the lateral wander scenarios considered in the Noorvand et al. (2017) study. They compared the pavement design subject to these loading scenarios and concluded that deployment of CAV-dedicated lanes with uniformly distributed autonomous trucks will reduce the design thickness of the pavement. Chen et al. (2019, 2020) compared different lateral control modes of autonomous trucks to maximize pavement performance life.

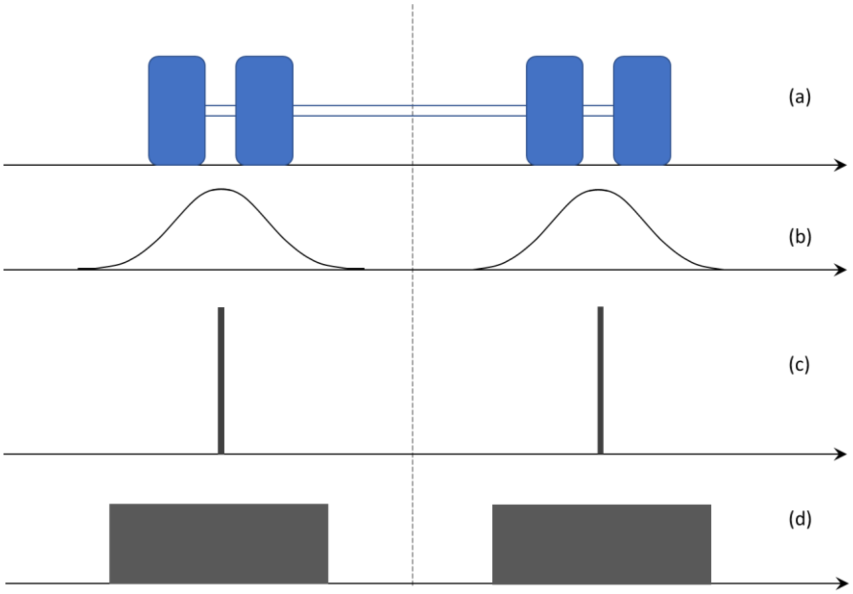


Figure 3.3 Distributions of truck loading on the pavement: (a) dual tire truck, (b) normal distribution, (c) zero lateral wander, and (d) uniform distribution.

Gungor et al. (2020) presented a longitudinal and lateral, autonomous truck positioning pattern in a platoon (Figure 3.4(b)), to minimize the agency rehabilitation costs and fuel consumption cost of the users due to the pavement roughness (IRI) and the aerodynamics of a vehicle in the platoon. They reported a 9% decrease in the overall costs in their case study. Gungor and Al-Qadi (2020) proposed a longitudinal and lateral positioning strategy for the truck platoon (Figure 3.4(c)), considering the damage effects on rehabilitation and fuel consumption costs. The results indicated up to 50% reduction in the pavement life cycle cost. These studies investigated the effects of transverse positioning of connected and automated trucks within a lane on the pavement performance.

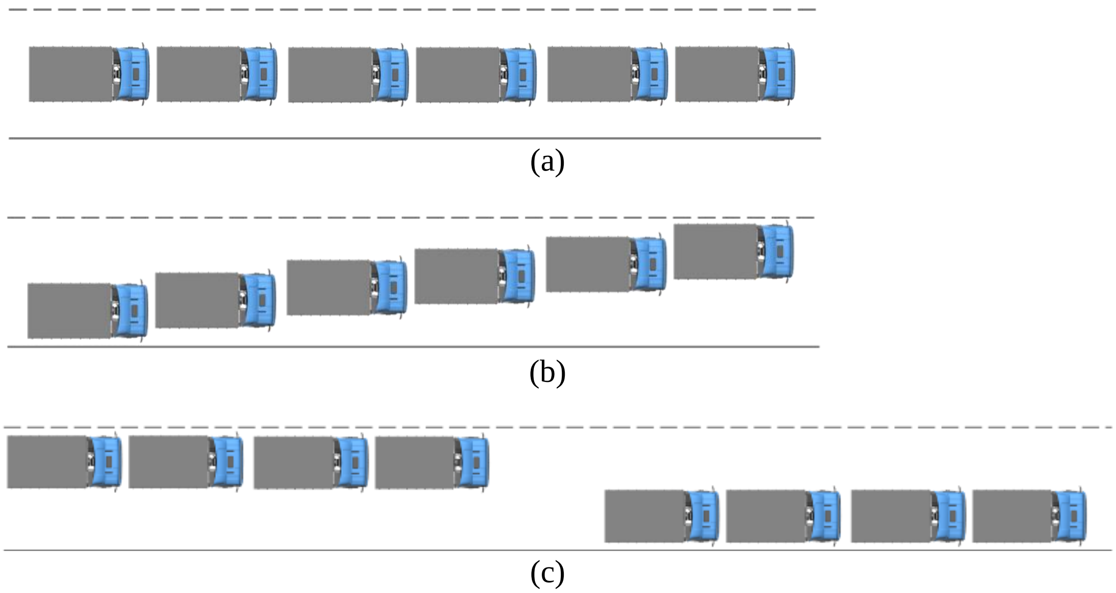


Figure 3.4 Truck platooning patterns: (a) truck platoon with zero lateral wander, (b) lateral and longitudinal repositioning of autonomous trucks in a platoon, (c) lateral and longitudinal repositioning of the autonomous truck platoons

The ability of connected and autonomous trucks (CATs) to operate with prespecified lateral distributions provides two types of benefits related to the pavement costs and operation, including: (i) reduction of lateral loading concentration on the pavement and (ii) allocation of reduced-width lanes to CATs for increasing the roadway capacity, to efficiently improve the utilization of limited roadway cross-section space. The reduced lane width can be close to the maximum vehicle width to accommodate more lanes, or the saved space could be used for other sustainability-related purposes, such as active transportation facilities (sidewalks, bike lanes, etc.) in the urban area (Dennis et al., 2017). Ghiasi et al. (2020) proposed a lane management scheme to identify the optimal number of reduced-width CAV-dedicated lanes to maximize the road segment throughput. Their analysis shows that narrower CAV-dedicated lanes result in higher roadway throughput. Mohajerpoor and Ramezani (2019) developed a lane allocation strategy for a mixed stream of CAVs and HDVs by minimizing the total delay, which was determined analytically based on headways between vehicles. It must be noted that reduced lane widths for CAVs will lead to more channelized traffic and will increase the pavement loading. Therefore, the trade-off between different effects and costs related to the proposed strategies must be considered to improve the sustainability of the proposed design.

3.4 Synergies with the present study

In this section, some possible lane management strategies for CAVL designs considering the degradation effects of the pavement, are investigated. For the sake of simplicity, it is assumed that there is no distinction between connected and automated non-heavy vehicles (CANHVs) and connected and automated heavy vehicles (CAHVs). For the transition period from HDVs to CAVs, three types of lanes can be considered: connected and autonomous heavy vehicle lanes (CAHVLs), connected and autonomous non-heavy vehicle lanes (CANHVLs), and general purpose lanes (GPLs) (Figure 3.5). It has been previously discussed that within CAVLs, vehicles can drive with reduced headways, which leads to increased lane capacity and improved mobility. Further refining the traffic stream by allocation of separate lanes to CANHVs and CAHVs has possible benefits that are subsequently discussed here briefly.

With the allocation of CAHVLs, trucks will be able to follow one another with minimum headways, which results in reduced air drag and improved fuel efficiency. Furthermore, forming platoons with reduced headways will increase the capacity of the lane and increase traffic efficiency. Platooning will cause channelized traffic loading because of the zero lateral wander of CAVs. However, such concentrated loading will increase the damage accumulation rate and will decrease the pavement service life. To address this issue, the autopilot features of the CAVs can be leveraged to optimize the lateral location of the platoons to minimize damage to the pavement. With increased CAHV market penetration rates, the allocation of CAHVLs will eventually eliminate the pavement damage caused by traffic loading on CANHVLs and GPLs, reducing the agency and VOCs of users due to pavement degradation on these lanes.

One other possible strategy is to allocate reduced lane widths to CAVs. This strategy does not allow for lateral traffic load distribution on the pavement, but it does increase the total number of lanes in the road network. Thus, the trade-off between reduced pavement damage and increased capacity must be considered in the lane management planning process. It should be noted that the applicability of a lane reallocation strategy highly depends on the number of existing lanes in a highway segment. For example, in a road segment with two lanes in each direction, due to the minimum capacity required for HDVs, the allocation of separate lanes to CAHVs and CANHVs is not practically feasible.

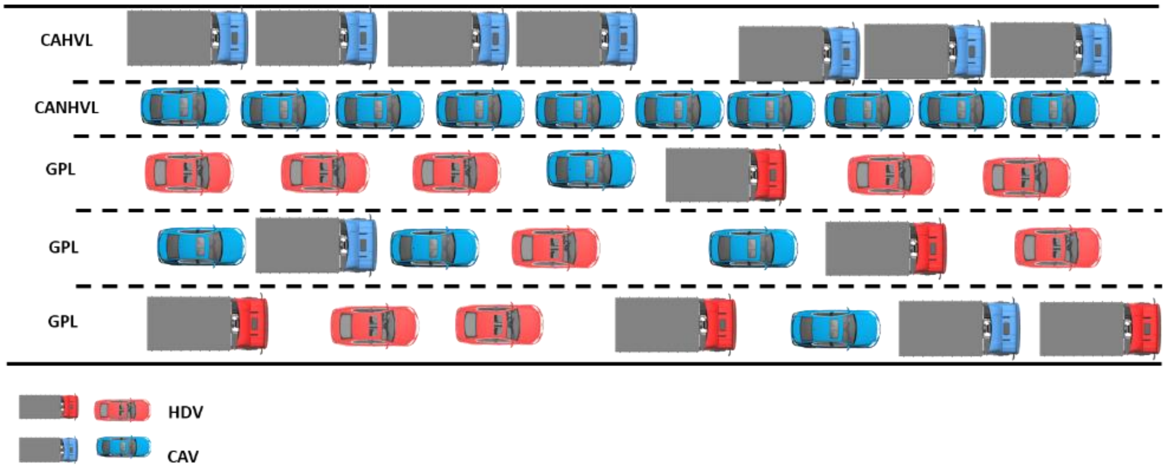


Figure 3.5 Highway section illustration with CAHV, CANHV, and GP lanes.

Besides the lane management and vehicle operation strategies discussed, alternative pavement designs can be effective when used jointly with lane reallocation with reduced lane width. To reduce the damage caused by channelized traffic on CAHVLs, the strength of the pavement only under the truck tires can be increased. However, the constructability and additional costs of such pavement "truck tracks" must be studied. As is evident from this discussion, in selecting the most efficient design, it is essential to consider the trade-off between effects that different strategies might have on the road network and infrastructure. For example, when considering the CAHVLs with reduced lane width the capacity of the lane and the number of the lanes will increase. However, this can result in increased pavement damage cost. Therefore, there is a trade-off between travel time decrease and pavement damage decrease that must be considered in the planning process. Therefore, it is useful to select the best strategy as the most sustainable only after duly considering all possible factors rather than a narrow set of factors.

4 REVIEW OF LITERATURE ON CAV-RELATED LANE MANAGEMENT

4.1 Introduction

The existing literature on the impacts of CAVL on traffic flow can be classified into two groups. The first group deals with the long-term impacts of deploying CAVLs and investigates the network-wide equilibrium state in the road transportation system. These studies mainly seek to identify the optimal lane deployment strategy in terms of the number of lanes to minimize the total travel time over the transition horizon, which has a duration of several years. Chen et al. (2016) investigated optimal deployment strategies for autonomous vehicle (AV) dedicated lanes during the AV transition period to minimize social costs, including safety and total travel costs for HDVs and AVs. They divided the transition period into smaller (1-year) periods and established the CAV market penetration using a diffusion model (where the market penetration rate in a given period depends on that of the preceding period), and they compared the net benefits of CAVs and HDVs in terms of safety and travel time savings.

Ye and Wang (2018) proposed the simultaneous design of traffic networks with the deployment of CAV lanes and congestion pricing to mitigate traffic congestion in the network. They showed that the integration of these planning strategies can outperform either CAV lane deployment alone or congestion pricing alone. Liu and Song (2019) developed a framework to identify the optimal road links to deploy CAVLs where HDV travelers are permitted to use these lanes by paying a toll. They demonstrated that by considering smaller headways for CAVs, the equilibrium flow may not be unique under mixed CAV and HDV flows. Using a bi-level framework, Madadi et al. (2020) investigated the decisions by urban agencies regarding road link retrofits. For example, installing machine-readable road signs and lane markings to accommodate AVs. At the upper level, the total cost of link retrofit, and total system travel time were minimized, and at the lower level, travelers' route-choice decisions were optimized using a logit-based stochastic user equilibrium model.

Subsequently, Madadi et al. (2021) combined the notion of a CAV-ready subnetwork with CAVLs to provide more flexibility for a road agency in accommodating CAVs during the transition horizon. They showed that the positive effect of CAVLs is greater than that of CAV-ready subnetwork when CAV market penetration is greater than 30%. Wu et al. (2020) carried out system-optimal design for a small network (with HDV streets and CAV expressways) under congestion pricing in a bid to minimize the cost of system travel time. Instead of considering fixed road capacity, Movaghar et al. (2020) captured the link capacity as a function of CAV proportion when deploying CAVLs and showed that CAVLs can lead to significantly higher efficiency in the system considering variable capacity.

The second group deals with the short-term impacts of deploying CAVL on traffic flow. This group addresses a road corridor over a few hours of time duration. Ghiasi et al. (2017) developed an analytical formulation using the Markov chain model to identify the optimal number of CAVLs. Their goal was to maximize traffic throughput under different CAV market penetration and CAV demands. They assumed that the lane widths are fixed and that maximization of throughput requires a trade-off between the numbers of CAVLs and general-purpose lanes (GPLs). Subsequently, Ghiasi et al. (2020) relaxed the assumption of fixed lane width to incorporate the possibility of narrower lanes in obtaining the optimal number of lanes and found that narrower lanes lead to higher throughput benefits under the higher CAV penetration rate. Ye and Yamamoto (2018) used a fundamental diagram approach and simulation to understand the throughput considering different CAV penetration rates and traffic density on a three-lane highway and found that setting a higher speed limit for CAVs can improve the efficiency of CAVLs. Table 4.1 summarizes the literature on CAVL planning.

Table 4.1 Summary of literature on CAVL planning

Network /Corridor level	Study	Objective	Lane reallocation strategy	Uncertainty (context)	Travel decisions	Other congestion management strategy
Network	Chen et al. (2016)	Costs of safety and total travel time	No	No	Route /Lane type choice	None
	Ye and Wang (2018)	Total travel time	No	No	Route /Lane type choice	Lane-specific tolling policy
	Liu and Song (2019)	Total travel time	No	Yes (i.e., Equilibrium flow for a mixed fleet of CAV-HDVs)	Route /Lane type choice	Lane-specific tolling policy
	Madadi et al. (2020)	Costs of network adjustment for CAVs and total travel time	No	No	Route /Lane type choice	None
	Wu et al. (2020)	Total travel time and distance	No	No	Route /Lane type choice	Cordon-based tolling policy
	Movaghar et al. (2020)	Total travel time	No	No	Route /Lane type choice	None
	Madadi et al. (2021)	Costs of network adjustment for CAVs and total travel time	No	No	Route /Lane type choice	None
	This report (Chapter 6)	**Worst-case total vehicle emissions**	**Yes**	**Yes (potential CAV market size)**	**Route /Lane type choice**	**None**
	This report (Chapter 7)	**Total travel time cost**	**No**	**No**	**Route /Lane type choice**	**Equitable TCS**
Corridor	Ghiasi et al. (2017)	Highway throughput	Yes	No	Lane choice	None
	Ye and Yamamoto (2018)	Highway throughput	No	No	Lane choice	None
	Ghiasi et al. (2020)	Highway throughput	Yes	No	Lane choice	None
	This report (Chapter 5)	**Total travel cost (travel time and schedule delay)**	**No**	**No**	**Departure time/Lane type choice**	**Lane-specific time-varying tolling policy**

4.2 Research gaps and contributions

Previous studies have thrown much light on CAVL deployment. However, there exists a need for a framework that enables the road agency to develop sustainable design of CAVLs during the transition horizon with a mixed stream of CAVs and HDVs. The first research gap is lack of economically sustainable designs of CAVLs for a road corridor during morning peaks considering commuters' departure-time choices. Studies in the literature captured only the route choice of commuters but overlooked the morning departure time choice of commuters. This design needs to be integrated with the optimal lane-specific tolling policy to achieve the maximum mobility in the system. The second research gap is the lack of an environmentally sustainable design of CAVL to minimize vehicle emissions at a network level. Studies in the literature focused on the total travel time and highway output as the goal of agency. However, CAVs can provide a valuable opportunity for urban transport agencies to reduce vehicle emissions by developing optimal network-level design of CAV-dedicated lanes. Such design needs to accommodate uncertainty associated with customers' willingness to purchase CAVs in the long term.

Furthermore, CAV lane reallocation could account for the smaller width of CAVLs. Another key gap is the lack of a socially sustainable CAV lane management that enables the urban road agency to foster social equity. Since CAV-dedicated lanes can reduce the available road capacity for HDVs, it could lead to public opposition. Therefore, there exists a need for an economic instrument to manage travel demand while avoiding the degradation of social equity. The current study addresses these gaps to some extent.

5 MANAGING BOTTLENECK CONGESTION WITH DEDICATED AUTONOMOUS-VEHICLE LANES IN A MIXED-FLEET TRAFFIC ENVIRONMENT

5.1 Introduction

To address the traffic congestion during the morning peak period, urban road agencies can take advantage of the emergence of vehicle automation by deploying dedicated lanes for this class of vehicles. Therefore, it is useful to study the impact of CAVL on morning commute congestion and possibly integrate this concept with other transportation demand management strategies such as congestion pricing to achieve maximum efficiency in the road network. Although several studies investigate the effects of CAVL on mobility at corridor- and network-level, they primarily deal with the lane and route choices of commuters. However, there is a need to also understand the departure time choices of commuters, particularly during the morning peak period. This chapter addresses the morning commute problem during the transition horizon with a mixed stream of CAVs and HDVs. This is often the case where there exists a bottleneck in the highway corridor that leads to a constriction in the traffic flow along the corridor.

The concept of a bottleneck model was first proposed by Vickrey (1969). The bottleneck model analyzes traffic congestion during the morning peak period when commuters traverse a constricting highway segment with a fixed capacity (referred to as a bottleneck). Commuters decide on their departure times such that they minimize their travel costs which consist of travel time and schedule delay costs. At equilibrium, commuters cannot further minimize their travel costs by unilaterally changing their departure times. Arnott et al. (1990) applied tolling as a travel demand management strategy to determine the system-optimal departure rates that minimize the total cost during the morning peak period. The total cost consists of the cost of the schedule delay and travel time.

The Vickrey (1969) and Arnott et al. (1990) studies were subsequently extended by several researchers who relaxed the assumptions, such as the homogeneity of commuters in terms of desired arrival time, schedule delay, and travel time penalties. The schedule delay penalty includes early and late arrival penalties for commuters. These studies can be categorized into two classes: the first class determines the commuters' departure rates under user equilibrium and the system-optimal conditions using the continuous-time model. After his early work in 1969, Vickrey (1973) proposed the tolling policy in the context of managing morning commute congestion where commuter homogeneity is relaxed by assuming the special case of heterogeneity. Based on this assumption, the ratio of schedule delay penalties to the value of time across commuter groups has a fixed value. Later, Daganzo (1985) developed a general formulation for analyzing the morning commute congestion with only two user groups. Lindsey (2004) proved the existence of an equilibrium solution of commuters' heterogeneity without providing a method to obtain the solution. Van den Berg and Verhoef (2011) determined the impact of tolling on managing morning commute congestion under the assumption that commuters have a continuous distribution of the value of time and a schedule delay penalty with identical desired arrival time. They also assumed that the ratio of late arrival penalty to early arrival penalty is constant.

Other studies on bottleneck models in continuous time setting use similar assumptions to examine the impact of tolling policy on the value of time and schedule delay penalty. In the context of CAVs, Liu (2018) explored the equilibrium conditions for departure time and parking location choices of commuters with a fully CAV fleet: after passing a bottleneck, CAV commuters are dropped off at the workplace, and then CAVs drive themselves to parking locations. The system-optimal design of the tolling policy and parking fees is determined to minimize the total system cost. Zhang et al. (2020) investigated the impact of a lower value of time for CAV commuters compared to HDV commuters to understand the departure time choice of commuters. This is because in a CAV, the commuter can spend their in-vehicle time on various activities such as work or entertainment (Kolarova et al., 2018; Steck et al. 2018). Using the long-term equilibrium condition, they investigated the market penetration of CAVs over the transition horizon, and determined that as CAV market penetration increases, the travel costs of CAV commuters increase due to the high competition between them for departing in a short time window.

The second class of studies uses a mathematical program in the context of a discrete time setting to analyze morning commute congestion. In this category of studies, the morning peak period is divided into several time intervals where the departure rates are determined for each time interval. This facilitates comprehension of the impact of travel demand management strategies on morning commute congestion with the heterogeneity of commuters in terms of schedule delay penalty, the value of time, and desired arrival time. Ramadurai et al. (2010) formulated the single bottleneck model as a linear complementarity problem (LCP) to determine the departure rates of morning commuters under the equilibrium condition and investigated the existence of a solution and the uniqueness of LCP of the equilibrium departure rates. Doan et al. (2011) extended the LCP to capture the impact of tolling on departure rates during the morning peak period, and formulated the system-optimal condition as a linear model that minimizes the total system cost. They proved that, under system-optimal condition, the travel time of commuters is equal to zero, which implies that the total system cost only includes the schedule delay cost of commuters. They also developed an optimal time-varying tolling policy that leads to system-optimal departure rates. Miralinaghi et al. (2019) used a tradable credit scheme to manage morning commute congestion, considering the loss aversion of commuters toward purchasing credits. They showed that without considering the heterogeneity of commuters, the efficiency of a travel demand management strategy in minimizing the total system cost is reduced. They also determined the Pareto-improving tradable credit scheme that makes everybody better off by developing a group-specific time-varying credit charging scheme. Their study falls into the second category of studies where the morning commute congestion is analyzed in a highway bottleneck with CAVLs during transition horizon with a mixed fleet of CAVs and HDVs.

This chapter addresses the morning commute problem during the transition horizon with a mixed fleet (CAVs and HDVs). During the morning peak period, commuters traverse a highway bottleneck located between their residences and their workplace. Two types of commuters are considered in the present study: (i) CAV commuters and (ii) HDV commuters. Commuters travel using either CAVs or HDVs. Commuters are identical in terms of schedule delay penalty and desired arrival time. CAV commuters have a lower value of time compared to HDV commuters. Two types of lanes exist in the bottleneck: (i) CAVLs and (ii) GPLs. The capacity of CAVLs is assumed to be higher than that of GPLs (Chen et al., 2016; Ghiasi et al., 2017, 2020; Liu & Song, 2019; Madadi et al., 2021). The capacity of GPLs is assumed to be independent of the proportion of CAVs and HDVs. CAV travelers can choose between CAVLs and GPLs, while HDV travelers are restricted to using only GPLs. Each lane on the highway is treated as a separate bottleneck where the commuters' lane-changing behaviors are not considered.

The contributions of the research in this chapter are threefold. First, this study develops a framework for managing morning commute congestion in a highway bottleneck during transition horizon with a mixed fleet (CAVs and HDVs) considering the departure time choices of commuters. To date, this is the first study that analyzes the synergetic impact of CAVLs and tolling schemes on managing morning commute congestion during the transition horizon. In this context, the linear complementarity problem is developed herein to identify the equilibrium departure rates of commuters under the CAVL and tolling schemes. This facilitates comprehension of the synergetic impact of CAVLs and tolling schemes on commuters' departure rates. The existence of a solution, in terms of departure rates, is proven.

Second, this study investigates the lane and departure time choices of CAV commuters and their impacts on their travel costs and travel times for CAVLs and GPLs. It is shown that in any time interval, the CAVL queuing delay is less than or equal to that for GPL. Further, CAV commuters use GPLs in any time interval only if they use CAVLs in that time interval. This implies that the equilibrium cost of CAV commuters is always lower than that of HDV commuters. This has social inequity implications in practice. Finally, the system-optimal design model as a linear problem is developed in the present study to determine the optimal tolling policy which could also be used to identify the optimal number of lanes. This leads to the minimum travel cost during the morning peak period.

The remaining sections of this chapter are presented as follows: Section 5.2 introduces the preliminary thoughts and notations. Next, the user equilibrium condition is presented in Section 5.3. Next, the solution's existence and properties are established under equilibrium conditions in Section 5.4. Section 5.5 provides some insights on the properties of CAVL and GPL queuing delays and departure rates. Then, the system-optimal condition using the tolling policy is formulated in Section 5.6. Next, the computational experiments are performed in Section 5.7 to understand the impacts of different parameters such as CAVL capacity and CAV market penetration. Finally, some concluding remarks are provided in Section 5.8.

5.2 Preliminaries

This section presents the summary of the preliminaries to investigate the morning commute congestion in a discrete time setting. Table 5.1 presents the notations used. In the morning commute congestion context, commuters travel on a highway from home to their workplace during the morning peak period which is divided into Γ time intervals. Let T denote the set of time intervals. The highway bottleneck includes multiple lanes, categorized as CAVL and GPL, shown in Figure 5.1. Let L denote the set of lanes with two subsets of L_{CAVL} and L_{GPL} that denote the CAVL and GPL, respectively. The numbers of CAVLs and GPLs are equal to $|L_{\mathrm{CAVL}}|$ and $|L_{\mathrm{GPL}}|$ and where $|X|$ denotes the cardinality of set X. Each lane l has a deterministic capacity, which is denoted by s_l. Upon reaching a bottleneck, commuters are served in a first-in-first-out order, and it is assumed that they do not change lanes for mathematical simplicity. In practice, commuters experience free-flow travel time and queueing delay in each lane. For mathematical simplification, the present study assumes that free-flow travel time is equal to zero similar to previous studies in this field (Doan et al., 2011; Miralinaghi et al., 2019; Miralinaghi et al., 2017; Ramadurai et al., 2010).

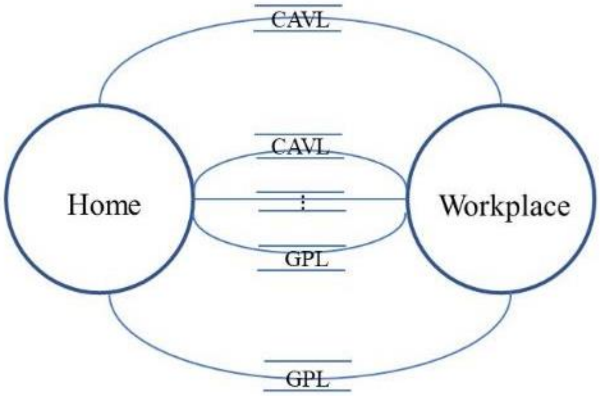
Table 5.1 List of notations (Chapter 5)

Sets	
L	Set of lanes
T	Set of time intervals

Parameter	
s_l	Capacity of lane l
N_g	Travel demand of group g
α_g	Value of time of group g
β_g	Early arrival penalty of group g
γ_g	Late arrival penalty of group g
t^*	Desired arrival time

Variables	
$r_{g,t,l}$	Departure rates of commuters of group g using lane l in time interval t
$\tau_{t,l}$	Queuing delay of commuters using lane l in time interval t
$e_{t,l}$	Early arrival duration of commuters departing in time interval t using lane l
$\sigma_{g,t,l}$	Travel cost of group g departing in time interval t using lane l
$p_{t,l}$	Toll of lane l for commuters departing at time interval t
μ_g	Equilibrium travel cost of commuters of group g

(a) Highway bottleneck with multiple lanes



(b) Transformed network

Figure 5.1 Highway bottleneck with CAVL and transformed network

Based on their choice of vehicle type, two groups of commuters are considered, denoted by G: (i) connected and autonomous vehicles ($g = 1$) and (ii) human-driven vehicles $g = 2$). Let N_g denote demand of commuters of group $g \in G$. It is assumed that commuters are identical in terms of schedule delay penalty, i.e., early arrival penalty β_g and late arrival penalty γ_g, which is expressed in \$/(time interval). The CAV and HDV commuters are assumed to have the same desired arrival time (that is, t^*). However, each group of commuters experiences different values of time, which is expressed in \$/(time interval). CAV commuters have a lower value of time compared to HDV commuters (that is, $\alpha_1 \leq \alpha_2$). Further, based on empirical studies, the early arrival penalty is assumed to be lower than the value of time for each group (i.e., $\beta_g \leq \alpha_g$) (Doan et al., 2011; Ramadurai et al., 2010; Small, 1982). Let $r_{g,t,l}$ represent the departure rates of commuters of group g using lane l in time interval t. Due to the options available to them, CAV commuters make both departure time and lane type choices (i.e., CAVL vs. GPL); on the other hand, HDV commuters make only departure time choices. These decisions are based on the total travel cost that includes (i) schedule delay, (ii) queuing delay, (iii) time-varying lane-specific tolling policy. HDV and CAV commuters are not able to reduce their travel costs by unilaterally changing their departure times (and for CAV commuters only, their travel lanes).

By modifying the function proposed by Ramadurai et al. (2010), the queuing delay of commuters can be formulated as follows:

$$\tau_{0,l} = max\ (0, \frac{\sum_g r_{g,0,l} - s_l}{s_l}) \qquad \forall l \in L \qquad (5.1)$$

$$\tau_{t,l} = max\ (0, \tau_{t-1,l} + \frac{\sum_g r_{g,t,l} - s_l}{s_l}) \qquad \forall t > 0, \forall\ l \in L \qquad (5.2)$$

Queuing delays of commuters using lane l departing at time interval t can be calculated using equations (5.1) and (5.2), respectively. These equations state that a queue is generated at bottleneck l if bottleneck capacity is less than the total departure rates of commuters. The early arrival duration of commuters departing in time interval t using lane l can be determined as follows:

$$e_{t,l} = max(0, t^* - t - \tau_{t,l}) \qquad \forall t \in T, \forall\ l \in L \qquad (5.3)$$

Constraints (5.3) state that if commuters using lane l arrive later than the desired arrival time, early arrival duration is equal to zero and they experience late arrival cost. Finally, the travel cost of commuters of group g departing at time t using lane l ($\sigma_{g,t,l}$) can be formulated as follows:

$$\sigma_{g,t,l} = \beta \cdot e_{t,l} + \alpha_g \cdot \tau_{t,l} + \gamma \cdot (e_{t,l} - (t^* - t - \tau_{t,l})) \qquad \forall t \in T, \forall l \in L \qquad (5.4)$$

5.3 User equilibrium under CAVL and tolling policies

This section presents the user equilibrium conditions for managing morning commute congestion under integrated policies of CAVL and tolling. The travel cost of commuters under the integrated policies can be formulated as follows:

$$\sigma_{g,t,l} = \beta \cdot e_{t,l} + \alpha_g \cdot \tau_{t,l} + \gamma \cdot \left(e_{t,l} - \left(t^* - t - \tau_{t,l}\right)\right) + p_{t,l} \qquad \forall t \in T, \forall l \in L \qquad (5.5)$$

here $p_{t,l}$ denotes the charged tolls for commuters using lane l departing at time interval t[1]. For generalization, the values of tolls are set to be lane specific in this study, which can vary Under the equilibrium conditions, (i) CAV commuters cannot reduce their travel costs further by unilaterally changing their departure times and lanes, and (ii) HDV commuters cannot reduce their travel costs further by unilaterally changing their departure times. The structure of equilibrium condition is shown in Figure 5.2.

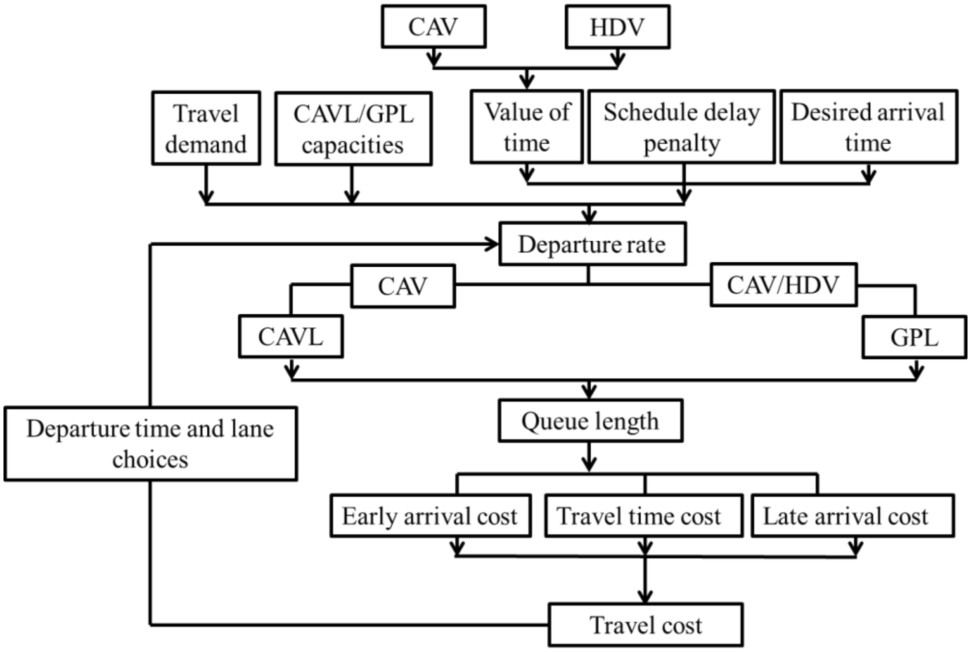


Figure 5.2 Structure of interactions between the factors

The equilibrium condition can be formulated as a mixed-linear complementarity problem (MLCP) as follows:

$$0 \le r_{g,t,l} \perp \alpha_g \cdot \tau_{t,l} + \beta \cdot e_{t,l} + \gamma \cdot \left(e_{t,l} - \left(t^* - t - \tau_{t,l}\right)\right) + p_{t,l} - \mu_g \ge 0 \qquad \forall t \in T, \forall l \in L, g = 1 \tag{5.6}$$

$$0 \le r_{g,t,l} \perp \alpha_g \cdot \tau_{t,l} + \beta \cdot e_{t,l} + \gamma \cdot \left(e_{t,l} - \left(t^* - t - \tau_{t,l}\right)\right) + p_{t,l} - \mu_g \ge 0 \qquad \forall t \in T, \forall l \in L_{GPL}, g = 2 \tag{5.7}$$

$$r_{g,t,l} = 0 \qquad \forall t \in T, \forall l \in L_{CAVL}, g = 2 \tag{5.8}$$

$$0 \le \tau_{0,l} \perp \tau_{0,l} - \frac{\sum_g r_{g,t,l} - s_l}{s_l} \ge 0 \qquad \forall l \in L \tag{5.9}$$

$$0 \le \tau_{t,l} \perp \tau_{t,l} - (\tau_{t-1,l} + \frac{\sum_g r_{g,t,l} - s_l}{s_l}) \ge 0 \qquad \forall t \in \mathrm{T}\backslash 0, \forall l \in L \tag{5.10}$$

$$0 \le e_{t,l} \perp e_{t,l} - \left(t^* - t - \tau_{t,l}\right) \ge 0 \qquad \forall t \in T, \forall l \in L \tag{5.11}$$

$$\sum_{l} \sum_{t} r_{g,t,l} - N_g = 0 \qquad \forall g \in G \tag{5.12}$$

where μ_g is the equilibrium travel cost of commuters of group g. The mathematical operator "⊥" is perpendicular, which means that vectors $z \perp d$ if and only if $z^T d = 0$. Complementarity constraints (5.6) and (5.7) are the user equilibrium conditions which state that commuters of group g depart at time interval t using lane l only if their travel costs, including queuing delay, schedule delay, and tolls are equal to the minimum travel cost of that group. Constraints (5.8) ensure that HDV commuters do not use CAVL. Complementarity constraints (5.9) and (5.10) calculate the queueing delay for lane l at time interval 0 and $t > 0$, respectively. Complementarity constraints (5.11) determine the early arrival duration for commuters using lane l departing at time interval t. Constraints (5.12) satisfy the travel demand of commuters of group g.

To apply the existing theorems in the context of linear complementarity problems (LCP) for investigating the solution existence, the MLCP (5.6)-(5.12) needs to be reformulated as the equivalent LCP as follows:

$$\begin{aligned} 0 \le r_{g,t,l} \perp \alpha_g \cdot \tau_{t,l} + \beta \cdot e_{t,l} + \gamma \cdot \left(e_{t,l} - \left(t^* - t - \tau_{t,l}\right)\right) \\ + \varphi_{g,t,l} + p_{t,l} - \mu_g \ge 0 \end{aligned} \qquad \forall t \in T, \forall l \in L, g \in G \tag{5.13}$$

$$0 \le \mu_g \perp \sum_{l} \sum_{t} r_{g,t,l} - N_g \ge 0 \qquad \forall g \in G \tag{5.14}$$

(5.9)-(5.11)

Let $\varphi_{g,t,l}$ denote the extra pseudo-cost incurred by the commuters due to using (traveling on) CAVLs. $\varphi_{2,t,CAVL}$ is a sufficiently large positive value to ensure that HDV commuters are not using CAVL. As CAVs are allowed to use CAVL, $\varphi_{1,t,l_{CAV}}$ is zero. As there is no restriction of using GPL for commuters, $\varphi_{g,t,l}$ is equal to zero for GPLs. The equivalence between MLCP and LCP can be established using the following theorem:

Theorem 1. MLCP is equivalent to LCP. This means that every solution to LCP can solve MLCP and vice versa.

Proof. LCP and MLCP are equivalent under the following two conditions:

1. $r_{2,t,l}$ are equal to zero for any $l \in L_{CAVL}$.
2. μ_g has a strictly positive value.

Condition 1 ensures that HDV travelers do not use CAVLs. that $\varphi_{g,t,l}$ is a sufficiently large positive constant for HDV commuters for using CAVLs. Therefore, the right-hand side of the constraint (5.13) is always greater than zero for $l \in L_{CAV}$. Given complementarity constraint (5.13), HDVs do not use CAVL.

As μ_g consists of several non-negative cost components (early arrival cost, travel time cost, late arrival cost, and toll), to prove the condition 2 it is sufficient to show that there is no solution to MLCP in which μ_g= 0.

This ensures that μ_g is strictly positive which means that travel demand is satisfied for complementarity constraints (5.14). This concludes the proof. ■

5.4 Solution existence

To facilitate proof that a solution exists, the right-hand side of the complementarity equation (5.13) and (5.14) is divided by $(\alpha_g + \gamma)$. Also, the right-hand side of the complementarity equations (5.9) and (5.10) are multiplied by S. The model can be described as follows:

$$0 \leq \boldsymbol{v} \ \perp \boldsymbol{Av} + \boldsymbol{b} \geq 0,$$

in which the $\boldsymbol{v}$ is the variable vector:

$$\boldsymbol{v} \equiv \begin{pmatrix} \boldsymbol{r} \\ \boldsymbol{\tau} \\ \boldsymbol{e} \\ \boldsymbol{\mu} \end{pmatrix}$$

where $\boldsymbol{r} \equiv (r_{g,t,l})_{(g,t,l)\in G\times T\times L}$, $\boldsymbol{\tau} \equiv (\tau_{t,l})_{(t,l)\in T\times L}$, $\boldsymbol{e} \equiv (e_{t,l})_{(t,l)\in T\times L}$, and $\boldsymbol{\mu} \equiv (\mu_g)_{g\in G}$. **b** is the constant vector:

$$\boldsymbol{b} \equiv \begin{pmatrix} \boldsymbol{b_1} \\ \boldsymbol{b_2} \\ \boldsymbol{b_3} \\ \mathbf{b_4} \end{pmatrix},$$

$$\boldsymbol{b_1} = \begin{pmatrix} \frac{1}{\alpha_1+\gamma}\left(-\gamma(t^* - t) + (\varphi_{1,t,l}) + (p_{t,l}) + M\right)_{t\in T,l\in L} \\ \frac{1}{\alpha_2+\gamma}\left(-\gamma(t^* - t) + (\varphi_{2,t,l}) + (p_{t,l}) + M\right)_{t\in T,l\in L} \\ \vdots \\ \frac{1}{\alpha_g+\gamma}\left(-\gamma(t^* - t) + (\varphi_{g,t,l}) + (p_{t,l}) + M\right)_{t\in T,l\in L} \end{pmatrix} \in \Re^{|G|\times|T|\times|L|},$$

$$\boldsymbol{b_2} = \begin{pmatrix} s_1 \\ s_2 \\ \vdots \\ s_l \\ s_1 \\ \vdots \\ s_l \\ \vdots \\ s_l \end{pmatrix} \in \Re^{|T|\times|L|},$$

$$\boldsymbol{b_3} = \left(-\left(t^* - t - \tau_{t,l}\right)_{t\in T,l\in L}\right) \in \Re^{|T|\times|L|},$$

$$b_4 = \begin{pmatrix} \frac{1}{\alpha_1+\gamma}N_1 \\ \frac{1}{\alpha_2+\gamma}N_2 \\ \vdots \\ \frac{1}{\alpha_g+\gamma}N_g \end{pmatrix} \in \Re^{|G|},$$

also, Matrix A is as follows:

$$\boldsymbol{A} \equiv \begin{pmatrix} 0 & \boldsymbol{A_1} & \boldsymbol{A_2} & -\boldsymbol{A_3} \\ -\boldsymbol{A_1^T} & \boldsymbol{S} & 0 & 0 \\ 0 & \boldsymbol{A_4} & \boldsymbol{A_5} & 0 \\ \boldsymbol{A_3^T} & 0 & 0 & 0 \end{pmatrix},$$

where

$$\boldsymbol{A_1} = \begin{pmatrix} \boldsymbol{I} \\ \boldsymbol{I} \\ \vdots \\ \boldsymbol{I} \end{pmatrix} \in \Re^{(|G|\times|T|\times|L|)} \times \Re^{(|T|\times|L|)},$$

$\boldsymbol{I}$ is an identity matrix: $\boldsymbol{I} = \begin{pmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{pmatrix} \in \Re^{(|T|\times|L|)} \times \Re^{(|T|\times|L|)},$

$$\boldsymbol{A_2} = \begin{pmatrix} \frac{\beta+\gamma}{\alpha_1+\gamma} & \cdots & \\ \vdots & \ddots & \vdots \\ & \cdots & \frac{\beta+\gamma}{\alpha_g+\gamma} \end{pmatrix} \in \Re^{(|G|\times|T|\times|L|)} \times \Re^{(|G|\times|T|\times|L|)},$$

$$\boldsymbol{A_3} = \begin{pmatrix} \frac{1}{\alpha_1+\gamma} & 0 & \ldots & 0 \\ \frac{1}{\alpha_1+\gamma} & 0 & \ldots & 0 \\ \vdots & \vdots & \vdots & 0 \\ 0 & \frac{1}{\alpha_2+\gamma} & \ldots & 0 \\ \vdots & \vdots & \vdots & 0 \\ 0 & 0 & 0 & \frac{1}{\alpha_g+\gamma} \end{pmatrix} \in \Re^{(|G|\times|T|\times|L|)} \times \Re^{(|G|)},$$

$$\boldsymbol{A_4} = \begin{pmatrix} \frac{1}{\alpha_1+\gamma}\boldsymbol{I} \\ \frac{1}{\alpha_2+\gamma}\boldsymbol{I} \\ \vdots \\ \frac{1}{\alpha_g+\gamma}\boldsymbol{I} \end{pmatrix} \in \Re^{(|G|\times|T|\times|L|)} \times \Re^{(|T|\times|L|)},$$

$$\boldsymbol{A_5} = \begin{pmatrix} \frac{1}{\alpha_1+\gamma} & \cdots & \\ \vdots & \ddots & \vdots \\ & \cdots & \frac{1}{\alpha_g+\gamma} \end{pmatrix} \in \Re^{(|G|\times|T|\times|L|)} \times \Re^{(|G|\times|T|\times|L|)},$$

$$\boldsymbol{S} = \begin{pmatrix} s_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & s_l \end{pmatrix} \in \Re^{(|T|\times|L|)} \times \Re^{(|T|\times|L|)}$$

The solution set of $LCP(\boldsymbol{b}, \boldsymbol{A})$ is denoted by $SOL(\boldsymbol{b}, \boldsymbol{A})$. Cottle et al. (1992) proved that $SOL(\boldsymbol{b}, \boldsymbol{A}) \neq \emptyset$ if the following conditions hold:

(i) Let $\boldsymbol{A} \in \Re^{n\times n}$. Then, A is called an $\boldsymbol{R_0}$-matrix if $SOL(0, \boldsymbol{A}) = \{0\}$. This class of matrices is denoted by $\boldsymbol{R_0}$.

(ii) $\boldsymbol{A}$ is copositive if $\boldsymbol{v}^T\boldsymbol{A}\boldsymbol{v} \geq 0$ for every nonnegative vector $\boldsymbol{v} \geq 0$.

If the above conditions hold, $LCP(\boldsymbol{b}, \boldsymbol{A})$ has existent solutions.

Proof.

Decompose matrix **A** into a positive semi-definite matrix $\widehat{\boldsymbol{A}}$ and a non-negative matrix $\overline{\boldsymbol{A}}$, $\boldsymbol{A} = \widehat{\boldsymbol{A}} + \overline{\boldsymbol{A}}$

$$\widehat{\boldsymbol{A}} \equiv \begin{pmatrix} 0 & \boldsymbol{A}_1 & 0 & -\boldsymbol{A}_3 \\ -\boldsymbol{A}_1^T & \boldsymbol{S} & 0 & 0 \\ 0 & 0 & \boldsymbol{A}_5 & 0 \\ \boldsymbol{A}_3^T & 0 & 0 & 0 \end{pmatrix}$$

$$\overline{\boldsymbol{A}} \equiv \begin{pmatrix} 0 & 0 & \boldsymbol{A}_2 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & \boldsymbol{A}_4 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

(i)

According to the definition of the $\boldsymbol{R_0}$ matrix, $\boldsymbol{v} = 0$ is the only solution of $SOL(0, \boldsymbol{A})$.
Clearly, $\boldsymbol{v} = 0$ yields in $\boldsymbol{Av} \geq 0, \boldsymbol{v} \geq 0$ and finally $\boldsymbol{v}^T\boldsymbol{Av} \geq 0$.
Then, it can be shown that if there exist a $\boldsymbol{v} \geq 0$ then $\boldsymbol{v}^T\boldsymbol{Av} \geq 0$, $v = 0$.
$\boldsymbol{v}^T\boldsymbol{Av} = \boldsymbol{v}^T\widehat{\boldsymbol{A}}\boldsymbol{v} + \boldsymbol{v}^T\overline{\boldsymbol{A}}\boldsymbol{v} = 0$. Therefore, $\boldsymbol{\tau S \tau} + \boldsymbol{eA_4\tau} + \boldsymbol{rA_2e} + \boldsymbol{eA_5e} = 0$. As $\boldsymbol{S}, \boldsymbol{A_2}, \boldsymbol{A_4},$ and $\boldsymbol{A_5}$ are positive matrices, therefore $\boldsymbol{r}, \boldsymbol{e},$ and $\boldsymbol{\tau}$ are zero matrices. As $\boldsymbol{r} = 0$, there is no traffic congestion and delay in the network which implies $\boldsymbol{\mu} = 0$ and thus $\boldsymbol{v} = 0$.

(ii)

$$\boldsymbol{v}^T\boldsymbol{Av} = \boldsymbol{v}^T\widehat{\boldsymbol{A}}\boldsymbol{x} + \boldsymbol{x}^T\overline{\boldsymbol{A}}\boldsymbol{x}$$

Since $\widehat{\boldsymbol{A}}$ is a positive semi-definite matrix and $\overline{\boldsymbol{A}}$ is a non-negative matrix.,

$$\boldsymbol{v}^T\widehat{\boldsymbol{A}}\boldsymbol{x} + \boldsymbol{v}^T\overline{\boldsymbol{A}}\boldsymbol{x} \geq 0$$

Therefore, $\boldsymbol{A}$ is a copositive matrix. The proof is complete.■

5.5 User equilibrium solution properties

This section analyzes the relationship between CAVL and GPL queuing delays and the departure rates of commuters under user equilibrium without tolling.

Proposition 1. Under the equilibrium condition, the queuing delay of CAVL for any time interval t is less than or equal to the one for GPL in that time interval (that is, $\tau_{t,l} \leq \tau_{t,l'}$ $\forall t$ where $l \in L_{CAVL}$ and $l' \in L_{GPL}$)

Proof. Proposition 1 is proved by contradiction. Under equilibrium conditions, assume that:

$$\tau_{t,l} > \tau_{t,l'} \qquad \forall t, l \in L_{CAVL}, l' \in L_{GPL} \qquad (5.15)$$

To conduct this proof, the peak period is divided into three parts, as follows:

Part 1. ($t + \tau_{t,l} \leq t^*$ for $l \in L_{CAVL}$)

In this part, both HDV and CAV commuters incur early arrival costs. The relationship between travel costs of CAV commuters using GPL and CAVL can be formulated as follows:

$$\alpha_1 \cdot \tau_{t,l'} + \beta \cdot \left(t^* - t - \tau_{t,l'}\right) < \alpha_1 \cdot \tau_{t,l} + \beta \cdot \left(t^* - t - \tau_{t,l}\right) \qquad \forall t \in T, l \in L_{CAVL}, \qquad (5.16)$$

$$l' \in L_{GPL}$$

this implies that:

$$\sigma_{1,t,l'} < \sigma_{1,t,l} \qquad \forall t \in T, l \in L_{CAVL}, l' \in L_{GPL} \qquad (5.17)$$

There are four cases regarding departure rates of CAV commuters as follows:

1) $r_{1,t,l'} > 0, r_{1,t,l} > 0$
2) $r_{1,t,l'} = 0, r_{1,t,l} > 0$
3) $r_{1,t,l'} > 0, r_{1,t,l} = 0$
4) $r_{1,t,l'} = 0, r_{1,t,l} = 0$

Given the lower travel costs of CAV commuters under GPL compared to CAVL, cases 1 and 2 cannot occur under the equilibrium conditions since CAV commuters can change lanes from CAVL to GPL to reduce their travel costs. The relationship between the travel times of CAV commuters using CAVL and GPL under case 3 can be formulated as follows:

$$\tau_{t-1,l'} + \frac{\sum_g r_{g,t,l'} - s_{l'}}{s_{l'}} < \tau_{t-1,l} \qquad \forall t \in T, l \in L_{CAVL}, l' \in L_{GPL} \qquad (5.18)$$

For case 4,

$$\tau_{t-1,l'} + \frac{r_{g,t,l'} - s_{l'}}{s_{l'}} < \tau_{t-1,l} \qquad \forall t \in T, l \in L_{CAVL}, l' \in L_{GPL} \qquad (5.19)$$

From inequalities (5.18) and (5.19), it follows that $\tau_{t-1,l'}$ is less than $\tau_{t-1,l}$. Similar to inequalities (5.16) and (5.17), it infers that $\sigma_{1,t-1,l'}$ is less than $\sigma_{2,t-1,l}$. Following the same pattern, it results that:

$$\tau_{t',l'} < \tau_{t',l} \qquad \forall t' \in T, l \qquad (5.20)$$

This implies that $\sigma_{1,t',l'}$ is strictly less than $\sigma_{2,t',l}$ for any $t' \leq t$. Given the higher cost of using CAVL, CAV commuters do not use CAVL and travel using GPL in any time interval $t' \leq t$. Since CAV commuters do not use CAVL, its queueing delay should be equal to zero ($\tau_{t,l} = 0, \forall t \in T, \forall l \in L_{CAVL}$). This means that the queuing delay of GPL is strictly less than zero, which is not possible. This completes the proof for part 1.■

Part 2. ($t + \tau_{t,l} \geq t^*$ and $t + \tau_{t,l'} \leq t^*$ for $l \in L_{CAVL}, l' \in L_{GPL}$)
In this part, CAV commuters using CAVL and GPL, incur early and late arrival delays, respectively. Let $\tilde{t}$ denote the greatest time interval in which departing commuters incur early arrival cost (that is, $\tilde{t} + \tau_{\tilde{t},l} \leq t^*$ and $\tilde{t} + 1 + \tau_{\tilde{t}+1,l} \geq t^*$ for $l \in L_{CAVL}$). Based on the part 1, it can be inferred that $\tau_{\tilde{t},l} \leq \tau_{\tilde{t},l'}$ and $\sigma_{1,t,l} \leq \sigma_{1,t,l'}$. If $t^* \leq \tilde{t} + 1 + \tau_{\tilde{t}+1,l'}$, then the proof can be done using part 3. Hence, for part 2, it is assumed that $t^* \geq \tilde{t} + 1 + \tau_{\tilde{t}+1,l'}$. It needs to be proven that $\tau_{\tilde{t}+1,l}$ is less than or equal to $\tau_{\tilde{t}+1,l'}$. To prove by contradiction, it needs to be proven that $\tau_{\tilde{t}+1,l} > \tau_{\tilde{t}+1,l'}$. Then,

$$\tau_{\tilde{t},l'} + \frac{\sum_g r_{g,\tilde{t}+1,l'} - s_{l'}}{s_{l'}} < \tau_{\tilde{t},l} + \frac{r_{1,\tilde{t}+1,l} - s_l}{s_l} \qquad l \in L_{CAVL}, l' \in L_{GPL} \tag{5.21}$$

Since $\tau_{\tilde{t},l'} \geq \tau_{\tilde{t},l}$ and $s_l \leq s_{l'}$, it follows that $r_{1,\tilde{t}+1,l} \geq \sum_g r_{g,\tilde{t}+1,l'}$ which implies that $\sigma_{\tilde{t}+1,1,l} \leq \sigma_{\tilde{t}+1,1,l'}$. Then,

$$\alpha_1 \cdot \tau_{\tilde{t}+1,l} + \gamma \cdot \left(\tilde{t} + 1 + \tau_{\tilde{t}+1,l} - t^*\right) < \alpha_1 \cdot \tau_{\tilde{t}+1,l'} + \beta \cdot \left(t^* - (\tilde{t}+1) - \tau_{\tilde{t}+1,l'}\right) \qquad l \in L_{CAVL}, l' \in L_{GPL} \tag{5.22}$$

Inequality (5.22) can be reformulated as follows:

$$(\alpha_1 + \gamma) \cdot \tau_{\tilde{t}+1,l} - \gamma \cdot \left(t^* - (\tilde{t}+1)\right) < (\alpha_1 - \beta) \cdot \tau_{\tilde{t}+1,l'} + \beta \cdot (t^* - (\tilde{t}+1)) \qquad l \in L_{CAVL}, l' \in L_{GPL} \tag{5.23}$$

By reformulating inequality (5.23), it follows that:

$$(\alpha_1 + \gamma) \cdot \tau_{\tilde{t}+1,l} - (\alpha_1 - \beta) \cdot \tau_{\tilde{t}+1,l'} < (\gamma + \beta) \cdot (t^* - (\tilde{t}+1)) \qquad l \in L_{CAVL}, l' \in L_{GPL} \tag{5.24}$$

Since $\tau_{\tilde{t}+1,l} \geq t^* - (\tilde{t}+1)$, it follows that:

$$(\alpha_1 + \gamma) \cdot \tau_{\tilde{t}+1,l} - (\alpha_1 - \beta) \cdot \tau_{\tilde{t}+1,l'} < (\gamma + \beta) \cdot \tau_{\tilde{t}+1,l} \qquad l \in L_{CAVL}, l' \in L_{GPL} \tag{5.25}$$

This means that $\tau_{\tilde{t}+1,l} < \tau_{\tilde{t}+1,l'}$ which contradicts the original assumption of $\tau_{\tilde{t}+1,l} > \tau_{\tilde{t}+1,l'}$. This completes the proof for part 2.■

Part 3. $(t + \tau_{t,l} \geq t^*$ for $l \in L_{CAVL})$

Similar to part 1, it can be shown that if $\exists t \geq t^*$ such that $\tau_{t,l} > \tau_{t,l'}$, then $\tau_{t-1,l} > \tau_{t-1,l'}$. This continues until $\tau_{\tilde{t}+1,l} > \tau_{\tilde{t}+1,l'}$ which contradicts the finding in part 2. This completes the proof.■

This proposition shows that the queuing delay of CAVL is less than or equal to the GPL in every time interval. This is because if the queuing delay of CAVL is higher than GPL in any time interval, then CAV commuters can change their lanes in that time interval to reduce their travel costs. This continues until the queuing delay for both lanes in that time interval becomes equal. Hence, HDV commuters experience higher queuing delays compared to CAV commuters in every time interval which is socially inequitable. This leads to proposition 2, which shows the relationship between the equilibrium travel costs of CAV and HDV commuters.

Proposition 2. Under the user equilibrium, the travel cost of CAV commuters is always less than the cost of HDV commuters.

Proof. Since CAV commuters can experience lower queuing delays in any time interval compared to HDV commuters who are restricted to GPL and given their lower value of time, it results in CAV commuters having a lower equilibrium travel cost compared to HDV commuters.

This proposition shows that the flexibility of CAV commuters in using both CAVL and GPL enables them to experience lower travel costs compared to HDV commuters. This is exacerbated by the lower value of time for CAV commuters. This has important equity implications in practice. In the early stages of adopting CAVs, such vehicles will be affordable only to the higher-income class of commuters. They can experience lower travel costs compared to lower-income commuters who cannot afford to purchase CAVs. Seilabi et al. (2020) proposed using a tradable credit scheme with a factoring equity constraint to address the social inequity raised by implementing the CAVL policy. They developed a Pareto-improving scheme that enables all travelers to experience lower travel costs, which can mitigate the public opposition due to social inequity. Next, the lane choice behavior of CAV commuters during the morning peak period is analyzed.

Proposition 3. CAV commuters use GPLs in time interval t only if there exists at least one CAV commuter who uses CAVL in that time interval.

Proof. To prove by contradiction, it is assumed that there exists a time interval t in which CAV commuters depart using GPL without using CAVL in that time period. Given proposition 1, the following three scenarios are possible for CAV travel costs using CAVL and GPL:

$$\alpha_1 \cdot \tau_{t,l'} + \beta \cdot \left(t^* - t - \tau_{t,l'}\right) < \alpha_1 \cdot \tau_{t,l} + \beta \cdot \left(t^* - t - \tau_{t,l}\right) \quad \forall t, l \in L_{CAVL}, l' \in L_{GPL} \tag{5.26}$$

$$\alpha_1 \cdot \tau_{t,l'} + \gamma \cdot \left(t + \tau_{t,l'} - t^*\right) < \alpha_1 \cdot \tau_{t,l} + \beta \cdot \left(t^* - t - \tau_{t,l}\right) \quad \forall t, l \in L_{CAVL}, l' \in L_{GPL} \tag{5.27}$$

$$\alpha_1 \cdot \tau_{t,l'} + \gamma \cdot \left(t + \tau_{t,l'} - t^*\right) < \alpha_1 \cdot \tau_{t,l} + \gamma \cdot \left(t + \tau_{t,l} - t^*\right) \quad \forall t, l \in L_{CAVL}, l' \in L_{GPL} \tag{5.28}$$

Scenarios 1 and 3 indicate when CAV commuters arrive either early or late, respectively. Scenario 2 corresponds to the case that CAV commuters using CAVL arrive earlier, while CAV commuters using GPL arrive later than the desired arrival time based on proposition 1. Under all scenarios, it results in the queuing delay at the CAVL being higher than that at the GPL, which contradicts proposition 1. This completes the proof.■

This proposition shows that CAVL always has a priority for CAV commuters because of the lower or equal queueing delay compared to GPL. These commuters choose to use GPL only if it allows them to reduce their queuing delay. This occurs only when GPL has significantly lower flow compared to CAVL. Otherwise, due to the higher capacity of CAVL, queueing delays are always higher for GPLs at a comparable level of flow. The next proposition shows that CAV and HDV commuters do not have overlap in departure rates in two or more consecutive time intervals.

Proposition 4. The departure rates of CAV and HDV commuters that use GPL do not overlap in two or more consecutive time intervals.

Proof. To prove by contradiction, it is assumed that CAV and HDV commuters depart using GPL in time intervals $t - 1$ and t. Then, it follows that:

$$\begin{aligned} &\alpha_1 \cdot \tau_{t-1,l'} + \beta \cdot e_{t-1,l'} + \gamma \cdot \left(e_{t-1,l'} - \left(t^* - (t-1) - \tau_{t-1,l}\right)\right) \\ &\qquad = \alpha_1 \cdot \tau_{t,l'} + \beta \cdot e_{t,l'} + \gamma \cdot \left(e_{t,l'} - \left(t^* - t - \tau_{t,l}\right)\right) \end{aligned} \quad \forall t, \forall l' \in L_{GPL} \tag{5.29}$$

$$\begin{aligned} &\alpha_2 \cdot \tau_{t-1,l'} + \beta \cdot e_{t-1,l'} + \gamma \cdot \left(e_{t-1,l'} - \left(t^* - (t-1) - \tau_{t-1,l}\right)\right) \\ &\qquad = \alpha_2 \cdot \tau_{t,l'} + \beta \cdot e_{t,l'} + \gamma \cdot \left(e_{t,l'} - \left(t^* - t - \tau_{t,l}\right)\right) \end{aligned} \quad \forall t, \forall l' \in L_{GPL} \tag{5.30}$$

By subtracting constraints (5.29) and (5.30), it follows that $\tau_{t-1,l'} = \tau_{t,l'}$. Substituting the equality of queueing delays in both time intervals $t-1$ and t into equations (5.29) and (5.30) yields:

$$(\beta+\gamma)\cdot e_{t-1,l'} + \gamma = (\beta+\gamma)\cdot e_{t,l'} \qquad \forall t, \forall l' \in L_{GPL} \tag{5.31}$$

If CAV commuters departing in time intervals $t-1$ and t arrive later than desired arrival time, $e_{t-1,l'}$ and $e_{t,l'}$ are equal to zero which implies that equation (5.31) is infeasible. If CAV commuters arrive earlier than desired arrival time, then it follows that:

$$(\beta+\gamma)\cdot(t^* - (t-1) - \tau_{t-1,l'}) + \gamma = (\beta+\gamma)\cdot(t^* - t - \tau_{t,l'}) \qquad \forall l' \in L_{GPL} \tag{5.32}$$

Equation (5.32) is also infeasible as β and γ are strictly greater than zero. Finally, if CAV commuters depart in time intervals $t-1$ and t arrive earlier and later than desired arrival time, then it follows that:

$$(\beta+\gamma)\cdot e_{t-1,l'} + \gamma = 0 \qquad \forall l' \in L_{GPL} \tag{5.33}$$

This equation is also infeasible as β, γ and $e_{t-1,l'}$ are positive. Hence, it is not possible for both CAV and HDV commuters to depart at consecutive intervals using GPL. The same proof can be applied to more than two time intervals. This completes the proof.■

5.6 System-optimal design of CAVL and tolling strategies

This section develops the system-optimal design of CAVL and tolling strategies using a linear model. The goal is to determine the optimal lane-specific tolls and number of CAVLs to achieve the minimum system cost, including total queueing and schedule delays. To develop a system-optimal tolling strategy for a single road bottleneck, Doan et al. (2011) proved that travelers experience zero queueing delays under system-optimal conditions. The same proof can be applied to the multiple road bottlenecks, which implies that queuing delays are equal to zero. This property enables us to develop a system-optimal tolling strategy. First, the method to determine the optimal tolling policy given the number of CAVLs is shown, and then is generalized to determine both the number of CAVLs and the optimal tolling policy. Under a given number of CAVLs and a zero-queuing delay property, the system-optimal model that determines the optimal departure rates and tolling strategy, can be expressed as the following mathematical model with complementarity constraints (MPCC):

$$0 \le r_{g,t,l} \perp \beta\cdot e_{t,l} + \gamma\cdot\left(e_{t,l} - (t^* - t)\right) + p_{t,l} + \varphi_{g,t,l} - \mu_g \ge 0 \qquad \forall t \in T, \forall l \in L, g \in G \tag{5.34}$$

$$0 \le e_{t,l} \perp e_{t,l} - (t^* - t) \ge 0 \qquad \forall t \in T, \forall l \in L \tag{5.35}$$

$$\sum_{l}\sum_{t} r_{g,t,l} - N_g = 0 \qquad \forall g \in G \tag{5.36}$$

By inserting zero queuing delays, constraints (5.34)-(5.36) satisfy user equilibrium constraints (5.6)-(5.12), respectively. The MPCC consists of linear complementarity constraints, which makes it difficult to solve. Hence, it is necessary to develop a mathematical program that can be easily solved. The MPCC can be formulated as the following linear program (LP):

$$\min_{p} Z = \sum_{(g,t,l)} r_{g,t,l} u_t \tag{5.37}$$

$$\sum_{g} \sum_{t} r_{g,t,l} \leq s_l \qquad \forall l \in L \tag{5.38}$$

$$r_{2,t,l} = 0 \qquad \forall t \in T, \forall l \in L_{CAVL} \tag{5.39}$$

$$\sum_{l} \sum_{t} r_{g,t,l} - N_g = 0 \qquad \forall g \in G \tag{5.40}$$

$$r_{g,t,l} \geq 0 \qquad \forall t \in T, \forall g \in G, \forall l \in L \tag{5.41}$$

where $u_t = \begin{cases} \beta(t^* - t) \\ \gamma(t - t^*) \end{cases}$ denotes the schedule delay of commuters departing in time interval t.

The objective function Z also denotes the travel cost, which only consists of schedule delay under the system-optimal condition. The objective function (5.37) is to minimize the total cost of commuters. Constraint (5.38) state the total departure rates of commuters using lane l should not exceed the capacity of that lane. Constraints (5.39) and (5.41) are identical to constraints (5.8) and (5.12), respectively. Using the first-order conditions, it is straightforward to demonstrate that the solution of LP (5.37)-(5.41) is also a solution to MPCC (5.34)-(5.36) where the Lagrangian multiplier for constraints (5.40) is the optimal time-varying lane-specific tolling policy. The capacities are constant across GPLs and CAVLs and vary only based on the lane type. Therefore, the right-hand sides of Equation (5.38) are identical. This results in the same toll for each lane type at different time intervals.

The main assumption (used to develop the LP (5.37)-(5.41)) is that, the number of CAVLs is constant. However, this could be another strategy for the urban road agency to further minimize the total travel cost. To develop the system-optimal CAVL and tolling strategy, it is necessary to solve LP (5.37)-(5.41) using the enumeration technique for the available number of lanes to allocate to CAVs. For example, if there are four lanes on a highway, the road agency can allocate up to 3 lanes to CAVs since it is necessary to have at least one lane for HDVs to use on this highway. Finally, the framework for deriving the optimal CAVL and tolling strategy can be formulated as follows:

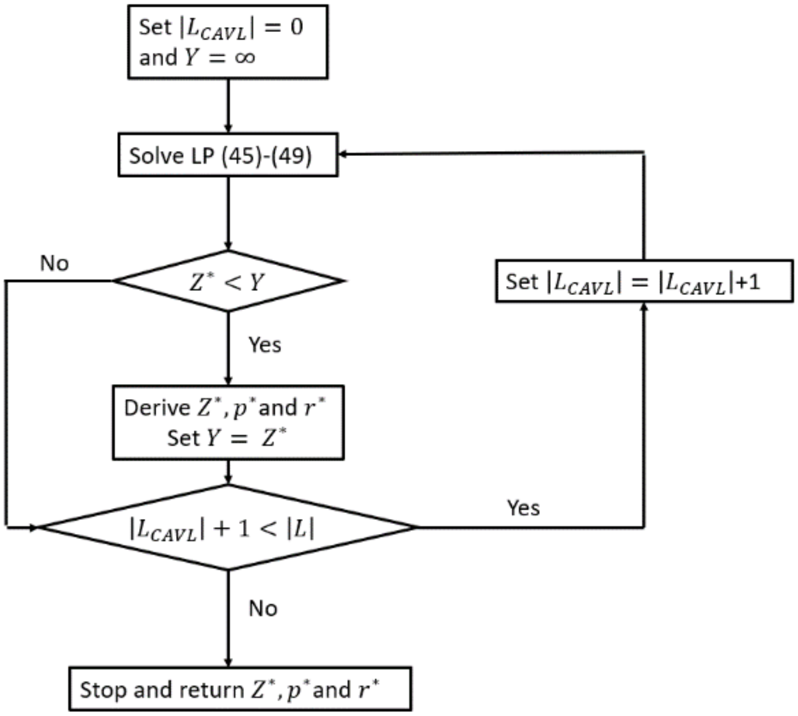


Figure 5.3 Solution algorithm to determine the optimal CAVL and tolling strategies

5.7 Computational experiments

This section seeks to analyze the impacts of the number of CAVLs and toll fees under different rates of CAV market penetration on the total system cost, and the lane and departure time choices of commuters. During the morning peak, the CAV and HDV commuters travel along the road with four lanes where the total travel demand is 1,000. The morning peak is divided into 100 time intervals, and commuters desire to arrive by the 70th time interval. The capacities of CAVL and GPL are assumed to be equal to 30 and 10 vehicles per lane per time interval, respectively. The early and late arrival penalties for CAV and HDV commuters are assumed to be equal to \$0.8 and \$4 per time interval, respectively. The CAV and HDV values of time are equal to \$1 and \$2 per time interval, respectively. Commercial solvers embedded in GAMS (Rosenthal, 2015) are used, including CONOPT (Drud, 1995) for MLCP (5.6)-(5.12) and CPLEX (GAMS Development Corporation, 2001) for LP (5.37)-(5.41).

First, the total system cost under different numbers of CAVLs and CAV penetration rates without a toll, is analyzed. Figure 5.4 presents the total system cost under user equilibrium conditions for different rates of CAV market penetration and the number of CAVLs. For zero CAVLs, the total system cost initially decreases as the CAV market penetration rate increases. This is mainly due to the smaller value of commuters' time in CAVs compared to HDVs. After achieving a minimum at approximately 45% CAV market penetration, total travel costs rise as CAV market penetration rate increases. Therefore, as CAV market penetration rate increases, more commuters reach their destination before the desired arrival time, despite incurring higher queuing delay due to the higher traffic congestion, to avoid a late arrival penalty (Figure 5.4). Consequently, the total system cost increases as commuters experience higher queueing delays. A similar pattern can be observed for one, two and three CAVLs, where total system cost initially reduces and then, it increases at different CAV market penetration rates. To determine the optimal number of CAVLs, Figure 5.4 is divided into four areas with blue circles. In each area, the total queuing delays of different CAV market penetrations are the minimum for either 0, 1, 2, or 3 CAVLs. In other words, the road agency deploys 0, 1, 2, and 3 CAVLs for market penetration levels 1, 2, 3, and 4, respectively.

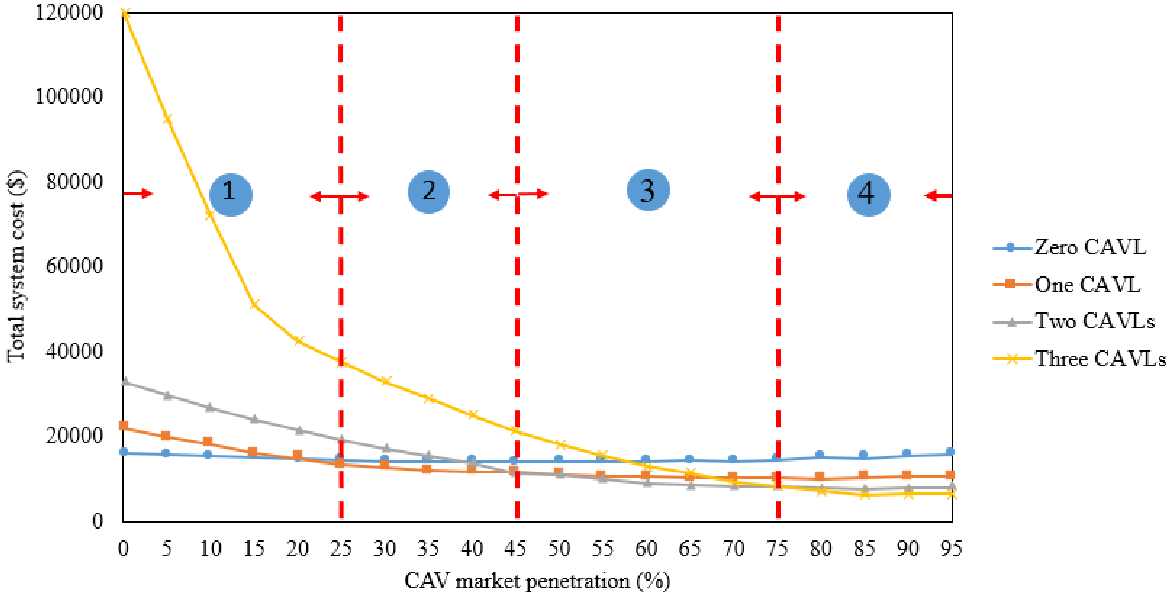
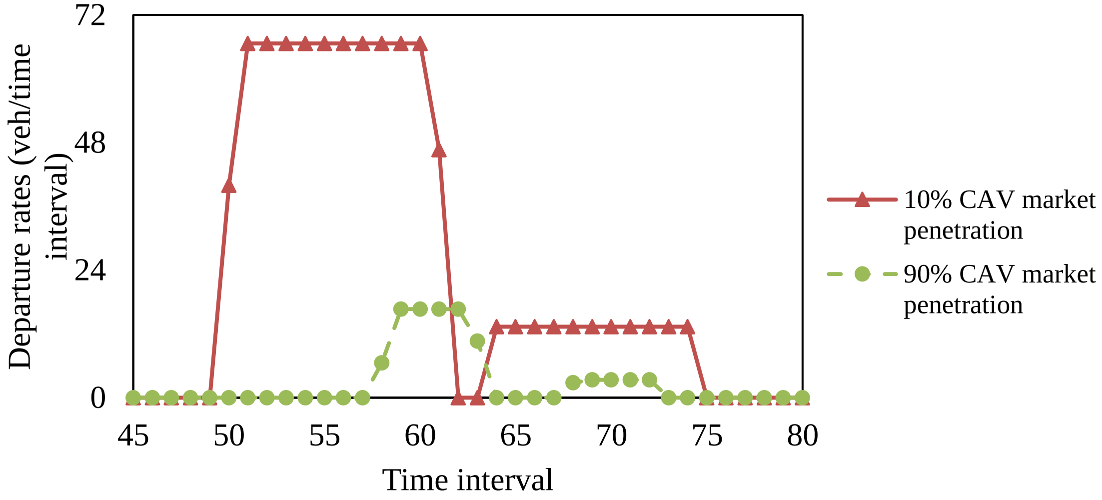
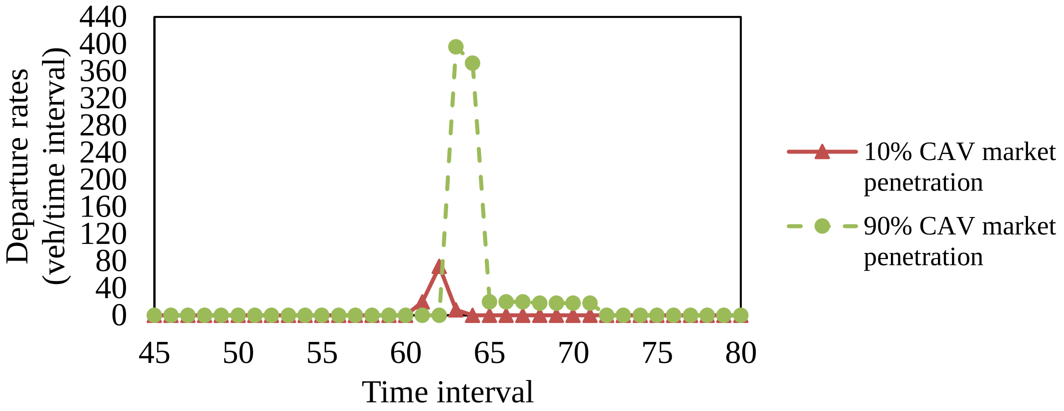


Figure 5.4 Total system cost under different CAVLs and CAV market penetration rates without tolling policy



(a) HDV commuter departure rates



(b) CAV commuter departure rates

Figure 5.5 Aggregate HDV and CAV departure rates under zero CAVLs, and without tolling policy

The optimal CAVL deployment plan without a tolling policy can be determined from Figure 5.5. Hereafter, this policy is referred to as “CAVL only”. Under this policy, the equilibrium travel costs of HDV and CAV commuters are presented for different levels of CAV market penetration (Figure 5.6). The equilibrium travel cost of CAVs is less than that of HDVs, which is consistent with proposition 2. When the CAV market penetration increases, the travel cost of CAV commuters will increase until the urban road agency deploys additional CAVLs on the road system. It is interesting that this also leads to a reduction in HDV travel costs. This is because although CAVL causes a reduction in road capacity for HDVs, it could also lead to an increase in available capacity as CAV prefers to use CAVL with higher capacity. This increases the mobility of the system and leads to a reduction in travel costs for HDVs as the CAV market penetration increases. Therefore, there is social inequity (difference between the CAV and HDV commuter travel costs).

Figure 5.6 Equilibrium travel costs under different levels of CAV market penetration

Next, Figure 5.7 presents the total system cost under different optimal strategies, in terms of CAVLs and a tolling policy (OCAVLT), to achieve the minimum total system cost. When there is no CAVL, the total system cost remains unchanged as CAV market penetration increases under optimal tolling policy. This is because it is assumed that the commuters experience zero queuing delay under system-optimal conditions, as discussed and justified in an earlier section of the chapter. Therefore, different combinations of HDV and CAV percentages in traffic flow have no impact on total system cost. On the other hand, the total system cost decreases for 1, 2, and 3 CAVLs. This is because CAVL increases in bottleneck corridor capacity; however, this increased capacity is available to CAV commuters only. Therefore, as the CAV market penetration increases, the total system cost is reduced. Figure 5.8 compares the system-optimal condition under the optimal CAVL only and OCAVLT policies. It is observed that the total system cost under OCAVLT is approximately 50% of that under the optimal CAVL only. Further, as CAV market penetration increases, there is a reduction in the system cost difference between these policies. This highlights the advantage of deploying CAVL.

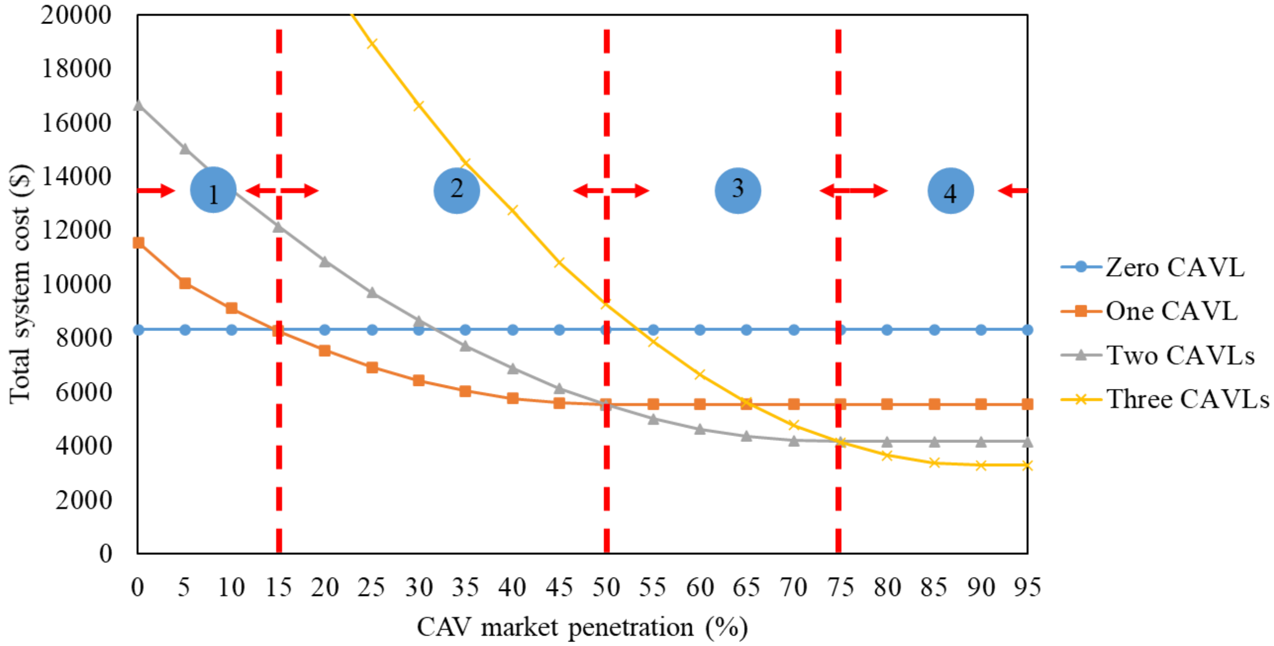


Figure 5.7 Optimal total system cost under OCAVLT for different levels of CAV market penetration

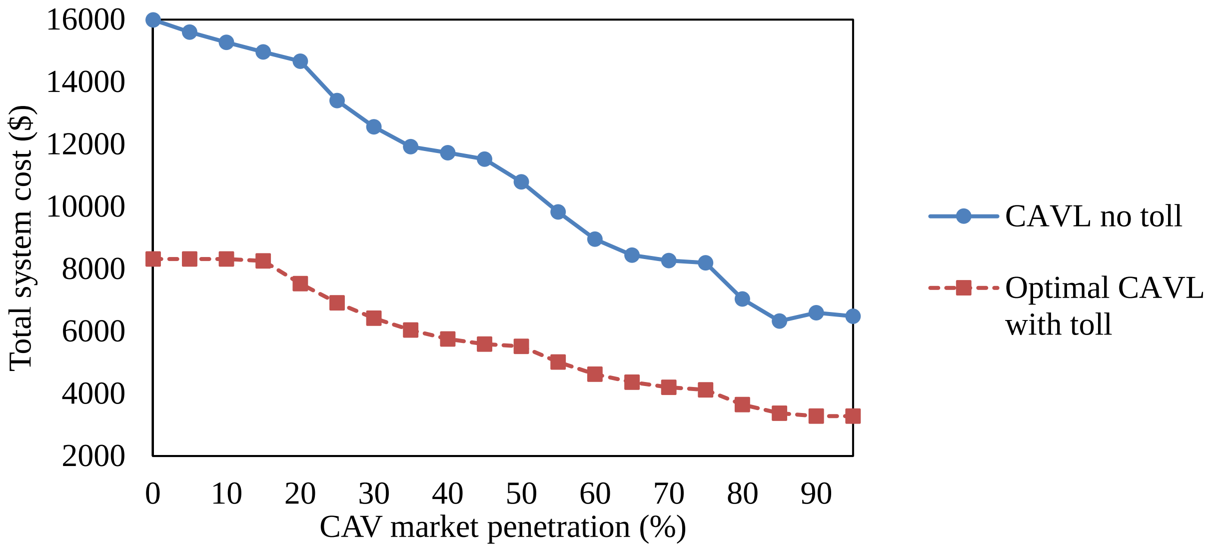


Figure 5.8 Comparison of the optimal total system cost under CAVL no toll and OCAVLT for different levels of CAV market penetration

Figure 5.9 presents the average of time-varying toll for CAV and HDV commuters under OCAVLT for different CAV market penetrations. Overall, this figure indicates higher tolls on GPL, which is mostly incurred by HDVs. When the CAV penetration is low, HDV commuters experience high tolling expenses in contrast to CAV commuters. As CAV market penetration increases, the average tolling expense of HDV commuters shows a decreasing trend. This decreasing trend continues until the average tolling expense of CAV commuters becomes higher compared to HDV commuters. This is because when CAV market penetration exceeds 70%, three lanes are allocated to CAVs, which leads to sufficient capacity for CAVs. Hence, HDV commuters need to pay less to travel using the remaining lane. This suggests that at high CAV market penetration, the social inequity (that is, the difference between CAV and HDV commuter travel costs) reduces. On the other hand, given the constant total travel demand, the total toll revenue collected by the agency is reduced as CAV market penetration rate increases. This highlights the importance of exploring alternative resources to supplement funds towards maintaining the urban road infrastructure in the CAV era. Figure 5.10 illustrates the impact of tolling policy on lane choice of CAV commuters under different CAV market penetration rates. It can be observed that under the system optimal tolling policy, CAV commuters utilize CAVLs more compared to the case without tolling policy. This is due to higher tolls on GPLs which discourages CAV commuters from using those lanes.

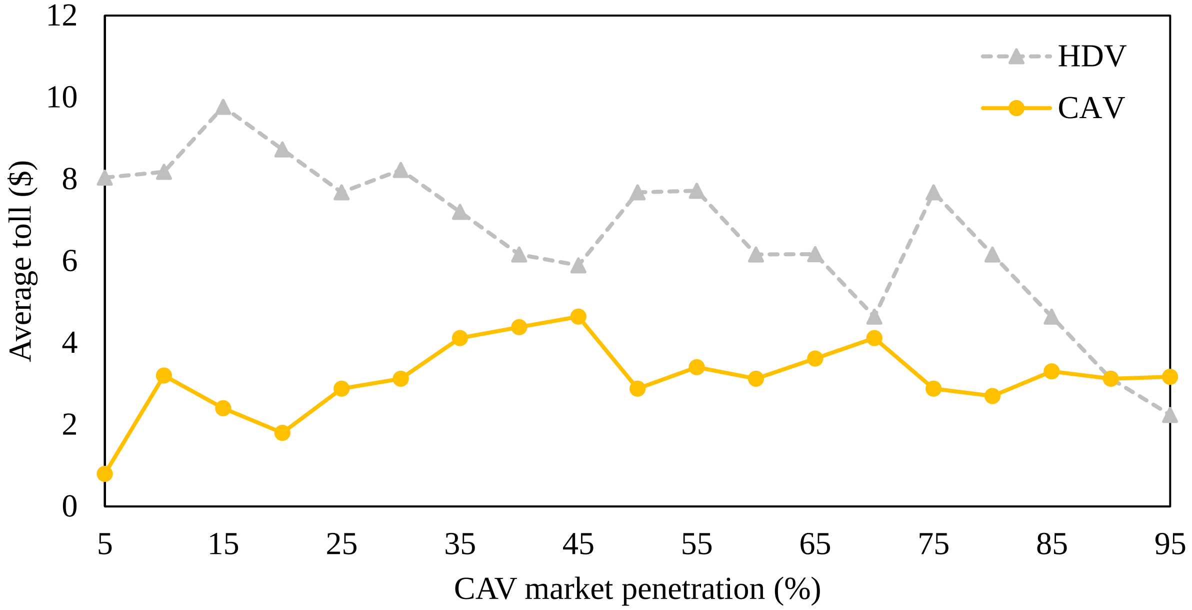
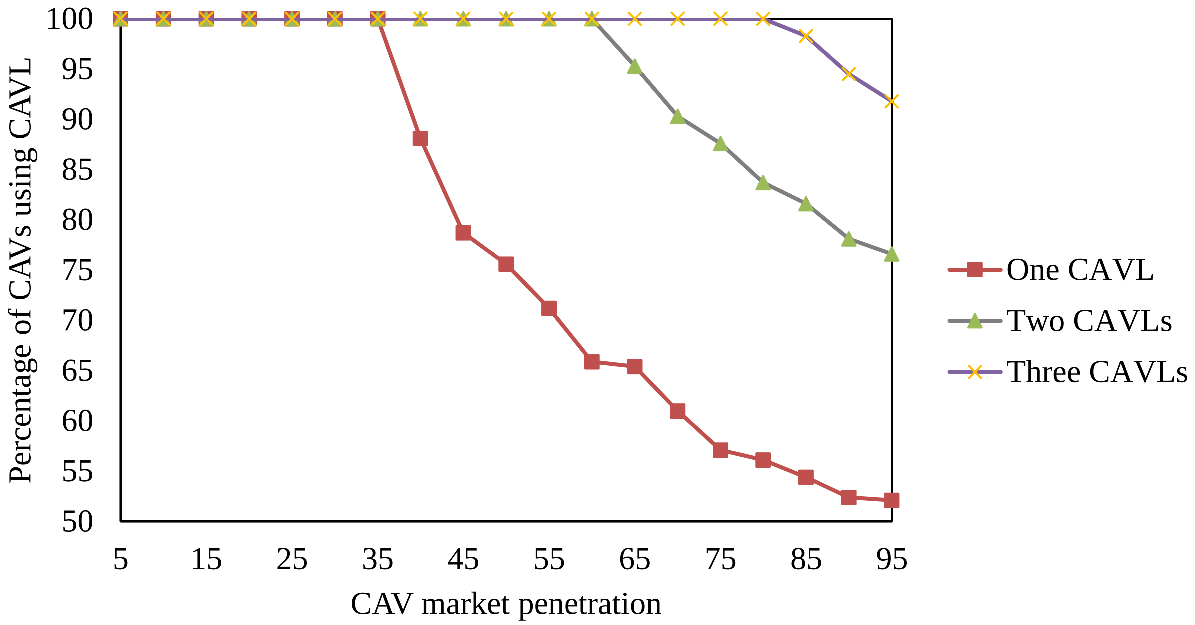
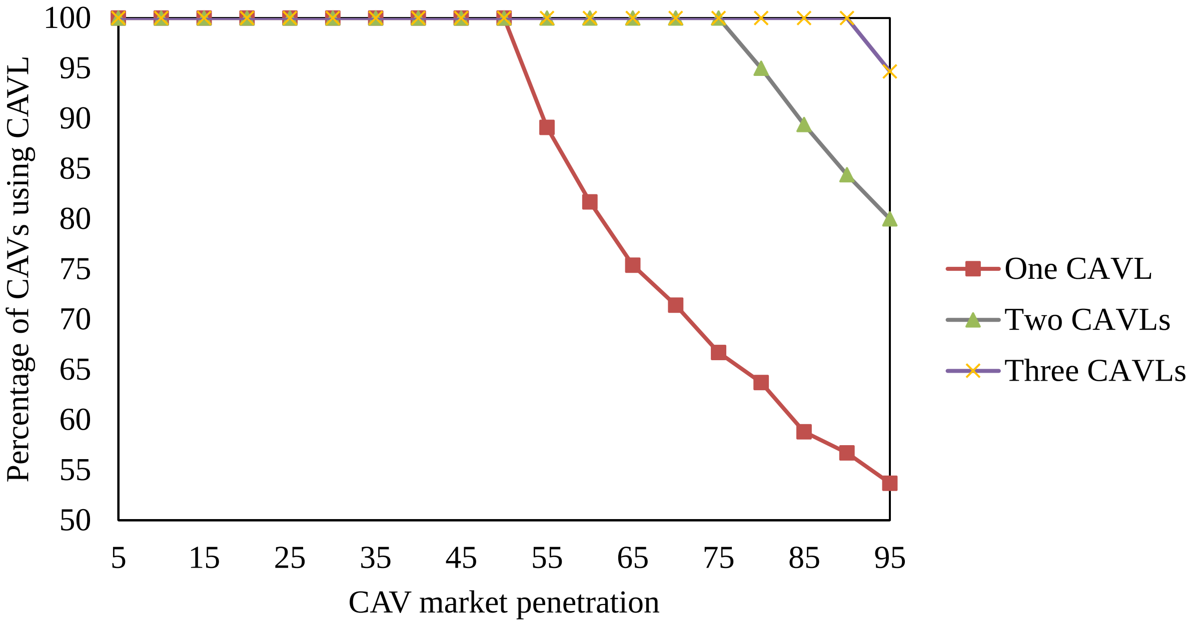


Figure 5.9 Average tolling expenditure per CAV and HDV commuters



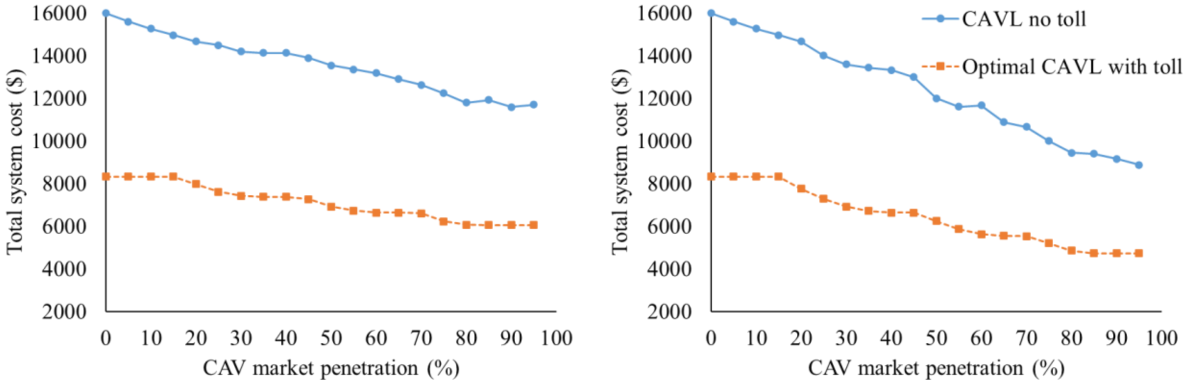
(a) Without tolling policy



(b) With optimal tolling policy

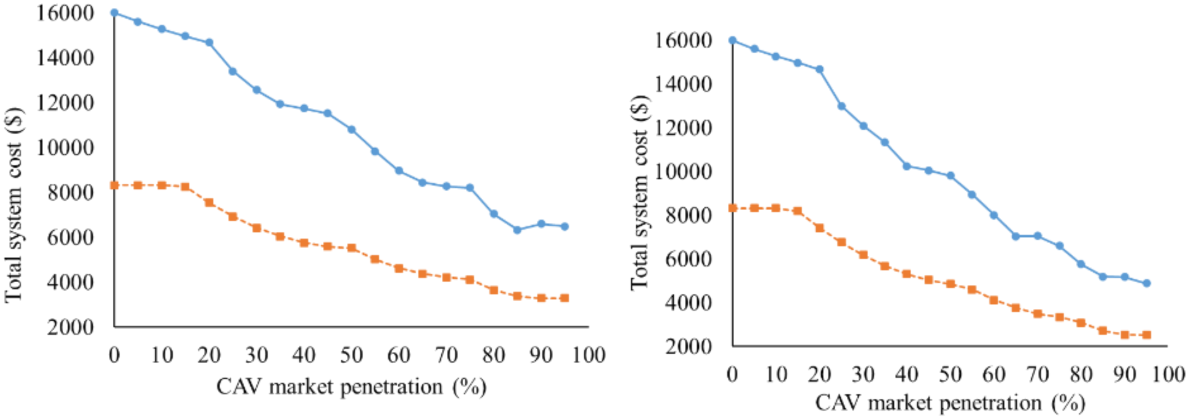
Figure 5.10 CAVL choice of CAV commuters under different levels of market penetration

Finally, the impacts of the CAVL capacity increase on the total system cost under optimal CAVL only and OCAVLT policies are investigated. So far, it is assumed that CAVL capacity is three times that of GPL capacity. That is, the capacities of CAVL and GPL are assumed to be equal to 30 and 10 vehicles per lane per time interval, respectively. That is, CAVL capacity coefficient is equal to 3. Figure 5.11 illustrates the impacts of CAVL capacity increase coefficients on total system cost under CAVL only and OCAVLT. As the CAVL capacity coefficient increases, the difference between the total system costs under CAVL only and OCAVLT decreases. This shows that the emerging transportation technologies of vehicle automation and connectivity can lead to capacity increases that obviate the need for implementing a tolling policy. For example, when the capacity of CAVL is 15 vehicles per time unit, the optimal system cost with the tolling policy is almost identical to the one under CAVL only when the CAVL capacity is 30 vehicles per time unit.



(a) Capacity increase coefficient = 1.5

(b) Capacity increase coefficient = 2



(c) Capacity increase coefficient = 3

(d) Capacity increase coefficient = 4

Figure 5.11 Total system costs under CAVL only and OCAVLT under different CAVL capacity increase coefficients

5.8 Concluding remarks

This part of the study proposes an analytical framework for lane management that can alleviate traffic congestion in a highway corridor during the transition era with a mixed fleet of CAVs and HDVs using CAVL and tolling policies. First, the user equilibrium condition is formulated as an LCP to understand the impact of CAVL on traffic congestion under different CAV market penetrations. The solution existence is investigated in terms of departure rates and travel costs. It is demonstrated that in any time interval, the CAVL queuing delay is less than or equal to the one for GPL. It is also proven that CAVs use GPL in any time interval if there is at least one CAV commuter who uses CAVL in that time interval. It is demonstrated that the departure rates of CAV and HDV commuters that use GPL do not overlap in two or more consecutive time intervals. Finally, the system-optimal condition (optimal number of CAVL and tolling policy) is determined to achieve the minimum system cost.

Computational experiments were conducted to help comprehend the impacts of different parameters, such as CAVL capacity and CAV market penetration, on the total system cost and departure rates. First, it is shown that HDV commuters' travel cost reduces as CAV market penetration increases by deploying CAVL. Further, it is shown that the difference between CAV and HDV travel costs reduces as CAV market penetration increases. This leads to lower social inequity in terms of the travel cost difference between HDVs and CAVs. In addition, the computational experiments illustrate that as CAV market penetration increases, the agency revenue in terms of tolling can be reduced. Furthermore, it is shown that CAV technological advancement, which leads to further increased CAVL capacity, can significantly improve traffic flow to an extent that is almost similar to the effect of tolling. It is also observed that as the CAV market penetration increases, the total system cost is reduced. Finally, it is illustrated that under a system optimal tolling policy, CAV commuters patronize CAVLs to a greater extent, compared to the case without a tolling policy.

6 ROBUST DESIGN OF CAV-DEDICATED LANES NETWORK CONSIDERING CAV DEMAND UNCERTAINTY AND LANE REALLOCATION POLICY

6.1 Introduction

This chapter focuses on environmentally sustainable design of CAVLs in the prospective era of CAVs from the perspectives of not only the urban road agency but also two other transportation stakeholders: (i) travelers and (ii) the community in general. While the route and vehicle type choices of travelers are considered, the CAVL is used as a tool to minimize vehicle emissions. The objective of this chapter is to develop an optimal network wide plan for deploying CAV-dedicated lanes (in terms of number of lanes to deploy, and which year to deploy each of them) that minimizes environmental impacts (vehicle emissions) while accounting for CAV market size uncertainty.

Existing studies in the context of network-wide CAV-dedicated lane deployment did not consider the possibility of having an increased total number of lanes due to the smaller width of CAV-dedicated lanes. It must be realized that an important aspect of CAV infrastructure planning is the possibility of lane reallocation – the appropriation of some existing HDV lanes to CAV exclusive use. Currently, the standard lane width for highways in the United States is 12 ft. Due to the little or zero lateral wander of CAVs (Ghiasi et al., 2020), CAV-dedicated lanes may have smaller lane widths from an HDV-only scenario to a mixed-stream scenario, and therefore, the number of lanes in a wide highway corridor can potentially be increased. The CAV-dedicated lane width could be close to the maximum vehicle width to accommodate more lanes (Dennis et al., 2017). For example, the width of the Tesla Model Y with unfolded mirrors is approximately 7 ft. Ghiasi et al. (2020) proposed a lane reallocation policy for a highway corridor to identify the optimal number of reduced-width CAV-dedicated lanes to maximize the highway segment throughput. In contrast to the network-level context of the present study, Ghiasi et al. (2020) captured the possibility of reducing the lane width to possibly increase the number of lanes for a single highway corridor.

The present study also considers the uncertainty in potential CAV market size in an urban area over a long-term planning horizon. The uncertainty in HDV and CAV travel demand generally stems from two main sources. The first is the uncertainty of travel demand over a long planning horizon due to changes in economic and demographic conditions over several years. The second is the uncertainty in consumers' willingness to purchase CAVs which translate into the CAV potential market size. Such uncertainty could be attributed to the lack of customer experience related to CAVs and consequently, variability in their anticipated purchases of this technology (Gkartzonikas & Gkritza, 2019). CAV market share could be estimated using customer surveys (Yang et al., 2020).

Chen et al. (2019) developed a two-stage stochastic programming model that considered uncertainty in the CAV purchase price. Liu and Song (2019) showed that the equilibrium flow may not be unique under a mixed flow of CAVs and HDVs considering the impact of mixed-flow on road capacity. The authors proposed a robust optimization program to minimize the maximum travel time under different equilibrium flows. However, none of these studies captured the uncertainty in consumers' responses to purchasing CAVs and, consequently, the potential CAV market size over several years. In the current study, the uncertainty in potential CAV market size is addressed with the assumption that the aggregate travel demand of HDVs and CAVs is given and therefore, do not consider the uncertainty in travel demand forecasts over several years.

To address the potential CAV market size uncertainty, a robust planning framework for CAV-dedicated lane deployment is developed in this chapter of the present study. This framework minimizes the total emissions costs relative to the worst-case scenario and is formulated as a bi-level problem where the upper level captures the decision of the urban road agency that seeks to minimize the maximum total emissions costs under different scenarios of potential CAV market size. It is assumed that CAVs are electric with zero local emissions. This is consistent with several studies on electric and automated vehicles (Azin et al., 2021; Zhuge & Wang, 2021) and the plans of several automakers, such as Waymo, Apple, and Tesla, to use electricity as the power source for future autonomous vehicles (Gurman, 2021; Tesla, 2021; Valdes-Dapena, 2018). Therefore, it is assumed that HDVs are the only source of significant emissions in the network. The decision to deploy CAV-dedicated lanes is subject to the total road width available. This encourages consumers to purchase CAVs, which is consistent with the goal of vehicle emissions minimization. The upper-level model is formulated as a mixed-integer nonlinear program. The potential CAV market size is assumed to be O-D specific to provide flexibility for urban road agency to capture the variation of CAV affordability for travelers of different regions.

The lower-level decision seeks to capture the vehicle type, route, and lane choices of travelers. It is assumed that the GP lanes is used by both HDV and CAV travelers. On the other hand, the CAV-dedicated lanes can be used by CAV travelers only. The values of time for two classes of travelers, CAV and HDV, are assumed to be different. In this regard, it is assumed that CAVs have a lower travel time value (Kolarova et al., 2018). Steck et al. (2018) provided empirical evidence that autonomous driving may lead to a reduction in the value of travel time for commuting trips. They found that driving autonomously in a privately-owned vehicle might reduce the value of travel time by 31% compared to driving manually and is perceived similarly to in-vehicle time on public transportation. However, travelers within each class are assumed to have the same value of time. Since the bi-level model contains integer variables and nonlinear constraints, it is classified as a non-polynomial (NP)-hard problem and is difficult to solve. Hence, the cutting-plane scheme is adopted to solve the problem.

The contributions of this chapter are threefold. First, this chapter develops a method for CAV-dedicated lane management considering, unlike most past studies, the uncertainty in the potential CAV market size over several years. This study explores the interaction between the impacts of uncertainty in the potential CAV market size on the CAV-dedicated lane deployment design at different CAV market penetrations. Secondly, the study captures the fact that CAVs require a smaller lane width compared to HDVs, and therefore, for existing urban corridors that are sufficiently wide, the urban road agency can increase the number of road lanes within the overall roadway cross-section. Thirdly, the context of the study is the deployment of CAV-dedicated lanes to minimize environmental (vehicle emissions) costs.

The remaining sections are structured as follows: Sections 6.2 and 6.3 provide the preliminaries and methodology. Section 6.4 briefly discusses the solution algorithm, followed by numerical experiments that compare the performance of robust and deterministic designs of CAVLs in Section 6.5. Finally, Section 6.6 provides the study insights and concluding remarks. Table 6.1 summarizes the notations used in this chapter.

Table 6.1 List of notations (chapter 6)

Sets

O	Set of nodes
A	Set of links
T	Set of the periods
W	Set of O-D pairs
$\bar{A}$	Set of candidate links for CAV-dedicated lanes
$\bar{\bar{A}}$	Set of candidate links for lanes reduction
H	Set of CAV-dedicated link pair candidates
N	Set of vehicle types (CAV vs. HDV)
Q	Network-level CAV market size uncertainty set
K_w^t	O-D pair CAV market size uncertainty set between O-D pair $w \in W$ in period t

Parameter

ϕ_a	per-lane per-hour capacity of link a
$J_{\bar{a}}$	Maximum number of lane increase for links $\bar{a}$
α_n	Value of time of passengers riding vehicle of class n
χ_w^t	Number of trips of O-D pair w in period t
ξ_w^t	CAV additional cost of O-D pair w in period t
u_a	Per-lane width of link a (ft. or meters)
Δ	Node-link incidence matrix
τ_a^0	Free-flow travel time of link a
κ	Monetized factor of emissions ($/kg)
$\hat{q}_w^{t,k}$	Potential CAV market size of O-D pair w, in time period t, in uncertainty set k
Λ^t	Uncertainty budget at period t
ε	A sufficiently small number

Variables

$q_w^{n,t}$	Travel demand of class n of O-D pair w in period t
$c_w^{n,t}$	Equilibrium travel time of vehicle type n of O-D pair w in period t
μ_w^t	Benefits gained by CAV travelers of O-D pair w in period t due to CAV-dedicated lane deployment
$\bar{q}_w^t$	Potential CAV market size
g_w^t	Intrinsic growth factor of O-D pair w at period t
τ_a^t	Travel time of link a in period t
e_a^t	Vehicle emissions of HDV travelers using link a in period t
ς_a^t	Capacity of link a in period t
TEC	Total vehicle emissions cost
$p_w^{t,k}$	Binary variable that is equal to 1 if scenario k is realized for O-D pair w in period t

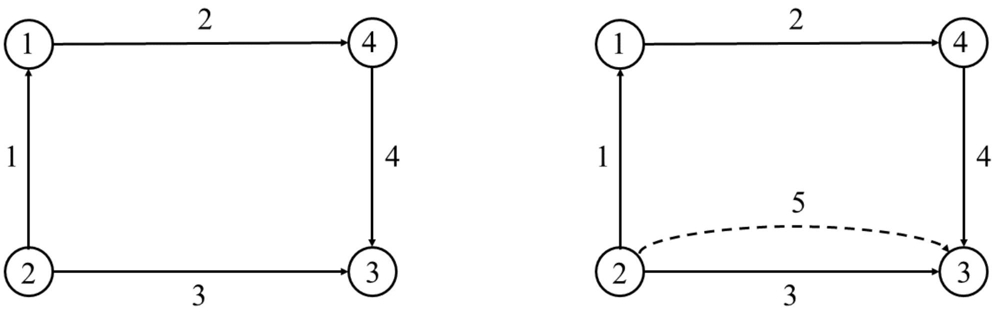
$\pi_{i,w}^{n,t}$	Equilibrium travel time of travelers of class n traveling between O-D pair w when reaching node i in period t
$y_{\bar{a}}^{t}$	Number of deployed CAV-dedicated lanes on link $\bar{a}$
$y_{\bar{\bar{a}}}^{t}$	Number of converted lanes on link $\bar{a}$
$x_{a,w}^{n,t}$	Traffic flow of vehicle type n at link a , between O-D pair w in period t
v_{a}^{t}	Aggregate flow of all vehicle types and O-D pairs at link a in period t

6.2 Preliminaries

The road network can be represented by graph $G = (O, A)$ where O and A are the sets of nodes and directed links, respectively. The planning horizon, with a duration of several years, is divided into T periods where each period is denoted by $t \in \mathrm{T}$ and comprises a few years. The set of O-D pairs is denoted by W. The sets of candidate existing links for lane reduction and CAV-dedicated links are denoted by $\bar{\bar{A}}$ and $\bar{A}$, respectively.

Consistent with previous research on CAV-dedicated lane deployment (Chen et al., 2016; Liu & Song, 2019), the set of CAV-dedicated link pair candidates is indexed by $H = [\bar{\bar{a}}, \bar{a}]$ where $\bar{\bar{a}} \in \bar{\bar{A}}$ and $\bar{a} \in \bar{A}$. This pair is constructed upon removing the first lane from link a. Then, during the planning horizon, lanes can be removed from $\bar{\bar{a}}$ and allocated to $\bar{a}$. For example, consider the four-node network in Figure 6.1(a) where link numbers are shown on node connectors. If link 3 is a candidate for CAV-dedicated lane deployment, then the network is transformed into Figure 6.1(b) where $A = \{1,2,3,4\}$, $\bar{A} = \{5\}$, $\bar{\bar{A}} = \{3\}$ and $H = \{[3,5]\}$. This transformation is due to the different capacities of CAV and GP lanes.

After this transformation, link 3 (referred to as general purpose (GP) link) only consists of GP lanes and remains a candidate link for CAV-dedicated lanes. Link 5 is a link with only CAV-dedicated lanes (referred to as "CAV-dedicated link"). Let u_a and y_a^t denote the width and number of converted (or reduced) lanes on link $\bar{a} \in \bar{A}$ (or link $\bar{\bar{a}} \in \bar{\bar{A}}$). Further, ϕ_a denotes the per-lane per-hour capacity of link a. Let $J_{\bar{a}}$ and $J_{\bar{\bar{a}}}$ denote the maximum increased and reduced number of lanes for links $\bar{a}$ and $\bar{\bar{a}}$, respectively.



(a)Original network

(b) Transformed network with CAV-dedicated link 5

Figure 6.1 A four-node network for illustration purposes

The mixed-traffic scenario consists of CAVs and HDVs, where N denotes the set of vehicle types. Let classes 1 and 2 denote HDVs and CAVs, respectively. Let $q_w^{n,t}$ denote the travel demand of class $n \in N$ of O-D pair $w \in W$ in period $t \in T$. The equilibrium travel time of vehicle type n of O-D pair w in period t is denoted by $c_w^{n,t}$. Let μ_w^t denote the benefits gained by CAV travelers of O-D pair w in period t due to CAV-dedicated lane deployment. A demand diffusion model is used in this study to capture the CAV travel demand. The diffusion model has been used in the context of transportation to obtain the travel demand for hydrogen-fueled vehicles (Park et al., 2011) and CAVs (Lavasani, Jin & Du, 2016). Chen et al. (2016) captured the impact of CAV travel cost reduction due to lane deployment policy on CAV travel demand using the following diffusion model:

$$q_w^{2,t} = q_w^{2,t-1} \cdot (1 + g(\mu_w^t) \cdot \left(1 - \frac{q_w^{2,t-1}}{\bar{q}_w^t}\right)) \qquad \forall w \in W, \forall t > 1 \qquad (6.1)$$

$$g(\mu_w^t) = \varphi \cdot e^{\iota \cdot (\mu_w^t - \bar{\mu}_w^t)} \qquad \forall w \in W, \forall t \in T \qquad (6.2)$$

$$\mu_w^t = \chi_w^t \cdot \left[\alpha_1 \cdot c_w^{1,t} - \alpha_2 \cdot c_w^{2,t}\right] - \xi_w^t \qquad \forall w \in W, \forall t \in T \qquad (6.3)$$

Equations (6.1) state that the CAV travel demand of each O-D pair in each period ($q_w^{2,t}$) depends on the demand on the previous period ($q_w^{2,t-1}$), the potential CAV market size ($\bar{q}_w^t$) and the gained benefits of that O-D pair (μ_w^t). Equations (6.2) denote the intrinsic growth coefficient of O-D pair $w \in W$ where φ and ι are positive constants and $\bar{\mu}_w^t$ denotes the O-D specific benefit threshold. Equations (6.3) calculate the benefits gained by O-D pair w in period t where α_n, χ_w^t and ξ_w^t are the value of time of class n, the number of trips, and CAV additional cost of O-D pair w in period t respectively. The additional cost can be due to the higher purchase price or operational costs.

It is assumed that these are essentially commuter trips that need to be repeated frequently therefore affecting the attractiveness of adopting a specific vehicle type (CAV vs HDV) .
Let $x_{a,w}^{n,t}$ denote the flow of link $a \in A$ between O-D pair w using vehicle type n in period t where $\boldsymbol{x}_w^{n,t}$ represents the vector of link flows for all links. Let v_a^t denote the aggregate flow of link a in period t while $\boldsymbol{v}$ represents the vector of aggregate flows. For a given travel demand vector $\boldsymbol{q}$ across different O-D pairs, vehicle types and time periods**,** $V(\boldsymbol{q})$ shows the set of feasible link flows, as follows:

$$V(\boldsymbol{q}) = \left\{\boldsymbol{v} \middle| \boldsymbol{v} = \textstyle\sum_{(w,n)} \boldsymbol{x}_w^{n,t}, \Delta \boldsymbol{x}_w^{n,t} = \boldsymbol{E}_w^n q_w^{n,t}, \boldsymbol{x}_w^{n,t} \geq 0, \forall w \in W, \forall n \in N\right\} \qquad (6.4)$$

where $\boldsymbol{E}_w^n$ is an input-output vector of length $|O|$ (representing origin and destination for O-D pair $w \in W$) and Δ is the node-link incidence matrix associated with the given network. There exist two non-zero components in vector $\boldsymbol{E}_w^n$, (i) 1 for the origin node of O-D pair w and (ii) –1 for the destination node of O-D pair w. In the node-link incidence matrix Δ, there exist two non-zero components, (i) 1 for the starting node, and (ii) -1 for the ending node. Let τ_a^t denote the travel time of link a in period t which is a monotonically-increasing function of link flow v_a^t.

In this study, the link flow is assumed to follow the well-known Bureau of Public Roads (BPR) function:

$$\tau_a^t(\nu_a^t, c_a^t) = \tau_a^0 \cdot (1 + 0.15 \left(\frac{\nu_a^t}{\varsigma_a^t}\right)^4) \qquad \forall a \in A \qquad (6.5)$$

where τ_a^0 and ς_a^t denote the free-flow travel time and capacity of link a. The vehicle emissions function of HDV travelers using link a in period t is denoted by e_a^t, that is assumed to be nonnegative and monotonically-increasing as a function of ν_a^t. Let κ denote the monetized unit of vehicle emissions. In this study, for computational simplicity, HDVs are assumed to be internal combustion engine vehicles (ICEVs), and they are the only source of local emissions in the network. The proposed bi-level model can be extended to relax this assumption by dividing travelers into three groups: (i) HDVs, (ii) electric HDVs, and (iii) CAVs. The total vehicle emissions cost TEC can be expressed as follows:

$$TEC = \sum_t \sum_a \kappa e_a^t(\nu_a^t) x_{a,w}^{1,t} \qquad \forall a \in A, \forall t \in T \qquad (6.6)$$

6.3 Methodology

This section presents the bi-level framework for the robust optimization of CAV-dedicated lane deployment, considering the possible reduction of the lane width and a subsequent increase in the number of total lanes on a link. The bi-level framework is consistent with the Stackelberg structure and consists of an upper-level and a lower-level model. The upper-level model captures urban road agency's goal, which is assumed to minimize the maximum emissions cost under all possible CAV market sizes over the long-term planning horizon. The decision for the urban road agency is to identify the number of existing GPL lanes to convert to CAVLs. The lower-level model captures the route and vehicle type choices of travelers. Figure 6.2 presents the structure of the bi-level framework. The figure also identifies the novel research elements in the context of existing research.

It is difficult to forecast reliably the potential CAV market size due to current lack of CAV experience among travelers; therefore, this variable has significant uncertainty. The potential CAV market size uncertainty for vehicle type n between O-D pair w in period t is represented by K_w^t where $k = 1$ denotes the average (nominal) potential CAV market size forecast in each period. Let $p_w^{t,k}$ denote the binary variable that is equal to 1 if scenario k is realized for O-D pair w in period t and this is the worst-case scenario. There exists only one potential CAV market size realized for each vehicle type n between O-D pair w in period t, $\sum_{k \in K_w^t} p_w^{t,k} = 1$.

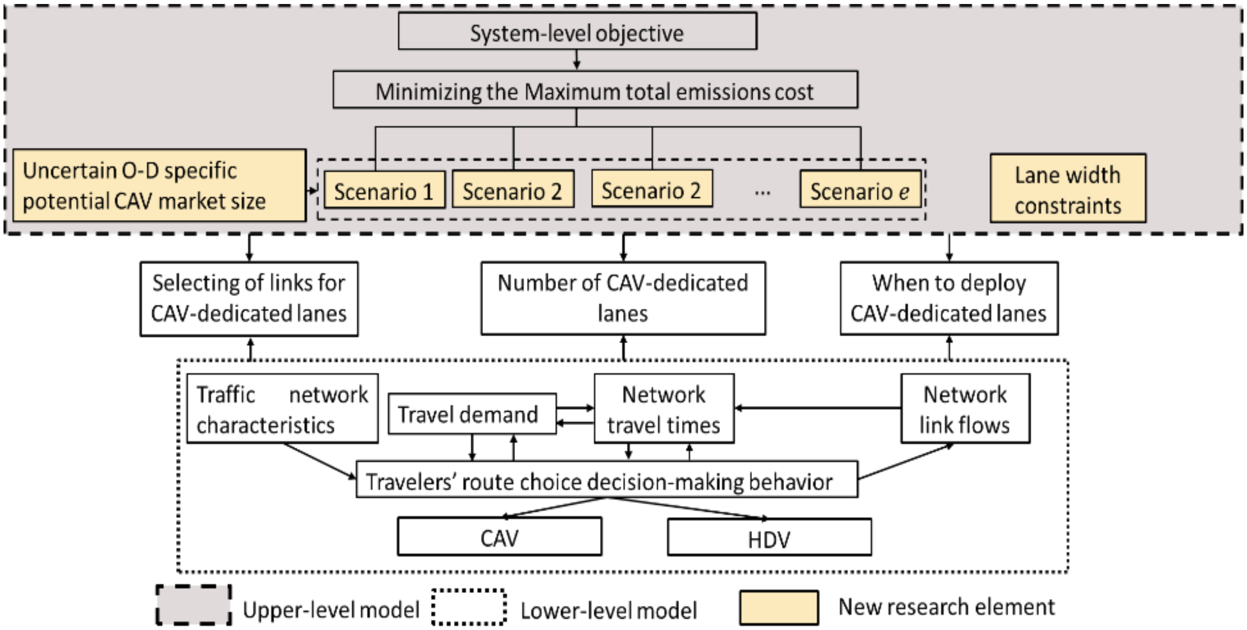


Figure 6.2 Bi-level framework for CAV-dedicated lane deployment

Let Λ^t denote the uncertainty budget in period t where it implies that $\sum_w \sum_{k=2}^{|K|} p_w^{t,k} \le \Lambda^t$. A highly uncertain budget increases the number of possible potential CAV market size scenarios which leads to a higher computational burden but higher reliability of the developed design. It also reflects the risk-taking attitude of the urban road agency where the high-uncertainty budget implies the risk-aversion attitude of the urban road agency regarding future travel demand. Given these notations, the network-level potential CAV market size uncertainty set Q can be formulated as follows:

$$Q = \{\bar{\boldsymbol{q}} | \sum_{k \in K_w^{m,t}} \hat{q}_w^{t,k} p_w^{t,k} = \bar{q}_w^t, \sum_{k \in K_w^{m,t}} p_w^{t,k} = 1, \sum_{(w)} \sum_{k=2}^{|K|} p_w^{t,k} \le \Lambda^t, p_w^{t,k} \in \{0,1\}\} \tag{6.7}$$

where $\bar{\boldsymbol{q}} = (\hat{q}_w^{t,k}, \forall w \in W, k \in K_w^{m,t}, \forall t \in T)$. Let $\pi_{i,w}^{n,t}$ denote the equilibrium travel time of travelers of class n between O-D pair w at node i in period t. This bi-level program is formulated as a mathematical program with equilibrium conditions (MPEC1) as follows:

$$\min_{y} \max_{x,p} \sum_{t} \sum_{a} \kappa e_a^t (v_a^t) x_{a,w}^{1,t} \tag{6.8}$$

$$\varsigma_{\bar{a}}^t = \varsigma_{\bar{a}}^{t-1} + \phi_{\bar{a}}\, y_{\bar{a}}^t \qquad \forall \bar{a} \in \bar{A}, \forall t > 1 \tag{6.9}$$

$$\varsigma_{\bar{\bar{a}}}^{t} = \varsigma_{\bar{\bar{a}}}^{t-1} - \phi_{\bar{\bar{a}}}\, y_{\bar{\bar{a}}}^{t} \qquad \forall \bar{\bar{a}} \in \bar{\bar{A}}, \forall t > 1 \qquad (6.10)$$

$$u_{\bar{a}} \cdot \left(\sum_{i=1}^{t} y_{\bar{a}}^{i} \right) \leq u_{\bar{\bar{a}}} \cdot \left(\sum_{i=1}^{t} y_{\bar{\bar{a}}}^{i} \right) \qquad \forall t \in T, \forall [\bar{\bar{a}}, \bar{a}] \in H \qquad (6.11)$$

$$\varsigma_{\bar{\bar{a}}}^{t} \geq \underline{\varsigma}_{\bar{\bar{a}}} \qquad \forall \bar{\bar{a}} \in \bar{\bar{A}}, \forall t \in T \qquad (6.12)$$

$$y_{\bar{\bar{a}}}^{t} \in \{0, \dots., J_{\bar{\bar{a}}}^{t}\} \qquad \forall \bar{\bar{a}} \in \bar{\bar{A}}, \forall t \in T \qquad (6.13)$$

$$y_{\bar{a}}^{t} \in \{0, \dots., J_{\bar{a}}^{t}\} \qquad \forall \bar{a} \in \bar{A} \qquad (6.14)$$

$$0 \leq x_{a,w}^{n,t} \perp \left(\tau_{a}^{t}(v_{a}^{t}, \varsigma_{a}^{t}) + \pi_{i,w}^{n,t} - \pi_{j,w}^{n,t} \right) \geq 0 \qquad \forall n \in N, \forall w \in W, \forall t \in T, \forall (i,j) = a \in A \backslash \bar{A} \qquad (6.15)$$

$$0 \leq x_{\bar{a},w}^{n,t} \perp \left(\tau_{\bar{a}}^{t}(v_{\bar{a}}^{t}, \varsigma_{\bar{a}}^{t}) + \pi_{i,w}^{n,t} - \pi_{j,w}^{n,t} - \theta_{\bar{a}}^{n,t} \right) \geq 0 \qquad \forall n \in N, \forall w \in W, \forall t, \forall (i,j) = \bar{a} \in \bar{A} \qquad (6.16)$$

$$x_{\bar{a},w}^{1,t} = 0 \qquad \forall w \in W, \forall t, \forall \bar{a} \in \bar{A} \qquad (6.17)$$

$$x_{\bar{a},w}^{2,t} \leq M \cdot \sum_{i=1}^{t} y_{\bar{a}}^{i} \qquad \forall w \in W, \forall t \in T, \forall \bar{a} \in \bar{A} \qquad (6.18)$$

$$x_{\bar{a},w}^{n,t} \cdot \theta_{\bar{a}}^{n,t} = 0 \qquad \forall w \in W, \forall n \in N, \forall t \in T, \forall \bar{a} \in \bar{A} \qquad (6.19)$$

$$\theta_{\bar{a}}^{n,t} \geq 0 \qquad \forall n \in N, \forall t \in T, \forall \bar{a} \in \bar{A} \qquad (6.20)$$

$$v \in V(q) \qquad (6.21)$$

$$\boldsymbol{q} \in Q \qquad (6.22)$$

(6.1)-(6.4), (6.7)

where θ captures the extra costs of HDV travelers due to the lack of ability to use CAVLs. Since CAV travelers can use CAVLs, this value can be only positive for HDV travelers. The upper-level model consists of equations (6.8)-(6.14). It is assumed that the goal of urban road agency is to minimize the worst-case total emissions cost that could occur under all possible CAV market size scenarios. Constraints (6.9) state that the capacity of CAV-dedicated link $\bar{a}$ in period t is equal to the sum of capacity of that link in period $t-1$ and additional capacity due to GPL-to-CAVL conversion(s) in period t. Constraints (6.10) state that the capacity of GP link $\bar{\bar{a}}$ in period t can be determined by the deduction of capacity of converted lanes in period t from the capacity of that link in period $t-1$. Constraints (6.11) ensure that, considering the lane reallocation strategy, the total width of CAVLs and GPLs for each link does not exceed the available link width. Constraints (6.12) ensure that there is a minimum road capacity for HDVs after lane reduction for each link in each period t. Constraints (6.13)-(6.14) describe the integer variables for the number of lanes increase and reduction on links $\bar{a}$ and $\bar{\bar{a}}$.

The lower-level model comprises equations (6.15)-(6.22), where the perpendicular operator $0 \leq A \perp B \geq 0$ means that $A \cdot B = 0$, $A \geq 0$, and $B \geq 0$. Equilibrium conditions (6.15)-(6.16) describe the route choice of travelers. Travelers alter their routes to reduce travel times unless they are unable to reduce them further by unilaterally altering the routes. Constraints (6.15) state the equilibrium conditions for the links, excluding those that are candidates for CAVLs. Constraints (6.16) state the equilibrium conditions for candidate links for CAVLs. It means that travelers of class n between O-D pair w use link a if this link is part of the shortest path between O-D pair w. Constraints (6.17) ensure that HDVs do not use CAV-dedicated links. Constraints (6.18) ensure that CAVs use CAV-dedicated links if some GPLs are converted to CAV-dedicated lanes. Constraints (6.19)-(6.20) impose additional costs θ on vehicles traversing link a which is not feasible due to a lack of permission to use the CAV-dedicated links for HDV travelers. Constraints (6.21) denote travel demand conservation constraints. Constraints (6.22) describe the uncertainty set for potential CAV market size. As a result, MPEC1 ((6.1)-(6.3), (6.7)-(6.22)) is a nonlinear mathematical program with integer variables and can be classified as an NP-hard problem (Bazaraa et al., 2013). Given the difficulty of solving this class of mathematical programs, the active-set algorithm (Lou et al, 2009) is adopted and used to solve the problem as explained in the next section.

6.4 Solution algorithm

There exist several techniques to solve MPEC1 ((6.1)-(6.4), (6.7)-(6.22)), such as nonsmooth penalization (Scholtes & Stöhr, 1999), and directly relaxing complementarity constraints and solving MPCC as nonlinear programs (Raghunathan & Biegler, 2012). The cutting-plane scheme is used in this research. This scheme, first proposed by Lou et al. (2009) to solve a robust discrete network design problem, solves a relaxed MPEC1 based on a definite set of potential CAV market sizes (set Q). To solve MPEC1 by implementing the cutting-plane scheme, two sub-problems must be defined: (i) an MPEC2, which is a relaxed MPEC1 and determines an optimal CAVL deployment plan based on a set of generated cuts, and (ii) a worst-case possible scenario (WPS) which generates new cuts that are worst-case potential CAV market size sets leading to higher levels of total emissions cost, on the basis of CAVL deployment.

The two subproblems are solved iteratively to find the optimal solution to MPEC1. First, MPEC1 must be reformulated as a mathematical program with equilibrium constraints (MPEC2) as follows:

$$\min_{z,v,p} \omega \tag{6.23}$$

$$\sum_{t}\sum_{a} \kappa e_a^t(v_a^t) v_a^t \leq \omega \qquad \forall q \in Q \tag{6.24}$$

$$v_a^{t,q} \in V(q) \qquad \forall q \in Q \tag{6.25}$$

$$\tau_a^{t,q}\left(\nu_a^{t,q}, c_a^t\right) = \tau_a^0 \cdot (1 + 0.15\left(\frac{\nu_a^{t,q}}{\varsigma_{\bar{a}}^t}\right)^4) \qquad \forall a \in A, \forall q \in Q \tag{6.26}$$

$$0 \le x_{a,w}^{n,t,q} \perp \left(\tau_a^{t,q}\left(\nu_a^{t,q}, \varsigma_{\bar{a}}^t\right) + \pi_{i,w}^{n,t,q} - \pi_{j,w}^{n,t,q}\right) \ge 0 \qquad \forall n \in N, \forall w \in W, \forall t \in T, \forall (i,j) = a \in A \backslash \bar{A}, \forall q \in Q \tag{6.27}$$

$$0 \le x_{\bar{a},w}^{n,t,q} \perp \left(\tau_{\bar{a}}^{t,q}\left(\nu_{\bar{a}}^{t,q}, \varsigma_{\bar{a}}^t\right) + \pi_{i,w}^{n,t,q} - \pi_{j,w}^{n,t,q} - \theta_{\bar{a}}^{n,t,q}\right) \ge 0 \qquad \forall n \in N, \forall w \in W, \forall t \in T, \forall (i,j) = \bar{a} \in \bar{A}, \forall q \in Q \tag{6.28}$$

$$x_{\bar{a},w}^{1,t,q} = 0 \qquad \forall w \in W, \forall t \in T, \forall \bar{a} \in \bar{A}, \forall q \in Q \tag{6.29}$$

$$x_{\bar{a},w}^{2,t,q} \le M \cdot \sum_{i=1}^{t} \sum_{\varrho=1}^{\Phi_a^t} zy_{\bar{a},\varrho}^{i} \qquad \forall w \in W, \forall t \in T, \forall \bar{a} \in \bar{A}, \forall q \in Q \tag{6.30}$$

$$x_{\bar{a},w}^{n,t,q} \cdot \theta_{\bar{a}}^{n,t,q} = 0 \qquad \forall n \in N, \forall w \in W, \forall t \in T, \forall \bar{a} \in \bar{A}, \forall q \in Q \tag{6.31}$$

$$\theta_{\bar{a}}^{n,t,q} \ge 0 \qquad \forall n \in N, \forall t \in T, \forall \bar{a} \in \bar{A}, \forall q \in Q \tag{6.32}$$

$$\varsigma_{\bar{a}}^t = \varsigma_{\bar{a}}^{t-1} + \phi_{\bar{a}} \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times z_{a,\varrho}^t \qquad \forall \bar{a} \in \bar{A}, \forall t > 1 \tag{6.33}$$

$$\varsigma_{\bar{\bar{a}}}^t = \varsigma_{\bar{\bar{a}}}^{t-1} - \phi_{\bar{\bar{a}}} \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times z_{a,\varrho}^t \qquad \forall \bar{\bar{a}} \in \bar{\bar{A}}, \forall t > 1 \tag{6.34}$$

$$u_{\bar{a}} \cdot \left(\sum_{i=1}^{t} \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times z_{a,\varrho}^t\right) \le u_{\bar{\bar{a}}} \cdot \left(\sum_{i=1}^{t} \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times z_{a,\varrho}^t\right) \qquad \forall t \in T, \forall [\bar{\bar{a}}, \bar{a}] \in H \tag{6.35}$$

$$x_{\bar{a},w}^{2,t} \le M \cdot \sum_{i=1}^{t} \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times z_{a,\varrho}^t \qquad \forall w \in W, \forall t \in T, \forall \bar{a} \in \bar{A} \tag{6.36}$$

(6.1)-(6.3), (6.6)

where the superscript $(\cdot)^q$ denotes the variables that are associated with a specific potential CAV market size scenario $q \in Q$. In MPEC2, the integer decision variables (y_a^t) is transformed to binary ones. As the decision variables have integer values, the expression $y_a^t = \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times z_{a,\varrho}^t$ is used, where $z_{a,\varrho}^t$ is binary and Φ_a^t is the largest integer that $J_a^t \le 2^{\Phi_a^t} - 1$. This transformation to binary variables enables us to solve the problem using active-set algorithm later in this section. All of the defined constraint to MPEC2 has similar concept to those of MPEC1. Next, the second subproblem, WPS, is presented as follows:

$$\max_{p} \sum_{t} \sum_{a} \kappa e_a^t\left(\nu_a^t, c_a^t\right) . \nu_a^t \tag{6.37}$$

$$\tau_a^t\left(\nu_a^t, \varsigma_{\bar{a}}^t\right) = \tau_a^0 \cdot (1 + 0.15\left(\frac{\nu_a^t}{\varsigma_{\bar{a}}^t}\right)^4) \qquad \forall a \in A \tag{6.38}$$

$$0 \le x_{a,w}^{n,t} \perp \left(\tau_a^t\left(\nu_a^t, \varsigma_{\bar{a}}^t\right) + \pi_{i,w}^{n,t} - \pi_{j,w}^{n,t}\right) \ge 0 \qquad \forall n \in N, \forall w \in W, \forall t \in T, \forall (i,j) = a \in A \backslash \bar{A} \tag{6.39}$$

$$0 \le x^{n,t}_{\bar{a},w} \perp \left(\tau^{t}_{\bar{a}}(\nu^{t}_{\bar{a}}, \varsigma^{t}_{\bar{a}}) + \pi^{n,t}_{i,w} - \pi^{n,t}_{j,w} - \theta^{n,t}_{\bar{a}}\right) \ge 0 \qquad \forall n \in N, \forall w \in W, \forall t \in T, \forall (i,j) = \bar{a} \in \bar{A} \tag{6.40}$$

$$x^{1,t}_{\bar{a},w} = 0 \qquad \forall w \in W, \forall t \in T, \forall \bar{a} \in \bar{A} \tag{6.41}$$

$$x^{2,t}_{\bar{a},w} \le M \cdot \sum_{i=1}^{t} \sum_{\varrho=1}^{\Phi^{t}_{a}} 2^{\varrho-1} \times \hat{z}^{t}_{a,\varrho} \qquad \forall w \in W, \forall t \in T, \forall \bar{a} \in \bar{A} \tag{6.42}$$

$$x^{n,t}_{\bar{a},w} \cdot \theta^{n,t}_{\bar{a}} = 0 \qquad \forall n \in N, \forall w \in W, \forall t \in T, \forall \bar{a} \in \bar{A} \tag{6.43}$$

$$\theta^{n,t}_{\bar{a}} \ge 0 \qquad \forall n \in N, \forall t \in T, \forall \bar{a} \in \bar{A} \tag{6.44}$$

(6.1)-(6.3)

All of the included constraints ((6.1)-(6.3),(6.38)-(6.44)) have similar concepts to the previous ones. The overall iterative solution algorithm of MPEC1 is shown in Algorithm 1. In this solution algorithm, WPS and MPEC2 are solved iteratively and provide each other's cut set and optimal CAVL deployment plan, respectively.

Algorithm 1 Overall solution procedure

```
1:  Initializing: set $\hat{z}^{t}_{a,\varrho} = 0$ and $Q = \{\ \}$
2:  Repeat
3:      Solve WPS based on $\hat{z}^{t}_{a,\varrho}$ and store the optimal solution in $\hat{p}^{t,k}_{w}$
4:      Update $Q$: $Q = \hat{p}^{t,k}_{w} \cup Q$
5:      Solve MPEC2 based on $Q$ and store the optimal solution in $\hat{z}^{t}_{a,\varrho}$
6:  Until termination condition is met
7:  Return $\hat{z}^{t}_{a,\varrho}$
```

In Step 1, the initial CAVL deployment plan ($\hat{z}^{t}_{a,\varrho}$) and set Q are defined. In this regard, no CAVLs are considered for the initial plan ($\hat{z}^{t}_{a,\varrho} = 0$). As no cuts are generated in the beginning, Q is an empty set ($Q = \{\ \}$). In the second step, an iterative process which includes Step 3 to Step 6 begins. WPS is solved based on the initial CAVL plan ($\hat{z}^{t}_{a,\varrho}$) (Step 3). Then, the determined worst-case potential CAV market size ($\hat{p}^{t,k}_{w}$) is added to set Q, as a new cut (Step 4). In the next step, MPEC2 is solved to determine an optimal CAVL plan based on the updated set Q (Step 5). Then, the termination condition is checked (Step 6). If the termination condition is not met, Steps 3 to 6 are repeated. If the termination condition is met, the solution procedure is terminated, and the optimal CAVL deployment plan is returned (Step 7). As the termination condition, this iterative procedure continues until the WSP does not result in a worst-case total emissions cost or the algorithm reaches the determined maximum number of iterations (cuts).

MPEC2 and WPS can be classified as a mathematical program with complementarity constraints (MPCC). There exist a number of algorithms to solve MPCC2 and WPS, such as non-smooth penalization (Scholtes & Stöhr, 1999) and smooth regularization (Birbil, Fang, & Han, 2004). In this study, the Active-set algorithm is adopted, which is shown by Zhang et al. (2009) to be able to determine a strong stationary solution. It has been applied in several studies to address network design problems (Chen et al., 2016; Liu, Du, Wong, Chang, & Jiang, 2020; Miralinaghi & Peeta, 2019; Song, He, & Zhang, 2017).

Algorithm 2 describes the applied Active-set solution procedure to solve the MPEC2. To solve MPEC2, Algorithm 2 starts with an initial feasible solution ($\hat{z}_{a,\varrho}^{t}$) which can be described with sets $\Omega_0 = \{(a,\varrho,t)|\hat{z}_{a,\varrho}^{t} = 0\}$ and $\Omega_1 = \{(a,\varrho,t)|\hat{z}_{a,\varrho}^{t} = 1\}$, where $\Omega_0 \cup \Omega_1 = \{(a,\varrho,t)|\forall a \in A, 0 \leq \varrho \leq \Phi_{a}^{t}, \forall t \in T\}$ and $\Omega_0 \cap \Omega_0 = \emptyset$ (Step 1). In the next steps, the current solution is adjusted using its Lagrangian multipliers. In Step 2, the Lagrangian multipliers, $\varkappa_{a,\varrho}^{t}$ and $\ell_{a,\varrho}^{t}$, associated with decision variables in Ω_0 and Ω_1, respectively, are determined. They approximate the improvement in the objective function of MPEC2 by changing the components of the current solution. To find a new feasible solution, Adjustment problem-MEPC2 (AP-M) is solved in the next step (Step 3). AP-M results in a candidate solution in a way that it is anticipated to provide the most improvement to the current total emissions cost.

To ensure that the candidate solution improves the current total emissions cost, it is evaluated in next steps. Next, if further improvement is anticipated (Step 4), the current solution is updated based on the solution of AP-M (Step 5). The new feasible solution is then evaluated based the total emissions cost (Step 6). If the new feasible solution results in an improvement (that is, a decrease) in the total emissions cost relative to the incumbent solution, considered as the new best solution, then the sets Ω_0 and Ω_1 are updated, accordingly (Step 7 (a)). If the feasible solution does not decrease the total emissions cost, then the incumbent feasible solution remains as is, and $\theta_{\text{AP}-M}$ is updated (Step 7 (b)). The algorithm goes to Step 3 again to solve AP-M to find a new adjusted solution, based on $\theta_{\text{AP}-M}$ updated. Updating $\theta_{\text{AP}-M}$ prevents obtaining the feasible solution that is just evaluated and does not result in improvement. Steps 3-7 are repeated until there is no further improvement in the incumbent feasible solution. If there is no further improvement in solution (Step 5), the incumbent feasible solution is returned as the optimal solution (Step 8).

Algorithm 2 Active-set algorithm to solve MPEC2

```
1.      Initializing: set $\hat{z}_{a,\varrho}^{t} = 0$, $\Omega_0 = \{(a,\varrho,t)|\hat{z}_{a,\varrho}^{t} = 0\}$, $\Omega_1 = \{(a,\varrho,t)|\hat{z}_{a,\varrho}^{t} = 1\}$, $stop = 0$, $and\ \theta_{K-M} = -\infty$
2.      Calculate the $\varkappa_{a,\varrho}^{t}$ and $\ell_{a,\varrho}^{t}$, Lagrangian multipliers corresponding to $\hat{z}_{a,\varrho}^{t}$ in $\Omega_0$ and $\Omega_1$
3.      Solve the AP-M
4.      If $\theta_{K-M} < 0$:
5.          Update $\hat{z}_{a,\varrho}^{t}$; if $g_{a,\varrho}^{t} = 1$ switch $\hat{z}_{a,\varrho}^{t}$ to 0. Else, if $h_{a,\varrho}^{t} = 1$, switch $\hat{z}_{a,\varrho}^{t}$ to 1.
            Otherwise; $\hat{z}_{a,\varrho}^{t}$ remain unchanged.
6.          Evaluate $\hat{z}_{a,\varrho}^{t}$
            If the total emissions cost is decreased:
7. (a)          Update $\Omega_0 = \{(a,\varrho,t)|\hat{z}_{a,\varrho}^{t} = 0\}$, $\Omega_1 = \{(a,\varrho,t)|\hat{z}_{a,\varrho}^{t} = 1\}$, $\theta_{K-M} = -\infty$
            Else:
                $\theta_{K-M} = \varepsilon + \sum_{(a,\varrho,t)\in\Omega_0} g_{a,\varrho}^{t}\varkappa_{a,\varrho}^{t} - \sum_{(a,\varrho,t)\in\Omega_1} h_{a,\varrho}^{t}\ell_{a,\varrho}^{t}$ and recover $\hat{z}_{a,\varrho}^{t}$ .
7. (b)          Then, go to 4.
        Else:
8.          Return $\hat{z}_{a,\varrho}^{t}$
```

To determine a new potential solution to MEPC2, or in other word, to adjust the current solution of MEPC2, according to the Lagrangian multipliers, it is required to solve the AP-M ((6.45)-(6.49)) in Step 3.

$$\min_{h,g} \sum_{(a,k,t)\in\Omega_0} g_{a,\varrho}^{t} \varkappa_{a,\varrho}^{t} - \sum_{(a,k,t)\in\Omega_1} h_{a,\varrho}^{t} \ell_{a,\varrho}^{t} \tag{6.45}$$

$$\begin{aligned} u_{\bar{a}} \cdot \left(\sum_{i=1}^{t} \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times z_{a,\varrho}^{t} \sum_{i=1}^{t} \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times g_{a,\varrho}^{t} - \sum_{i=1}^{t} \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times h_{a,\varrho}^{t} \right) \\ \leq u_{\bar{\bar{a}}} \cdot \left(\sum_{i=1}^{t} \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times z_{a,\varrho}^{t} + \sum_{i=1}^{t} \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times g_{a,\varrho}^{t} - \sum_{i=1}^{t} \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times h_{a,\varrho}^{t} \right) \end{aligned} \tag{6.46}$$

$$\begin{aligned} \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times z_{a,\varrho}^{t-1} + \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times g_{a,\varrho}^{t-1} - \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times h_{a,\varrho}^{t-1} \\ \leq \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times z_{a,\varrho}^{t} + \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times g_{a,\varrho}^{t} - \sum_{\varrho=1}^{\Phi_a^t} 2^{\varrho-1} \times h_{a,\varrho}^{t}, \end{aligned} \qquad \forall t \in T \tag{6.47}$$

$$\sum_{(a,k,t)\in\Omega_0} g_{a,\varrho}^{t} \varkappa_{a,\varrho}^{t} - \sum_{(a,k,t)\in\Omega_1} h_{a,\varrho}^{t} \ell_{a,\varrho}^{t} > \theta_{K-M} \tag{6.48}$$

$$g_{a,\varrho}^{t}, h_{a,\varrho}^{t} \in \{0,1\} \tag{6.49}$$

where equation (6.46) ensures that according to the new solution, the total width of CAVLs does not exceed the available corridor space. Equation (6.47) satisfies the deployment of CAVLs over the planning horizon. Equation (6.48) prevents the acquisition of solutions that are already found to not improve the current optimal solution. The decision variables are binary (Equation (6.49)).

A similar procedure is applied to solve the WSP. Algorithm 3 represents the pseudo-code of the applied Active-set algorithm to solve WSP. Prior to initiating the solution algorithms, sets Θ_0 and Θ_1 are defined such that $\Theta_0 = \left\{(w,k,t)|\hat{p}_w^{t,k} = 0\right\}$ and $\Theta_1 = \left\{(w,k,t)|\hat{p}_w^{t,k} = 1\right\}$ where $\Theta_0 \cup \Theta_1 = \{(w,k,t)|\forall w \in W, \forall k \in K, \forall t \in T\}$ and $\Theta_0 \cap \Theta_1 = \emptyset$. By solving WSP, the potential CAV market sizes that increase the total emissions cost are identified (in contrast to MEPC2 which attempts to decrease the total emissions cost). Algorithm 3 starts with initializing $\hat{p}_w^{t,k} = 0$, $\Theta_0 = \left\{(w,k,t)|\hat{p}_w^{t,k} = 0\right\}$, $\Theta_1 = \left\{(w,k,t)|\hat{p}_w^{t,k} = 1\right\}$, $stop = 0$, and $\theta_{K-W} = \infty$, in the first step. In Step 2, Lagrangian multipliers corresponding to $\hat{p}_w^{t,k}$ in sets Θ_0 and Θ_1, $\hat{\varkappa}_w^{t,k}$ and $\hat{\ell}_w^{t,k}$, are determined. Given Lagrangian multipliers, Adjustment problem-WPS (AP-W) is solved to adjust the current solution (Step 3). Then, if it is expected that the solution algorithm can provide an improved solution (Step 4), the current solution is updated according to the solution of AP-W (Step 5). Then the new solution is evaluated in Step 6. If the adjusted (updated) solution yields higher total network emissions cost, then an improved solution has been found, and the sets Θ_0 and Θ_1 are updated accordingly (Step 7 (a)). Otherwise, $\hat{p}_w^{t,k}$ is recovered to the previous solution and $\theta_{\mathrm{AP-W}}$ is updated (Step 7 (b)). Updating $\theta_{\mathrm{AP}-W}$ ensures preventing repetitive solutions that are evaluated. After updating $\theta_{\mathrm{AP}-W}$, Algorithm 3 goes to Step 3 to find another feasible solution. Whenever there is no possible improvement in the incumbent solution (Step 4), the algorithm terminates and returns the incumbent solution as the optimal solution, $\hat{p}_w^{t,k}$ (Step 9).

Algorithm 3 Active-set algorithm to solve WPS

```
1.      Initializing: set $\hat{p}_w^{t,k} = 0$, $\Theta_0 = \{(w,k,t)|\hat{p}_w^{t,k} = 0\}, \Theta_1 = \{(w,k,t)|\hat{p}_w^{t,k} = 1\}$,
        $stop = 0, and\ \theta_{K-W} = \infty$
2.      Calculate the $\hat{\varkappa}_w^{t,k}$ and $\hat{\ell}_w^{t,k}$, Lagrangian multipliers corresponding to $\hat{p}_w^{t,k}$ in $\Theta_0$ and $\Theta_1$
3.      Solve the AP-W
4.      If $\theta_{K-W} < 0$:
5.          Update $\hat{p}_w^{t,k}$; if $\hat{g}_{a,\varrho}^t = 1$ switch $\hat{p}_w^{t,k}$ to 0. Else, if $\hat{h}_{a,\varrho}^t = 1$, switch $\hat{p}_w^{t,k}$ to 1.
            Otherwise; $\hat{p}_w^{t,k}$ remain unchanged.
6.          Evaluate $\hat{p}_w^{t,k}$
            If the total emissions cost. is increased:
7 (a).          Update $\Theta_0 = \{(w,k,t)|\hat{p}_w^{t,k} = 0\}$, $\Theta_1 = \{(w,k,t)|\hat{p}_w^{t,k} = 1\}, \theta_{K-W} = \infty$
7 (b).      Else:
                $\theta_{K-W} = \varepsilon + \sum_{(w,k,t)\in\Theta_0} \hat{g}_w^{t,k}\hat{\varkappa}_w^{t,k} - \sum_{(w,k,t)\in\Theta_1} \hat{h}_w^{t,k}\hat{\ell}_w^{t,k}$, recover $\hat{p}_w^{t,k}$ go to 4.
8.      Else:
9.          Return $\hat{p}_w^{t,k}$
```

AP-W ((6.50)-(6.54)) is solved to provide an improved solution to WSP, based on the Lagrangian multipliers.

$$\max_{\hat{h},\hat{g}} \sum_{(w,k,t)\in\Theta_0} \hat{g}_w^{t,k}\hat{\varkappa}_w^{t,k} - \sum_{(w,k,t)\in\Theta_1} \hat{h}_w^{t,k}\hat{\ell}_w^{t,k} \tag{6.50}$$

$$\sum_{(w,k)\in\Theta_0} \hat{g}_w^{t,k} - \sum_{(w,k)\in\Theta_1} \hat{h}_w^{t,k} + \sum_{(w)}\sum_{k=2}^{|K|} p_w^{t,k} \le \Lambda^t, \qquad \forall t \in T \tag{6.51}$$

$$\sum_{(k)\in\Theta_0} \hat{g}_w^{t,k} - \sum_{(k)\in\Theta_1} \hat{h}_w^{t,k} + \sum_{k=2}^{|K|} p_w^{t,k} \le 1, \qquad \forall t \in T, \forall w \in W \tag{6.52}$$

$$\sum_{(w,k,t)\in\Theta_0} \hat{g}_w^{t,k}\hat{\varkappa}_w^{t,k} - \sum_{(w,k,t)\in\Theta_1} \hat{h}_w^{t,k}\hat{\ell}_w^{t,k} < \theta_{K-W} \tag{6.53}$$

$$\hat{g}_w^{t,k}, \hat{h}_w^{t,k} \in \{0,1\} \tag{6.54}$$

Equation (6.51) satisfies the uncertainty budget in each period of time. Equation (6.52) ensures that at most one uncertain scenario is selected for each O-D pair. Equation (6.53) prevents the development of repetitive solutions. The decision variables are binary (equation (6.54)). As discussed by Lou et al. (2009), the uncertainty set contains a finite number of components, and therefore, the cutting-plane scheme terminates after a finite number of iterations. The result is a global optimum solution for MPEC1 if, in each iteration, the solutions are global optimum for MPEC2, and WPS. However, this is not possible since these two models are nonconvex and violate the Mangasarian-Fromovitz constraint qualification (MFCQ) at different points of feasible space. Note that a deterministic plan solves the MCEP2 considering set $Q = \{q|\hat{p}_w^{t,k} = 0\}$. Given set Q, applying Algorithm 2 results in a deterministic plan.

6.5 Numerical experiment

6.5.1 Case study characteristics

The proposed MPEC2 problem is applied to the road network shown in Figure 6.3. The network has 10 nodes, 22 links, and 90 O-D pairs. The planning horizon is assumed to be equal to 16 years which is divided into 4 four-year planning periods. During successive periods, travel demand grows at a constant rate of 5% (per planning period) across all O-D pairs. Moreover, the O-D travel demand (presented in Table 6.2) is used for the first period without considering demand growth. However, the O-D travel demands in the following periods are determined after multiplying the corresponding growth factors by those of the first planning period. Also, each O-D pair's travel demand is assumed to be constant within each planning period. The link characteristics, including free-flow travel time and link capacity, are shown in Table 6.3.

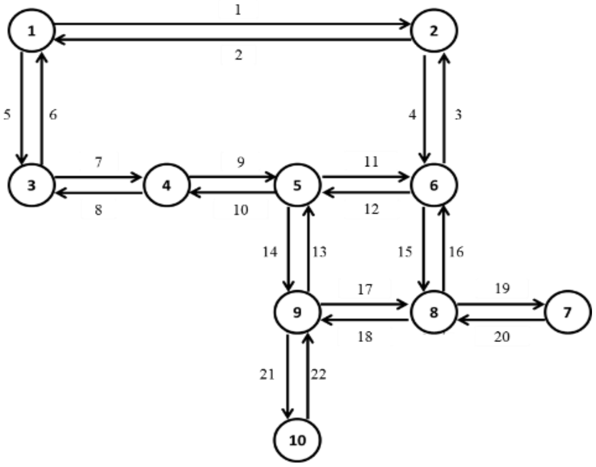


Figure 6.3 The study network

For three reasons, carbon monoxide (CO) is used as a proxy for vehicle emissions in this study. First, of the different vehicle emission types, CO is a major pollutant (Xu, Chen, & Cheng, 2015). Second, the CO emissions function is similar to (and therefore could be served as a proxy for) other pollutants. Let d_a and τ_a^t denote the length (in km) and travel time (in min) of link a in period t, respectively. The CO emissions function (in g/veh) of ICEVs (HDVs) using link a in period t is formulated by Wallace et al. (1998) and used by several studies (e.g. Ma et al., 2017, 2015; Xu et al., 2015; Yang et al., 2017, 2014) as follows:

$$e_a^t(v_a^t) = 0.2038\tau_a^t(v_a^t, c_a^t) \cdot exp\,\left(\frac{0.7962d_a}{\tau_a^t(v_a^t, c_a^t)}\right) \qquad \forall a, \forall t \qquad (6.55)$$

As stated earlier, as CAVLs are used by CAVs exclusively, their capacities are higher compared to GPLs. In this study, it is assumed that the per-lane capacity triples after converting a GPL to CAVL (Chen et al., 2016). With regard to travel time, according to Correia et al. (2019), the value of time of CAV travelers, compared to HDV travelers, could be almost 26% lower (additional research could refine that value further). Therefore, in this chapter, the values of time of HDV and CAV travelers are assumed to be 20 ($/h) and 15 ($/h), respectively.

The remaining numerical settings used in this chapter are: (1) number of trips of each traveler per year: $\chi_w^t = 720$ (trip/year); (2) excess cost of using CAV:$\xi_w^t = 1000$ (\$/year); (3) benefit threshold: $\bar{\mu}_w^t$ = 1000 \$; (4) $\varphi = 1.2$ (1/period); monetized cost of CO emission: $\vartheta = 50$ (\$/ton) Sinha and Labi (2007); and (5) $\iota = 0.00005$. χ_w^t, ξ_w^t, $\bar{\mu}_w^t$, φ, and ι are selected according to Chen et al. (2016) after adjusting for the four-year planning periods.

Table 6.2 O-D pair travel demand (× 10^3)

		Destination									
		1	2	3	4	5	6	7	8	9	10
Origin	1	0	0.4	0.4	2	0.8	1.2	2	3.2	2	5.2
	2	0.4	0	0.4	0.8	0.4	1.6	0.8	1.6	0.8	2.4
	3	0.4	0.4	0	0.8	0.4	1.2	0.4	0.8	0.4	1.2
	4	2	0.8	0.8	0	2	1.6	1.6	2.8	2.8	4.8
	5	0.8	0.4	0.4	2	0	0.8	0.8	2	3.2	4
	6	1.2	1.6	1.2	1.6	0.8	0	1.6	3.2	1.6	3.2
	7	2	0.8	0.4	1.6	0.8	1.6	0	4	2.4	7.6
	8	3.2	1.6	0.8	2.8	2	3.2	4	0	3.2	6.4
	9	2	0.8	0.4	2.8	3.2	1.6	2.4	3.2	0	4
	10	5.2	2.4	1.2	4.8	4	3.2	7.6	6.4	4	0

Table 6.3 Link characteristics of the network

Link ID	From	To	Free-flow Travel time (min)	Capacity × 10^3 (veh/h)
1	1	2	6	26
2	2	1	6	26
3	6	2	5	14
4	2	6	5	14
5	1	3	4	24
6	3	1	4	24
7	3	4	4	18
8	4	3	4	18
9	4	5	2	18
10	5	4	2	18
11	5	6	4	14
12	6	5	4	14
13	9	5	5	10
14	5	9	5	10
15	6	8	2	14
16	8	6	2	14
17	9	8	10	16
18	8	9	10	16
19	8	7	3	18
20	7	8	3	18
21	9	10	3	8
22	10	9	3	8

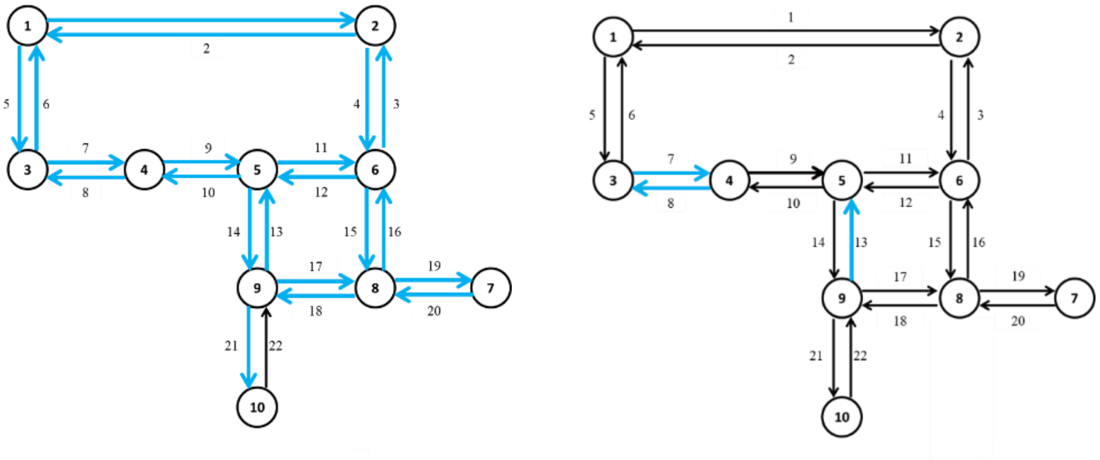
The algorithms proposed for solving the problem, Algorithm 1 to Algorithm 3 (presented earlier in this chapter) were implemented using the General Algebraic Modeling System (GAMS), and CPLEX, CONOPT, and CONOPT4 solvers. The results were obtained using a Core i7 processor with a 3.2 GHZ CPU and 32 GB RAM. The computation time of solving only MEPC2, to determine a deterministic plan, was approximately 8 minutes. To develop a robust plan, Algorithm 1 was used, taking approximately 04:10 (hour:minute). Solving algorithms 2 and 3 took 04:05 and 00:05, respectively. This introduced cuts to MEPC2, which made it more complex to solve.

6.5.2 Results and discussion

6.5.2.1 Analysis of lane reallocation policy impacts

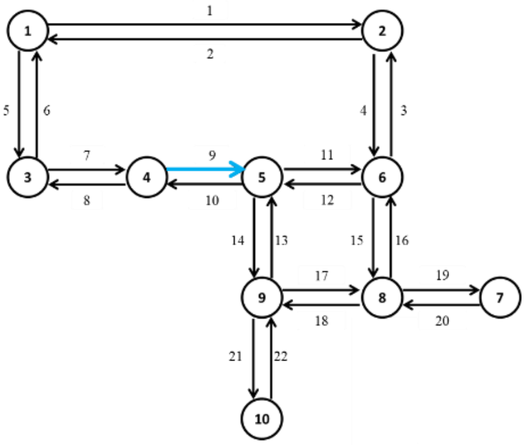
In this section, the impacts of different lane reallocation strategies on total emissions cost, system benefit in terms of reduced emissions, and CAV market penetration rates are investigated without considering the potential CAV market size uncertainty. Under this analysis, the deterministic plan is considered based on the nominal travel demand. The existing lanes width are assumed to be equal to 12 ft which is referred to as base case in this subsection. The total emissions cost corresponding to the deterministic plan, under the base case (12 ft), is equal to 20.48 million dollars. Three possible lane widths for CAVLs: 8 ft, 9 ft, and 10 ft are considered. For example, the urban road agency could allocate 3 dedicated lanes with 8 ft width to CAVs for each of the two conventional 12 ft lanes. The potential CAV market size for all of the O-D pairs is assumed to be equal to 75%. The CAV market size in all O-D pairs is assumed to be 10% at the beginning of the planning horizon. It should be noted that although this analysis indicates that the zero-lateral wander of CAVs can contribute to vehicle emissions reduction by reducing lane widths, there is a need to regulate the minimum lane width based on the CAV width with unfolded mirrors and CAV travelers’ safety perception.

First, different lane reallocation strategies, in terms of lane width in the last period in Figure 6.4 are illustrated. In this figure, the CAV-dedicated links that are deployed under the lane reallocation policy, are shown in blue arrows. Due to the convenience of applying the 8-ft lane reallocation policy (as for every two 12-ft lanes, there are three 8-ft CAVLs), the 8-ft lane reallocation policy is applied more than others during the planning horizon. On the other hand, the 10-ft lane reallocation policy is applied only once. Table 6.4 summarizes the total emissions costs of different CAVL deployment plans and a do-nothing plan. The latter refers to the plan under which there are no CAVLs. It was determined that, irrespective of how the lane reallocation policy is implemented, CAVL deployment plans can generally reduce the total system emissions costs by more than 20% compared to the do-nothing plan (that is, without CAVLs).



(a) 8-ft Lane reallocation policy

(b) 9-ft Lane reallocation policy



(c) 10-ft Lane reallocation policy

Figure 6.4 CAVL deployment plans for different lane-width policies

Table 6.4 Total emissions cost of CAV-dedicated lane deployment plans

CAV-dedicated lane deployment		Total emissions cost (Million $)	Improvement in total emissions cost relative to do-nothing plan (%)
Lane width	8 (ft)	19.20	26.21%
	9 (ft)	19.43	25.33%
	10 (ft)	20.23	22.25%
	12 (ft)	20.48	21.29%
Do-nothing plan		26.02	

Next, Figure 6.5 presents the total system benefits under different lane reallocation policies. The total system benefit is equal to the difference in total emissions costs after employing the lane reallocation strategy relative to the base case (12 ft). This diagram shows how increasing the road capacity because of reduced CAVL width can improve system performance by increasing total system benefits and decreasing total emissions cost. More specifically, considering the 10-ft, 9-ft, and 8-ft CAVLs results in 6.25%, 5.13%, and 1.22% improvement in total emissions cost relative to the 12-ft lane case, respectively. Moreover, the improvements account for 1.27, 1.04, and 0.25 million dollars of total system benefits relative to the 12-ft lane case, respect to 10-ft, 9-ft, and 8-ft CAVLs. Besides the improvements in total system emissions cost, lane reallocation policies have some benefits regarding CAV promotion in terms of its market penetration (CAVMP). Table 6.5 presents the evolution of CAVMP over the planning horizon for each lane reallocation policy. Due to the lane reallocation to CAVs, higher road capacities, and consequently, reduced travel time, are experienced. This motivates travelers to shift toward CAVs during the planning horizon. For example, at the fourth period, after implementing 10-ft, 9-ft, and 8-ft lane width policies, the CAVMP increases from 62.364% (when lane width is 12 ft) to 62.780% (when lane width is 10 ft), 64.009% (when lane width is 9 ft), and 64.183% (when lane width is 8 ft), respectively. These results suggest that CAV deployment provides an opportunity for urban road agencies to improve their system performance and promote the CAVs by only CAVL deployment and changing lane widths without other infrastructure investment.

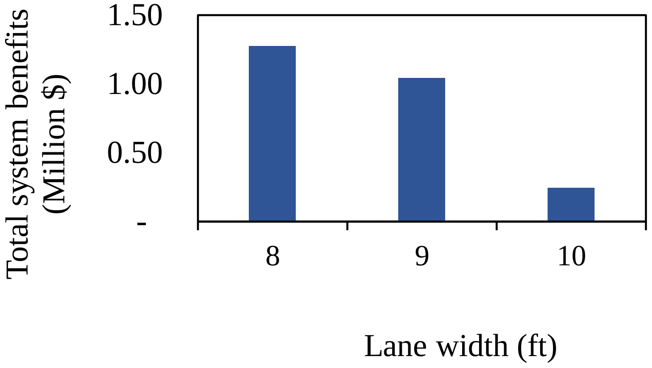


Figure 6.5 Impacts of lane reallocation policy on total system benefit in terms of emissions cost

Table 6.5 Impacts of lane reallocation policy on CAVMP (%) during the planning horizon

Lane width (ft)	Period 1	Period 2	Period 3	Period 4
8	10	43.368	52.922	64.183
9	10	43.255	52.758	64.009
10	10	32.946	50.952	62.780
12	10	32.946	50.951	62.364

6.5.2.1 Analysis of robust design impacts on vehicle emissions

In a bid to provide greater understanding of the importance of CAV demand uncertainty in the analysis, the study investigated the CAVL deployment under deterministic and robust plans alternatively. Under the deterministic plan, the potential CAVMPs are equal to the nominal values (75%) during the planning horizon. The robust plans consider the possible deviation of the market penetration from the in nominal values. For each period, five uncertainty sets are assumed for the potential CAV market size of each O-D pair:

(i) Set 1: 75% (nominal value)
(ii) Set 2: 70%
(iii) Set 3: 80%
(iv) Set 4: 65%
(v) Set 5: 60%

In addition, four different robust plans are considered based on the lane reallocation policies: (i) Robust (12 ft), (ii) Robust_LRP10 (10 ft), (iii) Robust_LRP9 (9 ft), and (iv) Robust_LRP8 (8 ft). The uncertainty budget is set at 27 O-D pairs under all robust plans. To evaluate the performance of the deterministic and robust plans, Monte Carlo simulation is carried out for different CAVL deployment plans. The performance of the defined plans is compared across five realized travel demand cases, ranging from pessimistic (Case 1) to optimistic (Case 5). Each simulation case has a specific share of Set 1, Sets 2 and 3, and Sets 4 and 5 stated earlier. These shares are chosen randomly (that is using a uniform distribution). For example, in Case 2, 18 O-D pairs have deterministic CAVMPs (Set 1) and 63 O-D pairs belong to Set 4 or Set 5. Overall, Case 1 is considered the most pessimistic case, given the high shares of sets 4 and 5. On the other hand, Case 5 is assumed to be the most optimistic case due to the high share of Set 1 and the low share of Sets 4 and 5. The other simulation cases (Cases 2 to 4) have some optimism due to the increase in the shares of Sets 1, 2, and 3, and some pessimism due to the decrease in the shares of Sets 4 and 5. Table 6.6 presents descriptions of the simulation cases.

Table 6.6 Description of simulation cases

		Number of O-D pairs		
	Simulation	Set 1 (Deterministic)	Set 2 and 3	Set 4 and 5
Pessimistic	Case 1	0	0	90
↓	Case 2	18	9	63
	Case 3	36	18	36
	Case 4	54	27	9
Optimistic	Case 5	81	9	0

Table 6.7 shows the average, maximum, minimum, and standard deviations of the total emissions costs of deterministic and robust CAVL plans under the five simulation cases. Overall, the robust plans have superior performance in terms of average, max, min, and standard deviation of total emissions cost compared to the deterministic plan under the pessimistic cases (Cases 1-3).

On the other hand, (under optimistic cases (Cases 4-5) the deterministic plan outperforms the robust plan. This is because the robust plan accounts for the worst-case demand scenario while the deterministic plan factors in the nominal values of CAVMP. Moreover, the robust plan exhibits superior performance in all of the five cases in terms of standard deviation. This is because to develop a robust optimal plan, multiple sets of potential CAV market size are captured in the design.

Next, the benefits of lane reallocation policies in robust planning are discussed. The results (Table 6.7) demonstrate the improvements in robust planning after lane reallocation policies are implemented. When lane reallocation policy is used in robust planning, robust plans (Robust-LRP8, Robust-LRP9, and Robust-LRP10) outperform the deterministic plans in all simulation cases (irrespective of measurement unit). These results suggest that a lane reallocation policy can also address the demand uncertainty. Applying a lane reallocation policy, in particular, improves the performance of robust plans in terms of average, maximum, and minimum total system emissions cost. Also, a smaller lane width is associated with superior overall performance. For example, Robust_LRP8, Robust_LRP9, and Robust_LRP10 exhibit the best performance. The comparative pattern of standard deviation between robust plans is different.

Overall, it is observed that using lane reallocation policy in robust planning increases the standard deviations of the total emissions costs, and this increment is greater in lane reallocation policies with smaller lane width. The discussed pattern of standard deviation among robust plans cannot be viewed as a disadvantage of lane reallocation policies because the superiority of such policies in terms of maximum and minimum total emissions cost have already demonstrated earlier in this section of the chapter. In other words, although lane reallocation policies (and among them, smaller lane widths) have higher standard deviations, these deviations are located in lower ranges or total emissions costs, based on the lower maximum and minimum total emissions cost.

Table 6.7 also highlights the effects of potential CAV market size. The performance of the optimal plans (deterministic and robust plans) improved from Case 1 to Case 5. This implies that the impact of uncertainty of consumers' willingness to purchase CAVs on vehicle emissions could possibly be mitigated by incentivizing travelers to purchase or patronize CAVs.

The study also carried out simulation to provide greater insight into the relative performance of the deterministic and robust plans. In these simulations, uncertain sets are assumed to have different shares of 0, 9, 18, 27, 36, 45, 54, 63, 72, 81, and 90 O-D pairs in each planning horizon. For simplicity, the share of Set 2 is considered 0 over all the simulations. Next, every possible combination of potential CAV market penetration size sets is detected, and O-D pairs are assigned randomly to the uncertain sets in such a way that the number of assigned O-D pairs to each uncertain set is equal to the share of uncertain sets. As an example, consider the following combinations of uncertain sets: Set 1 (18 O-D pairs), Set 2 (0 O-D pairs), Set 3 (9 O-D pairs), Set 4 (45 O-D pairs), and Set 5 (18 O-D pairs). After randomly assigning O-D pairs to uncertain sets, O-D pairs (1,5), (2,7), (6,9), (10,3), (4,8), (7,3), (2,5), (4,5), (3,10) are assigned to Set 4 and their corresponding potential CAV market size will be 60%.

Finally, the optimal CAV-dedicated plan is evaluated regarding the determined uncertain sets. As this assignment procedure is random (with uniform distribution), it repeats several times for each combination. Then, the average of the generated total emissions costs is determined as the metric for the performance of the optimal CAV-dedicated plan for each combination under consideration.

Table 6.7 Comparison of robust and deterministic plans using simulation

	Simulation case	Measurement	Deterministic	Robust	Robust-LRP10	Robust-LRP9	Robust-LRP8
Pessimistic	Case 1	Average (Million $)	23.68	22.54	22.040	21.819	21.64
		Maximum (Million $)	24.34	22.68	22.17	21.95	21.81
		Minimum (Million $)	23.18	22.39	21.90	21.67	21.48
		Standard Deviation (1,000s $)	257.33	69.28	65.81	65.64	71.25
	Case 2	Average (Million $)	23.22	22.16	21.707	21.520	21.37
		Maximum (Million $)	25.87	24.03	23.73	23.60	23.48
		Minimum (Million $)	22.15	21.69	21.21	20.99	20.86
		Standard Deviation (1,000s $)	813.23	296.52	322.92	339.94	352.97
	Case 3	Average (Million $)	22.00	21.61	21.182	20.999	20.85
		Maximum (Million $)	23.93	22.61	22.33	22.22	22.12
		Minimum (Million $)	21.25	21.02	20.65	20.48	20.33
		Standard Deviation (1,000s $)	523.80	251.52	272.52	284.91	299.07
	Case 4	Average (Million $)	20.84	20.86	20.487	20.320	20.17
		Maximum (Million $)	21.65	21.77	21.52	21.41	21.31
		Minimum (Million $)	20.38	20.42	20.08	19.92	19.78
		Standard Deviation (1,000s $)	199.26	178.56	174.65	174.71	176.29
Optimistic	Case 5	Average (Million $)	20.49	20.57	20.231	20.079	19.94
		Maximum (Million $)	20.60	20.68	20.35	20.20	20.06
		Minimum (Million $)	20.39	20.46	20.12	19.97	19.83
		Standard Deviation (1,000s $)	42.06	41.03	39.95	39.68	40.05

Figure 6.6 presents density distributions of the observed total emissions cost of deterministic and robust plans, under the described simulations. The deterministic plan shows a wider range of observed total emissions costs under the simulation cases compared to the robust plans. The deterministic plan also exhibited higher maximum and the lowest minimum of the total emissions costs. This implies higher variation and standard deviation of the deterministic plans compared to the robust plans, which is consistent with the results shown in Table 6.7. This is because the deterministic plan concentrates on only one uncertainty set (Set 1, which has the deterministic values). On the other hand, to determine robust plans, several sets of possible potential CAV market sizes (due to the cutting-plane algorithm application) are considered. As a result, robust plans lower the total emissions costs of a wider range of potential CAV market sizes. Also, the benefits of the lane reallocation policy are highlighted. The lane reallocation policy reduces the maximum and minimum range of the simulated total emissions costs compared to those under the robust plans. Moreover, the peaks of the total emissions cost histograms are relocated backward due to the lane reallocation policies. It means that total emissions costs are concentrated on the lower values, under lane reallocation policy implementation. In particular, the

lane reallocation policies with smaller lane widths are more effective in this regard because they use the available road space more efficiently and thus provide more capacity for CAVs. The discussed benefits of lane reallocation policies are consistent with the results presented in Table 6.7.

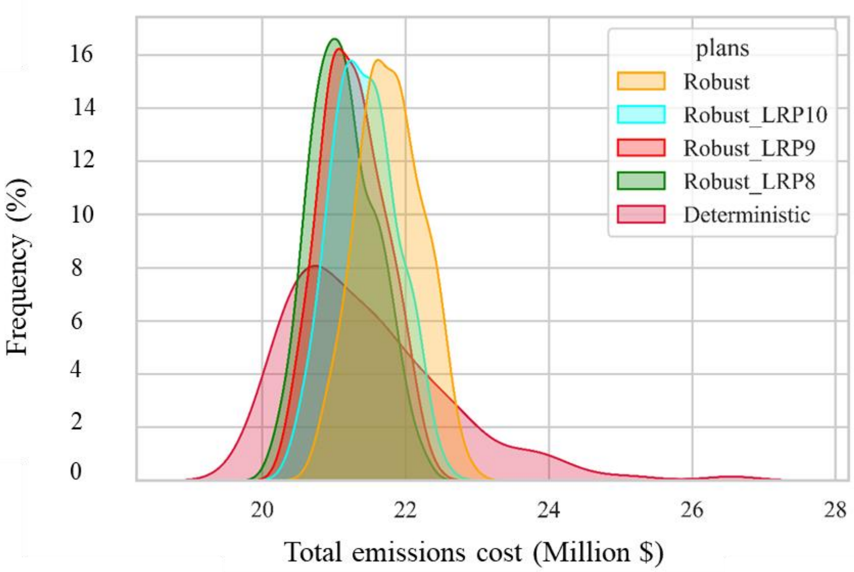
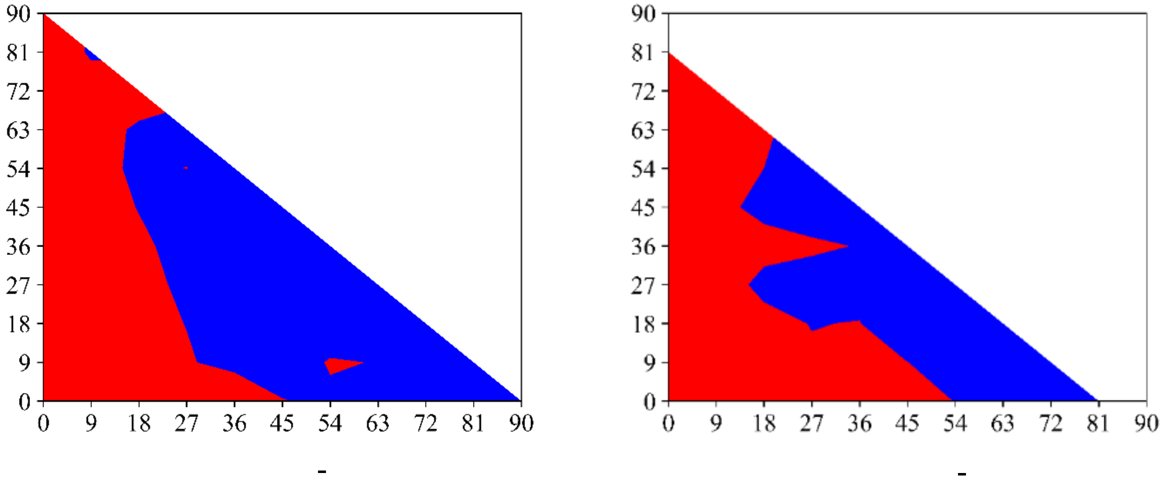


Figure 6.6 Density distribution of simulated total emissions costs under deterministic and robust plans

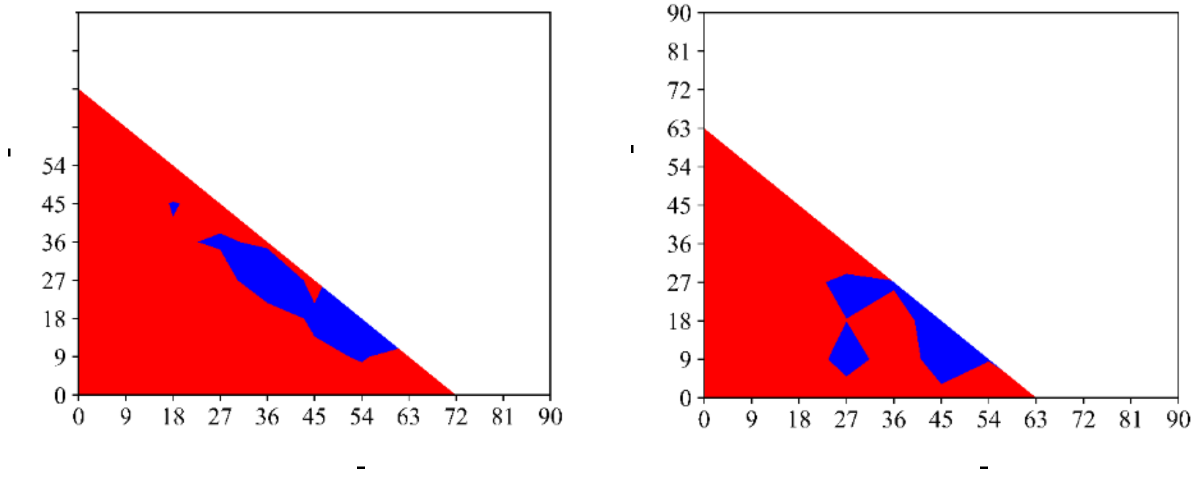
Finally, the performance of the deterministic plan and the robust plan is compared under the simulation technique (Figure 6.7). As stated before, under these simulations, uncertainty sets can have shares of 0, 9, 18, ..., and 90 O-D pairs. To have a continuous plot, the points between these values are interpolated. In Figure 6.7, the blue area indicates that the average total emissions cost of a deterministic plan is higher than that of a robust plan, which means that the robust plan is superior to the deterministic plan in that specific situation. On the other hand, the red area indicates the total emissions cost of the deterministic plan is less than that of the robust plan, which demonstrates the superiority of the deterministic plan in that specific situation.

The results show that by increasing the share of Set 3, the red area expands which indicates higher possibility of the superiority of the deterministic plan compared to the robust plan. For example, when the share of Set 3 is equal to 0 O-D pairs, the robust plan has superior performance compared to the deterministic plan under most simulations (approximately 52%). However, when the share of case 3 is equal to 27 O-D pairs, the robust plan outperforms the deterministic plan under relatively few simulations. In simulations where the share of case 3 exceeds 27 O-D pairs, it can be observed that the deterministic plan is superior to the robust plan in all simulations. This is because the high share of case 3 leads to a higher CAV adoption rate, which improves traffic flow. This implies that if urban road agencies motivate travelers to purchase CAVs, then the higher CAV adoption rate reduces the impact of forecast uncertainty of potential CAV market size on the total emissions cost.



(a) Set 3 (0 O-D pairs)

(b) Set 3 (9 O-D pairs)



(c) Set 3 (18 O-D pairs)

(d) Set 3 (27 O-D pairs)

Figure 6.7 Relative performance of deterministic and robust plans in terms of average total emissions cost

6.6 Concluding remarks

This chapter of the study describes the development of a robust optimization model to deploy CAV-dedicated lanes in a road network to address the inherent uncertainty in the forecast of potential CAV market size. This model is formulated as a bi-level framework. The upper-level model captures the goal of the urban road agency (which in this chapter, is to identify the optimal links to allocate to CAV and the number of lanes to allocate in a manner that minimizes the worst-case vehicle emissions. Given CAV's relatively small lateral wander and consequently, their requirement for smaller lane widths, it is possible, for wide roadways, to reallocate lanes on the roadway cross section for shared use (HDVs and CAVs) of the road corridor. In such lane reallocation, the total number of lanes can be increased. The lower-level model captures the route and vehicle type choices of travelers using the equilibrium condition and demand diffusion models, respectively. The bi-level model is formulated as a min-max mathematical program with equilibrium conditions and solved using the cutting-plane scheme and active-set algorithm.

The computational experiments demonstrate that long-term scheduling of CAV dedicated lanes via lane reallocation is feasible and can lead to significant reduction in total emissions costs. Specifically, it can provide a more than 6% reduction in vehicle emissions cost. Besides the benefits in total emissions cost, lane reallocation policy can contribute to the promotion of CAVs in the network. After evaluation of deterministic and robust plans using the Monte Carlo simulation technique, the deterministic plan shows a wider range of total emissions costs in the corresponding distribution. On the other hand, robust plans concentrate on limited ranges of total emissions cost. This implies a reduction in the uncertainty of potential total emissions costs in the future. Furthermore, lane reallocation policy improves robust design by lowering the average, maximum, minimum, and standard deviation of total emissions cost. Thus, it can be considered a synergistic policy in addressing potential CAV market size uncertainty. Also, computational experiments indicate that the impact of the uncertainty of consumers' willingness to purchase CAVs on vehicle emissions can be reduced by motivating travelers to purchase CAVs.

This research presented in this chapter can be extended in several directions. First, the current study assumes uncertainty only in the forecast of potential CAV market size over the planning horizon. However, given the long-term nature of the planning horizon and changes in economic and demographic conditions, there could be uncertainty in the forecast of aggregate travel demand for CAVs and HDVs. There is a need for a future study that develops a robust optimization model that accounts for such uncertainties. Also, the current study assumes that travelers have an identical value of time in their route choice. However, in practice, travelers have different values of time. Therefore, it is necessary to formulate the lower-level model as a set of multi-class equilibrium conditions that account for the different values of time of travelers within and across the two vehicle classes (HDV and CAV).

7 TRANSPORTATION DEMAND MANAGEMENT STRATEGY FOR CAV DEDICATED LANES CONSIDERING EQUITY CONSTRAINTS

7.1 Introduction

As has been demonstrated in Chapter-5 and in the literature, dedicated lanes for CAVs can significantly address urban traffic congestion. However, their implementation could generate significant public opposition because the appropriation of existing HDV lanes for dedicated use by CAVs will sharply reduce the available road capacity available to HDVs. As expected, this will cause a significant increase in travel time for HDV travelers compared to CAV travelers. Such differences in travel efficiency could give rise to equity issues because in the early years of the transition period, CAVs will likely be owned mostly by higher income groups. The social equity associated with transportation systems is always an issue (Amekudzi et al., 2015; Khisty, 1996), and therefore, can be considered a key aspect of sustainable development of new generation transportation systems. It is important to account for such inequities in CAV infrastructure planning so that such initiatives do not unduly impose high levels of inequity on low-income travelers.

7.1.1 CAV-enabled travel demand management

One of the most conventional and well-studied methods to address traffic congestion in the literature is congestion pricing. First proposed by Pigou (1920), congestion pricing seeks to recover the marginal external cost that road users impose on other users. Although it has been well studied in literature, congestion pricing has rarely been applied in practice due to public opposition. For example, in 2007, the U.K.'s national road-use charging plan was aborted after 1.8 million opposing signatures were collected (2011). Subsequent research work on road pricing was carried out by several researchers and highway agencies, including Small et al. (1989) and Bruzelius (2004). At the end of the first decade of the new millennium, a descendant of road pricing, TCS, was born. In TCS, the road authority establishes a free market for users to trade credits based on their travel needs, allocates travel credits to the users, and charges them for their use of the roads using this currency.

The concept of tradable credits has long existed in economics literature (OECD, 2001) and has been used in several contexts, including emissions (Hahnt & Nolltt, 1983), energy (Berry & David, 2002), recycling (Bailey et al., 2004). In transportation, the concept was first proposed by Yang and Wang (2011) and subsequently investigated by several researchers, including Wang et al. (2012), Bao et al. (2014), Wang et al. (2014), Shirmohammadi and Yin (2016), and Xu and Grant-Muller (2016). Grant-Muller and Xu (2014) and Miralinaghi (2018) provided a comprehensive review of the TCS literature.

The concept of the Pareto-improving design in the context of congestion pricing was first proposed by Daganzo (1985) to ensure that travelers get better off (in terms of travel costs) after implementation of tolling schemes. Subsequently, it was used in several studies (Guo & Yang, 2010; Miralinaghi et al., 2017; Song et al., 2009; Lawphongpanich & Yin, 2010; Xiao et al., 2013). Miralinaghi et al. (2019) demonstrated that a well-designed TCS can lead to a Pareto-improving scheme which makes all users better off compared to the case without TCS. This concept can be leveraged to address the social inequity associated with CAV dedicated lanes. Researchers have stated that TCS is most successful where transactions among the transport agency, travel marketplace, and user (vehicles) can be made quickly, seamlessly, and in real time, and where the travel credit marketplace status and information, can be viewed and interpreted quickly using automation. Fortunately, these could be made possible by the automation and connectivity capabilities of CAVs. Therefore, the coupling of automation-with-connectivity and TCS can potentially vastly improve the efficacy of TCS implementation.

7.1.2 Objectives and scope of this chapter

This chapter seeks to integrate the deployment of CAV links with TCS schemes to enable the urban road agency to achieve the benefits of network congestion reduction and social equity. To do this, the chapter develops a bi-level framework for solving this problem. The framework, termed travel demand and lane management in the CAV transition period (TLMCAV), prescribes the optimal amount of credit to be allocated and the travel fee, given the specified CAVL locations in the road network. Under this scheme, the road agency allocates credits among travelers at the network level based on their vehicle type (CAV and HDV), and then travelers are charged based on the links and lanes that they use. It is assumed that CAV users are able to also travel on GPLs alongside HDVs. At the upper level, the urban road agency seeks to minimize the cost of total system travel time subject to the constraint that HDV travelers' cost should not be increased beyond pre-specified thresholds by the urban road agency. These values could be determined using public surveys to understand the acceptability of practice. At the lower level, travelers seek to minimize their travel costs given the optimal credit allocation and charging schemes decided at the upper level. The chapter formulates this problem as a mathematical program with complementarity constraints.

The remaining sections of this chapter are presented as follows: Section 7.2 introduces the preliminary and notations (Table 7.1). Then, the bi-level model, which includes the upper-level model of the road agency and the lower-level model of travelers, is formulated in Section 7.3. Next, the numerical experiments are used to investigate the impact of TLMCAV design parameters on the transportation system performance in Section 7.4. Finally, Section 7.5 discusses the results.

Table 7.1 List of notations (chapter 7)

Sets	
A	Set of links
N	Set of nodes
M	Set of vehicle types
W	Set of O-D pairs
R_w	Set of paths between O-D pair w
$\bar{R}_w$	Subset of R_w which consists of paths with one or more of CAV dedicated links
Parameter	
$\beta_g^{m,t}$	Value of time of group g using vehicle type m in period t
$q_{g,w}^{m,t}$	Travel demand of group g of O-D pair w using vehicle type m in period t
ϕ^t	Equity threshold
$\gamma_{g,r,w}^{m,t}$	Cost of travelers of group g using vehicle type m due to the CAV dedicated link restriction on path r of O-D pair w in period t
Variables	
c_a^t	Travel time of link a in period t
v_a^t	Flow of link a in period t
$f_{g,r,w}^{m,t}$	Flow of path r of group g between O-D pair w using vehicle type m in period t
$v_{g,a}^{m,t}$	Flow of group g using vehicle type m on link a in period t
$d_{g,w}^t$	Aggregate travel demand of O-D pair w of group g in period t
$\delta_{a,r,w}$	Binary variable which is equal to 1 if link a belongs to path r between O-D pair w, and equal to zero otherwise
$n^{m,t}$	Credits allocated to travelers using vehicle type m in period t
$N^{m,t}$	Total allocated credits to travelers using vehicle type m in period t
u_a^t	Credits charged for using link a in period t
p^t	Credit price in period t
$\mu_{g,w}^{m,t}$	Travel cost of group g of O-D pair w using vehicle type m in period t
$B_{g,w}^{m,t}$	Benefit of travelers of group g of O-D pair w that use vehicle type m in period t

7.2 Preliminaries

Let $G(N, A)$ represent a directed road network, where A and N denote the set of links and nodes respectively in the network. Consider that the road agency divides the HDV-to-CAV transition horizon into T periods, each with a duration of multiple years. There are two vehicle types m in the road network: (i) HDV as type 1 and (ii) CAV as type 2. Let M denote the set of vehicle types. To facilitate illustration of the road network with CAVLs, the links with this lane type are separated into two links, referred to as CAV dedicated links ($\bar{A}$) and GP links ($\bar{\bar{A}}$). For example, the road network consists of one link (1-2) with CAVL in Figure 7.1. For modeling purposes, the links with CAVLs are divided into separate CAV-dedicated and GP links. Link (1-2) is divided into link 1-2 as a GP link and links (1-5 and 5-2) as CAV dedicated links (with including additional node (5)). The travel time of each link a in period t is denoted by c_a^t which is the monotonically increasing function of its flow v_a^t. The travel time is assumed to follow the Bureau of Public Roads (BPR) function.

Travelers are grouped based on their socioeconomic characteristics; the set is denoted by G. The value of time of group $g \in G$ using vehicle type m in period t is denoted by $\beta_g^{m,t}$. The travelers can engage in a range of in-vehicle activities (such as entertainment, reading, and resting) during the CAV trip. Therefore, the value of time of travelers group g is smaller if they use CAVs compared to when they use HDVs (that is, $\beta_g^{1,t} \geq \beta_g^{2,t}$) (Tian et al., 2019). Let W denote the set of O-D pairs where $r(w)$ and $s(w)$ denote the origin and destination of O-D pair w. The set of paths between O-D pair w is denoted by R_w. Let $\bar{R}_w$ denote the subset of R_w which consists of paths with one or more CAV dedicated links. Let $q_{g,w}^{m,t}$ denote the travel demand of group g of O-D pair w using vehicle type m in period t which is given and assumed to be independent of TLMCAV strategy. $f_{g,r,w}^{m,t}$ denotes the flow of path r of group g between O-D pair w using vehicle type m in period t. Let $v_{g,a}^{m,t}$ denote the flow of group g using vehicle type m on link a in period t. The aggregate travel demand of O-D pair w of group g in period t is represented by $d_{g,w}^t$. Let $\delta_{a,r,w}$ indicate a binary variable which is equal to 1 if link a belongs to path r between O-D pair w, and equal to zero otherwise. Under TLMCAV, the road agency implements on each vehicle type a specific credit allocation scheme, such that $n^{m,t}$ credits are allocated to travelers using vehicle type m in period t. Let $N^{m,t}$ denote the total allocated credits to travelers using vehicle type m in period t (that is, $n^{m,t} \sum_{g,w} q_{g,w}^{m,t} = N^{m,t}$). The road agency implements the lane-specific credit charging scheme under which travelers are charged u_a^t credits for using link a in period t.

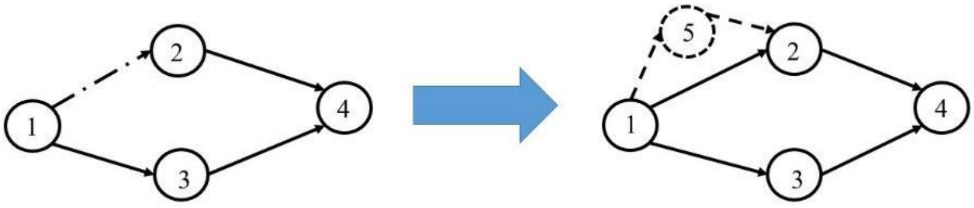


Figure 7.1 Revision of road network with CAVL

7.3 Methodology

In this section, a bi-level model is developed to obtain the Pareto-improving design of TLMCAV, which ensures that every traveler is better off. In this model, the road agency is the decision-maker at the upper level that seeks to identify the optimal credit allocation and charging schemes to minimize the total travel time. This decision is subject to constraints that include: (i) a Pareto-improving stipulation, which ensures that everyone ends up better off, and (ii) equity constraints, which ensure that HDV travelers are reimbursed for their higher travel times due to lane allocation to CAVs, particularly during the early periods of the transition horizon. The agency makes decisions with cognizance of the travel choices of the travelers (who, in turn, are the decision-makers in the lower level). In other words, it is assumed that the agency can forecast travelers' route choices in response to their (the agency's) decisions. It is further assumed that travelers seek to minimize their travel costs (which comprise travel time and credit consumption costs), by choosing their respective optimal route and lane types. Figure 7.2 illustrates the structure of the bi-level model.

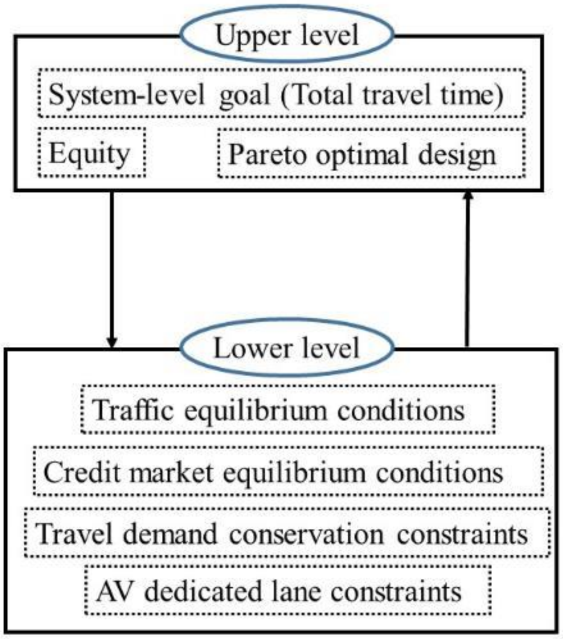


Figure 7.2 Structure of the bi-level model for TLMCAV design

7.3.1 Upper-level model

This section presents details of the upper-level model used to establish the credit allocation and charging schemes. The goal of the road agency is to minimize the total travel time during the transition horizon. The credit allocation scheme $\boldsymbol{n}$ prescribes the total number of allocated credits and method of credit allocation in each period. The credit charging scheme $\boldsymbol{u}$ prescribes the credit fee for each link and lane in each period. In this chapter, it is assumed that the credit allocation and charging schemes are constant within each period but may vary across the periods. The credit allocation scheme is vehicle specific, which implies that credits are allocated to travelers based on their vehicle types. The credit charging scheme is link- and lane-specific, which means that credits are charged based on the used link and lane type. In the road network, for a pair of connected nodes, the interconnecting link with CAVL and that with GPL, as two distinct links, are considered. Therefore, for a given vehicle, the number of charged credits may be different for the CAV-only and the GP links that comprise the link u_a^t. Then, the notation for the credit charging scheme is link-specific only within each period. Based on this discussion, the upper-level model can be formulated as follows:

$$\min_{n^{m,t}, u_a^t} \sum_{t \in \Gamma} \sum_{a \in A} c_a^t (v_a^t) \, v_a^t \tag{7.1}$$

$$B_{g,w}^{m,t} = \mu_{g,w}^{m,t,0} - (\mu_{g,w}^{m,t} - p^t n^{m,t}) \qquad \forall m, g, w, t \tag{7.2}$$

$$B_{g,w}^{1,t} \geq \phi^t B_{g,w}^{2,t} \qquad \forall g, w, t \tag{7.3}$$

$$n^{m,t}, u_a^t \geq 0 \qquad \forall m, a, t \tag{7.4}$$

$$n^{m,t} \sum_{g,w} q_{g,w}^{m,t} = N^{m,t} \qquad \forall m, t \tag{7.5}$$

$$B_{g,w}^{m,t} \geq 0 \qquad \forall m, g, w, t \tag{7.6}$$

where $\mu_{g,w}^{m,t}$ denotes the travel cost of group g of O-D pair w using vehicle type m in period t. The travel cost of travelers without TLMCAV (CAVL and TCS), in period t is denoted by $\mu_{g,w}^{m,t,0}$. The objective function (7.1) states that the road agency seeks to minimize the total system travel time. Constraint (7.2) determines the benefit of travelers of group g of O-D pair w that use vehicle type m in period t, by comparing the travel costs with and without TLMCAV. Constraint (7.3) represents the social equity constraints where ϕ^t denotes the “equity threshold” or the lowest acceptable ratio of HDV benefit to CAV benefit in period t. It is more likely that higher-income travelers compared to lower income travelers will purchase CAVs earlier in the transition horizon, and therefore, will patronize the CAV lanes. Constraint 7.3 enables the road agency to protect the benefit to lower income travelers who will experience generally higher travel times due to capacity allocation (i.e., $\phi^1 = 1$). However, towards the later periods of transition horizon where CAVs have high market penetration, the road agency can gradually reduce the equity threshold so that HDV travelers will be motivated to shift towards CAV patronage. Constraint (7.4) ensures the nonnegativity of allocated and charged credits. Constraint (7.5) determines the total number of allocated credits. Constraint (7.6) ensures the Pareto-improving design of TLMCAV which implies that every traveler is better off with TLMCAV policy intervention.

7.3.2 Lower-level model

Based on the decisions of the agency in the upper level, travelers will generally choose their routes based on their anticipations of the travel time and credit consumption costs associated with each alternative route. In this chapter, we assume that HDV travelers are restricted to the use of GP links only, while CAV travelers can use either GP or CAV links. The lower-level model is characterized by travel equilibrium and credit market equilibrium conditions. The former refers to the equilibrium state under which travelers are not able to further reduce their travel costs by unilaterally changing the routes. The latter refers to the equilibrium state where credit price is positive if all the credit supply in each period is consumed by the travelers. Given the above discussion, the lower-level problem can be formulated as the following mathematical program with equilibrium constraints (MPEC) (Equations 7.7-7.13):

$$0 \leq (\sum_{a \in A} \left((\beta_g^{m,t} c_a^t(v_a^t) + p^t u_a^t) \delta_{a,r,w} \right) + \gamma_{g,r,w}^{m,t} - \mu_{g,w}^{m,t}) \perp f_{g,r,w}^{m,t} \geq 0 \qquad \forall m, g, w, t, \forall r \in R_w \qquad (7.7)$$

$$f_{g,r,w}^{1,t} = 0 \qquad \forall g, w, t, \forall r \in \bar{R}_w \qquad (7.8)$$

$$0 \leq p^t \perp (\sum_m N^{m,t} - \sum_{a \in A} u_a^t v_a^t) \geq 0 \qquad \forall t \qquad (7.9)$$

$$\sum_{w,r} f_{g,r,w}^{m,t} \delta_{a,r,w} = v_{g,a}^{m,t} \qquad \forall a, t, g, m \qquad (7.10)$$

$$\sum_{r \in R_w} f_{g,r,w}^{m,t} = q_{g,w}^{m,t} \qquad \forall g, w, t, m \qquad (7.11)$$

$$\sum_{m,g} v_{g,a}^{m,t} = v_a^t \qquad \forall a, t \qquad (7.12)$$

$$v_a^t \geq 0 \qquad \forall a, g, r, w, m, t \qquad (7.13)$$

where: $\gamma_{g,r,w}^{m,t}$ denotes the associated cost of travelers of group g using vehicle type m due to the CAV dedicated link restriction on path r of O-D pair w in period t. For vectors x and y, $0 \leq x \perp y \geq 0$ denotes the following: $x \cdot y = 0$, $x \geq 0$ and $y \geq 0$. Constraint (7.7) presents the user equilibrium condition and means that CAV/HDV travelers of class g use path r between O-D pair w if its travel cost is equal to the minimum travel cost of CAV/HDV travelers between O-D pair w. It also states that the travel costs of paths between O-D pair w are greater than or equal to the minimum travel cost of that O-D pair. Constraint (7.8) ensures that the HDV travelers do not use path $r \in \bar{R}_w$ that includes any CAV dedicated link. Constraint (7.9) ensures that the credit price is positive in period t if and only if credit demand of travelers is equal to the credit supply of that period. Constraints (7.10)-(7.12) determine the aggregate link flow, and link flow of travelers of different vehicle types based on the path flows. Constraint (7.13) denotes the nonnegativity of link flows. The following propositions ensure the existence of a solution for the lower-level model.

Proposition 1. The following variational inequality (VI) problem (7.8),(7.10)-(7.13), (7.14), (7.15) is equivalent to MPEC (7.7)-(7.13).

$$\sum_{t \in \Gamma} \left(\sum_{a \in A} \sum_{g \in G} \sum_{m \in M} \beta_g^{m,t} c_a^t \left(v_a^{t^*} \right) (v_{g,a}^{t,m} - v_{g,a}^{t,m^*}) \right) \geq 0 \qquad (7.14)$$

$$\sum_{a\in A} u_a^t v_a^t \leq \sum_{m} N^{m,t} \qquad \forall t \qquad (7.15)$$

(7.8), (7.10)-(7.13)

Proof. The VI problem (7.8),(7.10)-(7.13) (7.14), (7.15) is solved by $(\boldsymbol{f}^*, \boldsymbol{\nu}^*, \boldsymbol{p}^*)$ if and only if it solves the following linear optimization problem:

$$min \sum_{t\in\Gamma} \left(\sum_{a\in A} \sum_{g\in G} \sum_{m\in M} \beta_g^{m,t} c_a^t\left(\nu_a^{t^*}\right)\left(\nu_{g,a}^{t,m}\right) \right) \qquad (7.16)$$

$$\sum_{a\in A} u_a^t v_a^t \leq \sum_{m} N^{m,t} \qquad \forall t \qquad (7.17)$$

(7.10)-(7.13), (7.15)

The set of Lagrangian multipliers of the credit conservation constraints (7.15) is denoted by $\boldsymbol{\sigma} = \{\sigma^t, \forall t\}$. Let $\gamma = \{\gamma_{g,r,w}^{1,t}, \forall m, g, w, t, r \in \bar{R}_w\}$ denote the set of Lagrangian multipliers associated with constraint (7.17). The first-order conditions of VI problem can be formulated as a mathematical program with complementarity constraints (MPCC) as follows:

$$0 \leq (\sum_{a\in A} \left(\left(\beta_g^{m,t} c_a^t\left(\nu_a^{t^*}\right) + \sigma^t u_a^t\right)\delta_{a,r,w} \right) - \mu_{g,w}^{m,t}) \perp f_{g,r,w}^{m,t} \geq 0 \qquad \forall m, g, w, t, \forall r \in R^w - \bar{R}_w \qquad (7.18)$$

$$0 \leq (\sum_{a\in A} \left(\left(\beta_g^{m,t} c_a^t\left(\nu_a^{t^*}\right) + \sigma^t u_a^t\right)\delta_{a,r,w} \right) + \gamma_{g,r,w}^{1,t} - \mu_{g,w}^{1,t}) \perp f_{g,r,w}^{1,t} \geq 0 \qquad \forall m, g, w, t, \forall r \in \bar{R}_w \qquad (7.19)$$

$$0 \leq (\sum_{a\in A} \left(\left(\beta_g^{m,t} c_a^t\left(\nu_a^{t^*}\right) + \sigma^t u_a^t\right)\delta_{a,r,w} \right) - \mu_{g,w}^{m,t}) \perp f_{g,r,w}^{m,t} \geq 0 \qquad \forall m, g, w, t, \forall r \in R^w \qquad (7.20)$$

$$f_{g,r,w}^{1,t} = 0 \qquad \forall g, w, t, \forall r \in \bar{R}_w \qquad (7.21)$$

$$0 \leq \sigma^t \perp (\sum_{m} N^{m,t} - \sum_{a\in A} u_a^t v_a^t) \geq 0 \qquad \forall t \qquad (7.22)$$

(7.10)-(7.13) (7.23)

where $\boldsymbol{\mu} = \{\mu_{g,w}^{m,t}, \forall t, g, w, m\}$ denote the set of Lagrange multipliers of travel demand conservation constraints (7.11). The integration of constraints (7.18)-(7.20) is equivalent to constraint (7.7). The comparison of MPCC (7.10)-(7.12), (7.18)-(7.23) with MPEC (7.7)-(7.13) concludes that they are equivalent where $\boldsymbol{\sigma}$ is the set of credit price $\boldsymbol{p}$. Hence, the solution to VI problem (7.8),(7.10)-(7.15) also solves MPEC (7.7)-(7.13). This concludes the proof. ■

Proposition 2. The VI problem (7.8),(7.10)-(7.15) admits at least one solution.
<u>Proof.</u> The feasible solution space of VI problem is compact and convex. Further, $c_a^t\left(\nu_a^{t^*}\right)$ is continuous with respect to the aggregate link flows. Then, according to Facchinei and Pang (2003), there exists at least one solution to the VI problem (7.8),(7.10)-(7.15).
The uniqueness of equilibrium credit price and link flows can be proved using the approach proposed in previous studies (Bao et al., 2014; Miralinaghi & Peeta, 2018; Wang et al., 2012). The bi-level model (7.1)-(7.13) consists of equilibrium conditions and hence, it is classified as NP[†]-hard problem. There are several solution techniques such as active-set algorithm (Miralinaghi et al., 2020; L. Zhang et al., 2009), and smoothing regularization (Birbil et al., 2004). In this chapter, the relaxation method is used which solves the bi-level model with the direct relaxation of equilibrium conditions, as follows:

$$\left(\sum_{a\in A}\left(\left(\beta_g^{m,t} c_a^t(\nu_a^t)+p^t u_a^t\right)\delta_{a,r,w}\right)-\mu_{g,w}^{m,t}\right)\cdot f_{g,r,w}^{m,t}\le \varepsilon \qquad \forall m,g,w,t,\forall r\in R_w \tag{7.24}$$

$$\left(\sum_{a\in A}\left(\left(\beta_g^{m,t} c_a^t(\nu_a^t)+p^t u_a^t\right)\delta_{a,r,w}\right)-\mu_{g,w}^{m,t}\right)\ge 0 \qquad \forall m,g,w,t,\forall r\in R_w \tag{7.25}$$

$$f_{g,r,w}^{m,t}\ge 0 \qquad \forall m,g,w,t,\forall r\in R_w \tag{7.26}$$

where, ε is a small positive constant.

7.4 Numerical experiments

This section investigates the impact of travelers' heterogeneity and equity consideration on the TLMCAV design. The bi-level model (7.1)-(7.13) is applied to the small network that consists of eight nodes and fourteen links. The transition horizon consists of 10 periods. Travelers are divided into three groups, and it is assumed that groups 1, 2 and 3 include 20%, 50% and 30% of travelers, respectively. The values of time of group 1 using HDV and CAV are 15 and 5, respectively. The values of time of group 2 using HDV and CAV are 20 and 10, respectively, in \$/hr. The values of time of group 3 using HDV and CAV are 25 and 15, respectively, in \$/hr. Since value of time can be considered as a proxy for travelers' income, groups 1 and 3 could represent the low-income and high-income classes, respectively. There are two O-D pairs where the aggregate travel demands between O-D pairs (1,2) and (1,3) are 22 units and 33 units in the first period, respectively. The travel demand grows at a 10% rate during the transition horizon ($d_{g,w}^t=(1+0.1)^{t-1}\cdot d_{g,w}^1$). In the first period, the demand rates consist of CAVs (10%) and HDVs (90%), where the CAV market penetration increases at the rate of 10% through the transition horizon.

[†] Non-deterministic polynomial-time

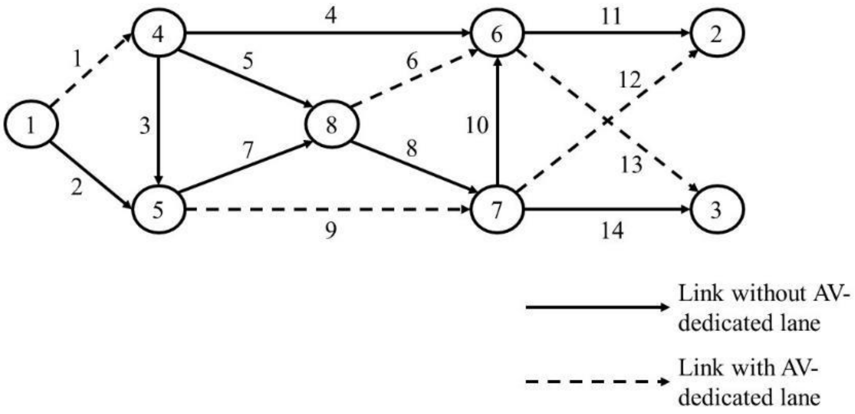


Figure 7.3 Case study illustration

Table 7.2 Link characteristics for the eight-node network

Link ID	Start node-end node	Free-flow travel time (min)	GPL capacities	CAVL capacities
1	1-4	5	12	18
2	1-5	6	18	N/A^*
3	4-5	9	20	N/A^*
4	4-6	2	11	N/A^*
5	4-8	8	26	N/A^*
6	8-6	4	26	32
7	5-8	7	32	N/A^*
8	8-7	8	30	N/A^*
9	5-7	6	33	40
10	7-6	4	36	N/A^*
11	6-2	3	25	N/A^*
12	7-2	8	39	50
13	6-3	6	24	32
14	7-3	6	43	N/A^*

*Not applicable

First, the TLMCAV design, which can address the social inequity impact of CAVLs, is investigated. Accordingly, four cases of traffic equilibrium conditions with different traffic management policies are investigated as follows:

Case 1. without CAVL, TCS and equity consideration (referred to as no-TLMCAV case).
Case 2. with CAVL without TCS and equity consideration (referred to as the CAVL only case).
Case 3. with CAVL and TCS without equity considerations (referred to as the No-equity case).
Case 4. with CAV dedicated lane, TCS and equity consideration (referred to as TLMCAV).

In this analysis, case 1 is used as a benchmark to compare and understand the impact of each policy on traffic management in the road network. For each case, the average travel time of travelers using vehicle type m in period t can be computed as follows:

$$\tau^{m,t} = \frac{\sum_{(a,g)} c_a(v_a^t) v_{g,a}^{m,t}}{\sum_{(g,w)} q_{g,w}^{m,t}} \qquad \forall t, m \qquad (7.27)$$

Then, the average reduction of travel time cost for travelers using vehicle type m in period t under cases 2-4 compared to case 1 (no-TLMCAV) can be calculated as follows:

$$\theta^{m,t} = \frac{\sum_{(g,w)} q_{g,w}^{m,t} \mu_{g,w}^{m,t,0} - \sum_{(a,g)} c_a(v_a^t) v_{g,a}^{m,t}}{\sum_{(g,w)} q_{g,w}^{m,t}} \qquad \forall t, m \qquad (7.28)$$

Finally, the average reduction of travel cost, including cost of travel time and tradable credits, for travelers using vehicle type m in period t, can be formulated as follows:

$$\varphi^{m,t} = \frac{\sum_{(g,w)} q_{g,w}^{m,t} \cdot (\mu_{g,w}^{m,t,0} - \mu_{g,w}^{m,t,0} + p^t \cdot n^{m,t})}{\sum_{(g,w)} q_{g,w}^{m,t}} \qquad \forall t, m \qquad (7.29)$$

7.4.1 Numerical results

Table 7.3 and Table 7.4 illustrate the impact of traffic management policies under four cases for HDV and CAV users, respectively. Under case 1, the total travel time is equal to 87,784 units. When the urban road agency implements a CAVL (case 2), the total travel time reduces to 42,247 units. This is mainly due to the higher capacity of the road network which, in turn, is due to the smaller headways associated with CAV operations at CAVLs. While this leads to a drastic reduction in total or average travel time for all users in general, it leads to an increase in the average travel time of HDV users in the first period. Compared to CAV users, HDV users experience higher average travel times in periods 1-5. It can be observed, however, that the average travel times of HDV and CAV users are identical in periods 6-10. It is because the market penetration of CAV users increases significantly toward the later periods of transition horizon, and therefore, the CAV users adjust their routes which results in identical travel times for routes with and without CAV links. As explained earlier in the chapter, CAV users generally have a lower value of time; therefore, they have a higher travel cost reduction compared to HDV users.

Under case 3, the road agency implements TCS in addition to CAVLs without considering equity among travelers. Under the optimal TCS, the total travel time is further reduced to 41,354 units. In case 3, although HDV users experience a smaller travel time compared to case 1, they experience a higher credit consumption cost. This is because the optimal TCS motivates travelers to follow the system optimal behavior which causes a higher number of charged credits used by HDV users. Compared with case 2, case 3 leads to higher benefits in terms of total cost reduction for CAV users. Therefore, it is imperative to consider equity in TLMCAV design, particularly in the early years of the transition horizon where most travelers, mainly low-income travelers, use HDVs. As a matter of good practice, the restriction on equity could be gradually relaxed over the transition horizon to provide sufficient opportunity for travelers to shift to CAVs.

To implement this restriction in the model, the equity threshold in each period t is formulated as follows:

$$\phi^t = max(0,1.01 - 0.15t) \qquad \forall t \qquad (7.30)$$

In case 4, the TLMCAV is designed. This considers CAV dedicated lane, TCS, and equity constraints. The resulting total travel time is 41,644 units. Although this exceeds the travel time associated with case 3, it is still less than that of case 2. Since the equity constraint seeks to adjust the travel cost reduction of HDV users in the early periods of transition horizon, the number of charged credits of HDV users is reduced compared to case 3. Consequently, the system under case 4 is not as efficient as case 3, but it can reduce the equity gap between HDV and CAV users. The effect of equity constraints diminishes toward later periods of the transition horizon as the equity threshold approaches zero.

Next, the impact of the TLMCAV design on the travel cost of different groups is investigated. Figure 7.4 presents the travel costs of groups 1-3 between O-D pair 1-2 under the CAVL only and TLMCAV designs. Under the TLMCAV design, during periods 1-5, the travel costs of HDV travelers of groups 1-3 reduce compared to the CAVL-only design which reflects the importance of including equity constraint. This equity effect is higher for group 1 as low-income class where the average reduction percentages for groups 1, 2, and 3 are equal to 42%, 32%, and 27%, respectively. This demonstrates another feature of this method that contributes more to the low-income travelers compared to the high-income travelers. Because of the equity focus of agency in periods 1-5, CAV travelers experience higher travel costs under TLMCAV design compared to CAVL-only design. However, toward the end of transition horizon, their travel costs reduce significantly. This effect is also higher for group 1 where the average travel cost percentage reduction in periods 6-10 for groups 1, 2 and 3 are 84%, 40% and 28%, respectively. This ensures that the TLMCAV design captures the equity across the traveler groups irrespective of their vehicle types.

Finally, the impact of equity threshold on travel cost reductions is investigated. Figure 7.5 illustrates the average travel cost reduction for HDV and CAV users under the optimal TLMCAV design with two cases of equity thresholds, ϕ_1 and ϕ_2. The equity threshold ϕ_1 is determined from equation (7.30). The equity threshold ϕ_2 is formulated as follows:

$$\phi^t = 1.01 - 0.01t \qquad \forall t \qquad (7.31)$$

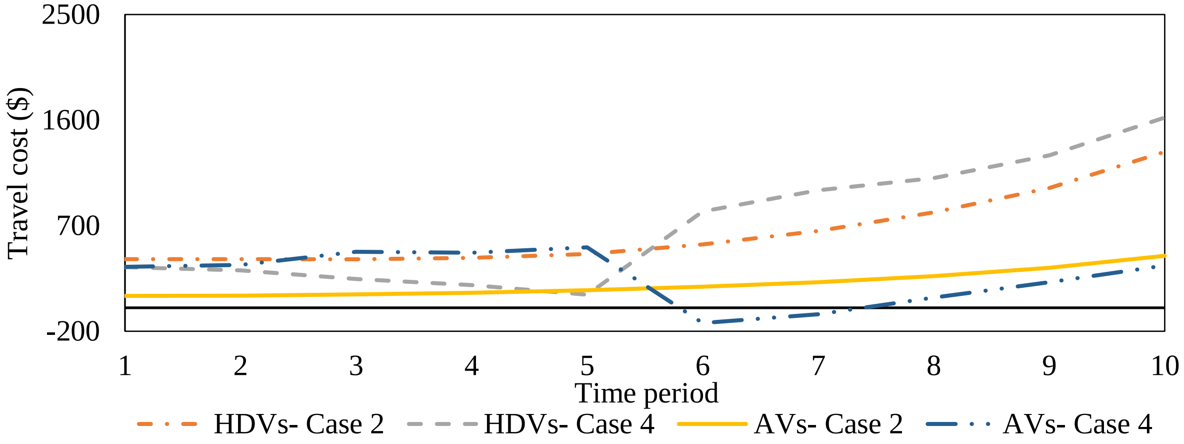
Under the equity threshold ϕ_1, the optimal TLMCAV design is more flexible in regulating higher travel costs for HDV users, particularly in the later years of the transition horizon. As observed in Figure 7.5, HDV travelers experience a higher travel cost reduction under the second equity threshold compared to the first threshold. This effect is more severe toward the end of the transition horizon where, unlike the first case, the equity threshold is still positive under the first case of equity threshold. Consequently, CAV travelers experience a higher travel cost under the second equity threshold. However, this reduces the effectiveness of TLMCAV because the total travel time increases to 41,821 units. The second case of the equity threshold also leads to an inequitable scheme where the average travel cost of CAV travelers (who constitute the majority of travelers) increases. This illustrates the importance of careful design of equity thresholds which impacts the TLMCAV efficiency and travel cost reduction for CAV and HDV users. The latter is particularly important in situations where the urban road agency seeks to promote CAVs.

Table 7.3 Impact of traffic management policies on HDV users

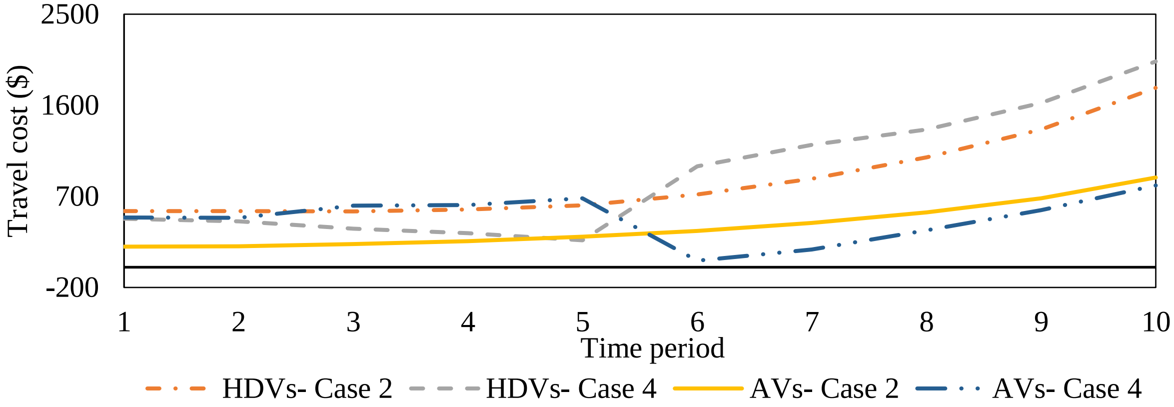
Time period	No-TLMCAV	CAV dedicated lane only			No-equity			TLMCAV		
	Average travel time	Average travel time	Average travel time cost benefit	Average total cost benefit	Average travel time	Average travel time cost benefit	Average total cost benefit	Average travel time	Average travel time cost benefit	Average total cost benefit
1	26.26	27.12	-17.62	-17.62	26.73	-9.77	6.15	26.83	-11.73	18.96
2	29.30	26.96	48.10	48.10	26.62	54.98	88.75	26.62	55.08	118.38
3	33.86	26.75	146.01	146.01	26.70	146.87	304.78	27.13	138.11	283.84
4	40.63	28.52	248.08	248.08	28.29	252.84	359.87	28.73	243.83	453.13
5	50.59	31.59	389.45	389.45	30.96	402.46	765.50	31.31	395.12	723.58
6	65.22	36.71	584.45	584.45	34.87	622.32	276.10	35.47	619.03	292.78
7	86.70	43.87	877.98	877.98	40.86	939.68	476.30	41.75	921.42	515.71
8	117.29	54.06	1296.9	1296.9	50.00	1379.42	948.01	51.11	1356.72	985.50
9	161.66	68.17	1916.59	1916.59	63.45	2013.37	1585.50	64.78	1985.99	1623.68
10	226.79	88.95	2825.65	2825.65	83.08	2945.98	2510.19	84.35	2920.01	2533.93

Table 7.4 Impact of traffic management policies on CAV users

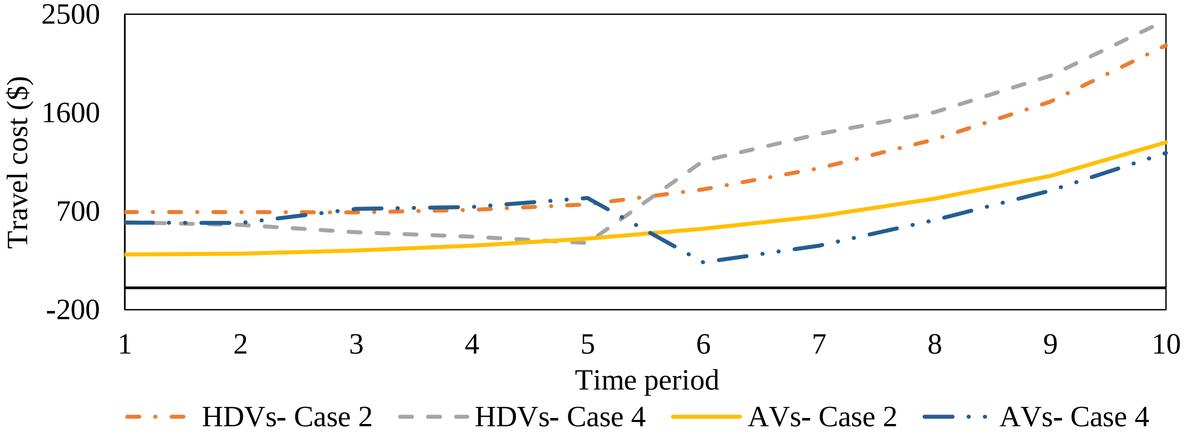
Time period	no-TLMCAV	CAV dedicated lane only			No-equity			TLMCAV		
	Average travel time	Average travel time	Average travel time cost benefit	Average total cost benefit	Average travel time	Average travel time cost benefit	Average total cost benefit	Average travel time	Average travel time cost benefit	Average total cost benefit
1	26.26	21.95	88.16	88.16	22.02	86.77	158.12	23.27	61.23	8.32
2	29.30	22.37	142.04	142.04	22.49	139.61	214.82	23.67	115.28	76.02
3	33.86	24.20	197.97	197.97	25.07	180.21	113.29	24.82	185.27	48.12
4	40.63	26.91	281.04	281.04	27.10	277.26	359.87	27.04	278.42	182.31
5	50.59	31.12	399.07	399.07	31.77	385.57	265.05	30.63	409.06	319.69
6	65.22	36.71	584.53	584.53	36.79	582.80	1251.79	36.11	596.70	1233.97
7	86.70	43.86	877.98	877.98	43.52	884.97	1599.25	43.91	877.03	1559.77
8	117.29	54.06	1296.08	1296.08	53.03	1317.23	2021.71	53.34	1310.83	1993.20
9	161.66	68.16	1916.58	1916.58	67.01	1940.3	2716.28	67.48	1930.62	2695.34
10	226.79	88.95	2825.65	2825.65	87.52	2855.02	3784.73	88.03	2844.50	3775.44



(a) Group 1

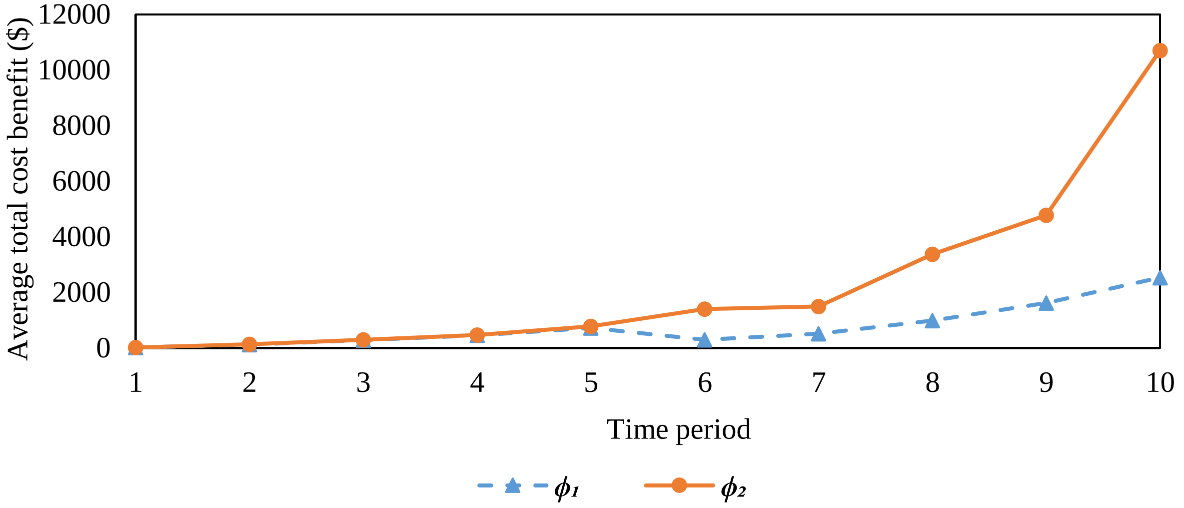


(b) Group 2

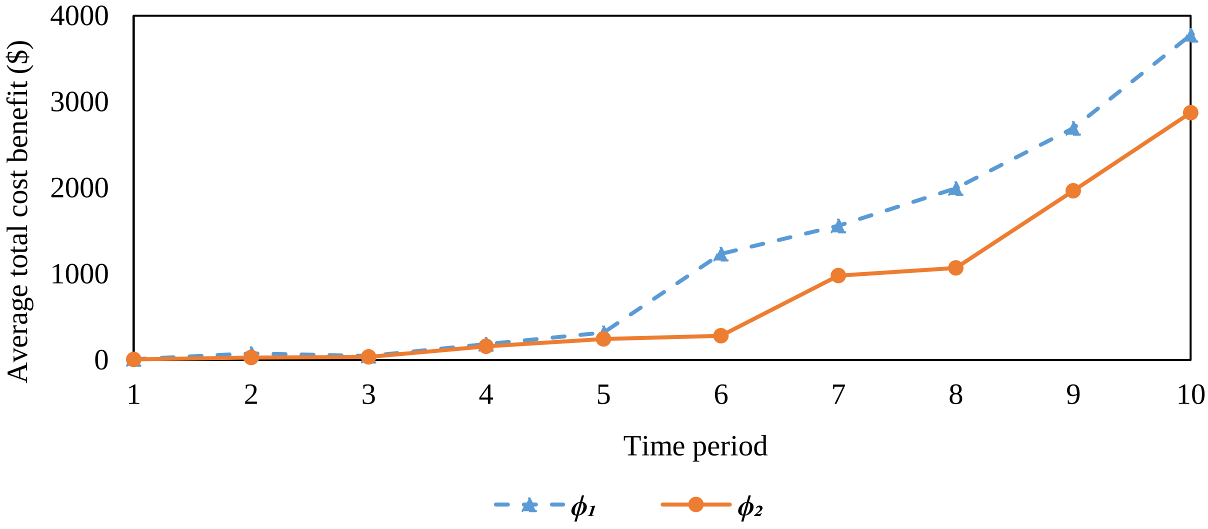


(c) Group 3

Figure 7.4 Travel costs of different groups under CAVL only & TLMCAV design (Cases 2 & 4)



(a) HDV



(b) CAV

Figure 7.5 Average travel cost reduction for HDVs and CAVs at different equity thresholds

7.5 Concluding remarks

CAVLs on the network can help reduce traffic congestion as CAVs need smaller headways compared to HDVs. As such, motivation exists to reallocate HDV lanes to CAVs. However, such reallocations reduce the road capacity available to HDV users, resulting in an increase in their travel times. To address this issue, this chapter proposes a TLMCAV scheme to manage travel demand during the CAV transition period. In this chapter's bi-level framework, the upper-level model generates the Pareto-improving design of TCS by considering equity. The equity constraint ensures that the resulting reduction in travel time for HDV users is not unduly excessive compared to that of AV users. In the lower level, travelers who are grouped based on their value-of-time seek to minimize their travel time. The bi-level model was formulated as MPEC and a relaxation method is used to obtain the optimal solution.

In the chapter, we describe numerical experiments that were conducted to understand the performance and sensitivity of the proposed TLMCAV design. We demonstrated that if the road agency considers equity constraints in TLMCAV design, such consideration could lead to a reduction not only in the total travel time but also in HDV travelers' cost compared to the design with CAVL only. This can be achieved by allocating a higher number of credits to HDVs and/or charging fewer credits for HDV use of the road. Further, it is demonstrated that the equity constraint can be formulated adequately and included in the model. It is also shown that it is useful to gradually relax the equity constraint through the early periods of transition horizon. That way, CAV users receive higher benefits in terms of travel time toward later periods of the CAV transition period. This capability is useful to urban road agencies that particularly seek to promote CAVs to maximize the usage efficiency of their road networks. It is also illustrated that TLMCAV can promote equity across the traveler groups by preventing excessive reduction in benefits for groups that have lower value of time (value of time is considered herein as a proxy for traveler income).

Finally, the numerical experiments illustrate the feasibility and importance of careful design of equity thresholds to promote equity and efficiency of travel demand and lane management in the CAV transition period.

8 IMPLEMENTATION ISSUES, CHALLENGES, AND OPPORTUNITIES

8.1 Introduction

8.1.1 Background

In the United States, the rapid growth in vehicle miles traveled coupled with the relatively miniscule scale of highway capacity expansion leaves departments of transportation, metropolitan planning organizations (MPOs), and other planning agencies in a conundrum. Typically, they find it impossible to provide adequate physical capacity to keep pace with increasing travel demand (FHWA, 2008). Such difficulty is exacerbated by factors including higher construction costs, environmental concerns, right-of-way constraints, and funding limitations. For these reasons, it is difficult for agencies to add new lanes on existing roads and highways, particularly at urban areas, to satisfy existing demand.

The growing demand combined with restricted supply is leading to a high price paid by road users in the form of congestion, delay, safety, and other adversities. In a bid to address this growing problem, highway agencies seek to adopt solutions that are based on not only supply, but also demand. It is desired to use the existing right of way as prudently as possible. Lane management (Collier and Goodin, 2004; Carson, 2005) is one way to do this. Lane managemen can be defined as the (re)assignment of lanes across a highway cross section to a specific class of vehicles, with the general overall intention of separating streams of vehicles that have different characteristics. The lanes of such restrictions are generally termed “Special Lanes” or “Dedicated Lanes”, and the restrictions may be based on considerations such as:

- Vehicle **occupancy**, such as in HOV lanes (Burrus et al., 2009; Jang et al., 2014; Boysen et al., 2021), carpool lanes (Goodin et al., 2009), or ridesharing-only lanes.
- Vehicles’ **need for speed** (such as express lanes (Schultz et al., 2016), sometimes combined with vehicle’s ability to pay for reduced **travel time** or increased **travel time reliability**, such as tolled express lanes.
- Vehicle **propulsion type**: electric vehicles (EV) or other alternative fuel vehicles (Scauzillo, 2018), including charging lanes for EVs only (Suh et al., 2011).
- Vehicle **size or classification** for example, truck-only lanes, bus-only lanes, and two-wheeler-only lanes (De Palma et al., 2008; Schultz et al., 2016).
- Vehicle **load type**, for example, freight vs. passenger (Schultz et al., 2016).
- Vehicle **automation** level, for example, levels 0-3 vs. levels 4-5 (Mohajerpoor and Ramezani, 2019; Hamad and Alozi, 2022).
- Vehicle **connectivity** (CV) status or need for connectivity (Guo et al., 2020).
- Any combination of the above, such as:
    - **Need for speed and occupancy**, such as HOT express lanes (Hultgren and Kawada, 1999; Burris and Stockton, 2004; Zhang et al., 2013)
    - **AV and CV** (Ye and Yamamoto, 2018; Yu et al., 2019; Ramzi Rad et al., 2020).

According to FHWA, the managed lanes concept can be viewed as a “freeway-within-a-freeway” where the freeway cross-section includes a set of lanes separated from the general-purpose lanes, and that the ideal managed lane is operationally flexible at different times to allow for quick response to changing traffic demand and needs. The FHWA also indicated that managed lanes are operated using a portfolio of design, policy, and institutional initiatives (including vehicle eligibility, pricing, and access control) to enhance the safety and performance of the managed lanes.

8.1.1 Pricing of Managed Lanes

A managed lane may or may not have a toll. Tolling is often used as a travel demand reduction and/or revenue generation strategy. Toll may be on a gradated scale depending on vehicle size (auto vs. truck), vehicle status (example, extent of EV (full EV vs. hybrid), occupancy, and so on. For each of these, the toll price may also vary by direction, time of day, and day of week (Lou et al., 2011; IBI Group, 2015; Zhu and Ukkusuri, 2015; Toledo et al., 2017; Tan and Gao, 2018). For certain special managed lane programs such as the *eRoadArlanda* at Sweden, electric vehicles are charged by billing the driver for the amount of electricity used on the road.

8.2 Motivation (Rationale) for Managed Lanes

Lane management is often intended by a desire to reduce turbulence, regulate demand, and utilize available and unused capacity. Also, the literature provides various motivations for lane management (Mannering & Hamed, 1990; Rodier & Johnston, 1997; Wellander & Leotta, 2001; Kuhn et al., 2005; Jou et al., 2005; Menendez & Daganzo, 2007; Kwon and Varaiya, 2008; Plotz et al., 2010; FHWA, 2008; Shewmake (2012)). These include:

- improved safety (De Palma et al., 2008; Abdel-Aty et al., 2020).
- reduced congestion (Daganzo and Cassidy, 2008).
- improved mobility or travel efficiency (Schultz et al., 2016; Ye and Yamamoto, 2018; Kadeha et al., 2020).
- improved air quality (Kessler and Schroeer, 1995; Johnston and Ceerla, 1996)
- ability to serve customers (road users) with different urgencies.
- revenue generation (Goodin et al., 2009).

Citing evidence from a 2001 survey of I-15 users in San Diego (where 92% of respondents agreed that I-15’s managed lanes help save time), Obenberger argued that managed lanes can enhance public perception highway agencies’ efforts to reduce freeway congestion. De Palma et al. (2008) cited the safety benefits of managed lanes in the context of the effect of vehicle size variations. Ginger Goodin, former chair of the Transportation Research Board’s Joint Subcommittee on Managed Lanes stated: “If you subscribe to the notion that you cannot build your way out of congestion in developed urban freeway corridors, then managed lanes offer an opportunity to preserve a portion of the freeway capacity for a higher level of service” (Obenberger, 2004). In certain cases, there exist unintended disbenefits of managed lanes. Dahlgren (1998) cautioned that high occupancy vehicle lanes may not always be more effective than general purpose lanes. Weinstein and Sciara (2006) discussed equity issues associated with lane management in the context of vehicle occupancy and tolling. In addition, it has been recognized that even though managed lanes generally improve safety within the stretch of the managed lane, crashes often occur at access points and due to sight distance (FHWA, 2008). For example, crashes happen at the transition areas when drivers attempt to make unexpected maneuvers in violation of access restrictions.

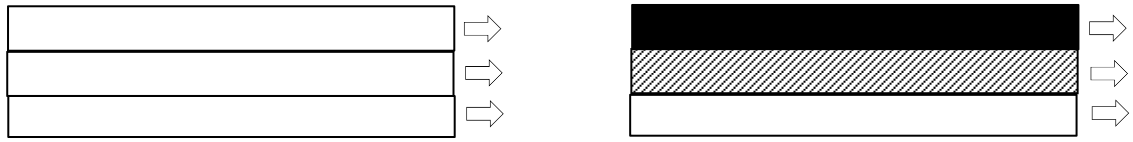
8.3 Configurations of Managed Lanes

Managed lanes are generally a combination of traditional vehicle (TV) lanes and special vehicle lanes (such as AV-dedicated lanes, EV-lanes, truck-only lanes, etc.). Here, the word "traditional" is used to represent the basic type of vehicle (for example, automobile, no-toll, zero or basic automation, single occupancy, and so on). A "special" vehicle refers to one of specific characteristics such as size, occupancy, toll-paying, automation level, propulsion-energy type, and so on. This term is used in the context of specific characteristics whose emergence, dominance, or specific attribute necessitated the assignment of road space to them. A dedicated lane is a lane used by traditional vehicles only or special vehicles(SV) only. A shared lane is a lane used by both traditional and special vehicles at the same time; this is also referred to as a mixed-traffic lane. A TV+SP lane refers to a lane where both traditional vehicles and special vehicles use the lane at the same time, i.e., a mixed-traffic lane or shared lane. This is not the same as a shared roadway corridor or shared road cross section.

Figure 8.1 presents the major configurations of managed lanes. These could be realized through greenfield development or by reallocating the existing road space (that is appropriating lanes from traditional vehicles to special vehicles, for use either as dedicated lanes or as shared-use lanes). The figure is presented for one direction only and for three lanes only. As suggested in the figure, the major configuration types (the situations where the roadway cross section has various combinations of TV and SV) are:

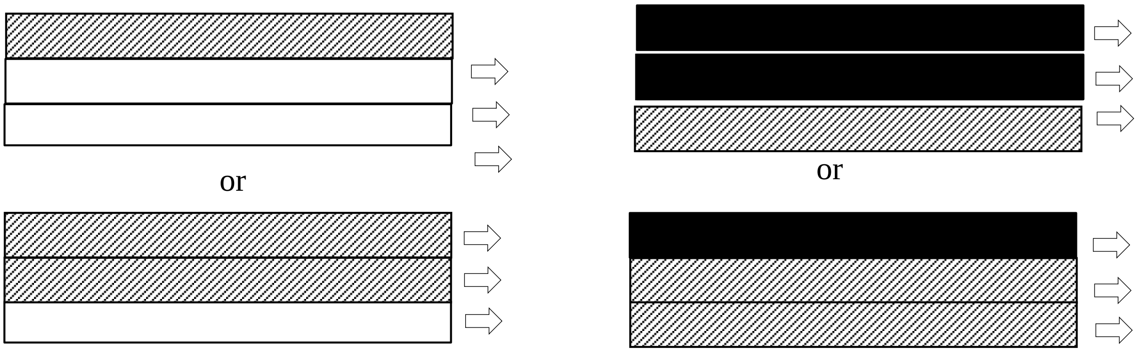
- TV-only lanes (the existing or base-case configuration)
- TV, TV+SP, SP lanes (the Paripassu configuration)
- TV, TV+SP lanes (the TV Fitihawi configuration)
- TV+SV, SV lanes (the SV Fitihawi configuration)
- TV, SV lanes (TV only and SV only or fully-dedicated configuration, TV dominant)
- SV, TV lanes (TV only and SV only or fully-dedicated configuration, SV dominant)
- TV+SV lanes (the fully mixed-traffic (FMF) configuration)
- SV only

☐ TV ■ SV ▨ Mixed traffic lanes (both TV and SV use the lane)



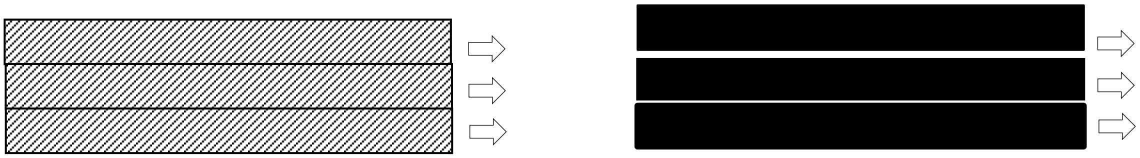
(a) TV Only

(b) TV, TV+SV, SV (The Pari-passu model)



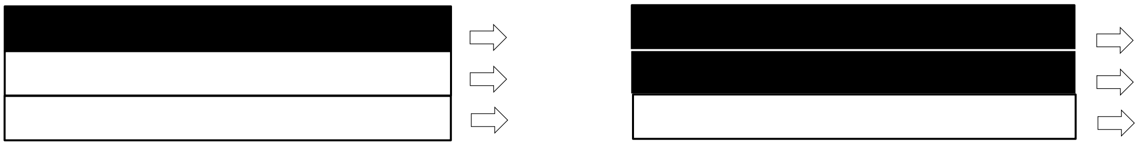
(c) TV, TV+SV (The TV Fitihawi model)

(d) TV+SV, SV (The SV Fitihawi model)



(e) TV+SV (The fully mixed-traffic (FMF) model)

(f) SV Only



(g) TV,SV (The Fully Dedicated Model, TV dominant)

(h) TV,SV (The Fully Dedicated Model, SV dominant)

Figure 8.1. Eight configurations of managed lanes (this is illustrated for one direction only and for three lanes only)

The traditional vehicles (TV)-only configuration is the existing or base-case scenario where all lanes are used by traditional vehicles only. *Paripassu* is a Latin phrase that literally means equal sharing. In the Pari-passu model (TV, TV+SV, SV), the number of traditional vehicle lanes is equal to that of special vehicle lanes. Here, there is equal sharing not only of the road cross section but also of the road space use in at least one lane. (TV, TV+SP) represents the case where existing lanes for traditional vehicles and lanes for a mixed stream (traditional vehicles and special vehicles). This is the *Fitihawi* model skewed in the favor of traditional vehicles. *Fitihawi* is an Amharic word meaning unequal sharing. The Fitihawi model is where there is unequal redistribution of the existing lanes. In the TV Fitihawi model (TV, TV+SV), the number of TV lanes exceed that of the SV lanes. In the SV Fitihawi model (TV+SV, SV), the number of SV lanes exceeds that of the TV lanes. TV+SV refers to the total mixed traffic (TMF) or the general-purpose lane configuration) where each lane can be used by both traditional and special vehicles at the same time; that is, all lanes are mixed-traffic lanes (there is no dedicated lane).

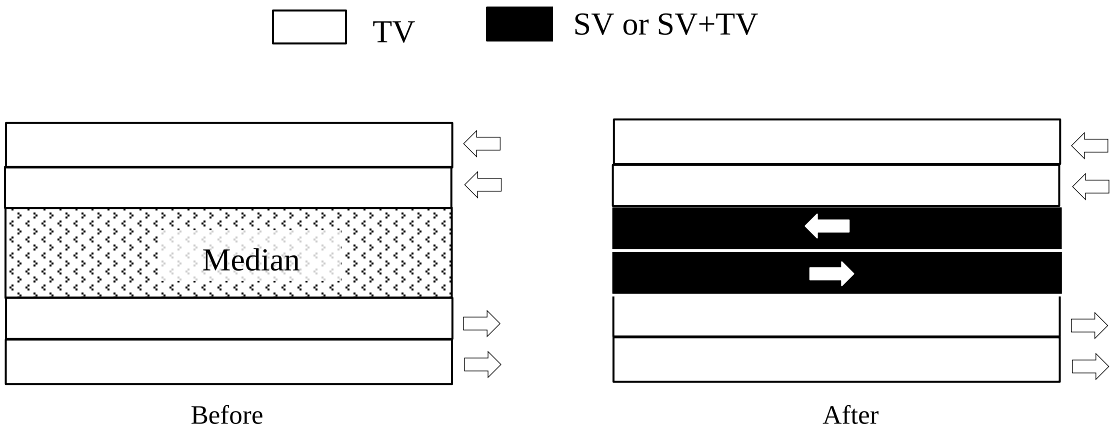
In the Fully Dedicated model (TV, SV), the road space is shared between traditional vehicles and special vehicles, but there is no lane where they both use at least one lane at the same time, that is, there is no mixed traffic; all lanes are dedicated to either TV or SV only. In some situations, the TV has a greater number of dedicated lanes compared to the SVs; in other situations, the reverse is the case.

8.4 Appropriation Status of Managed Lanes

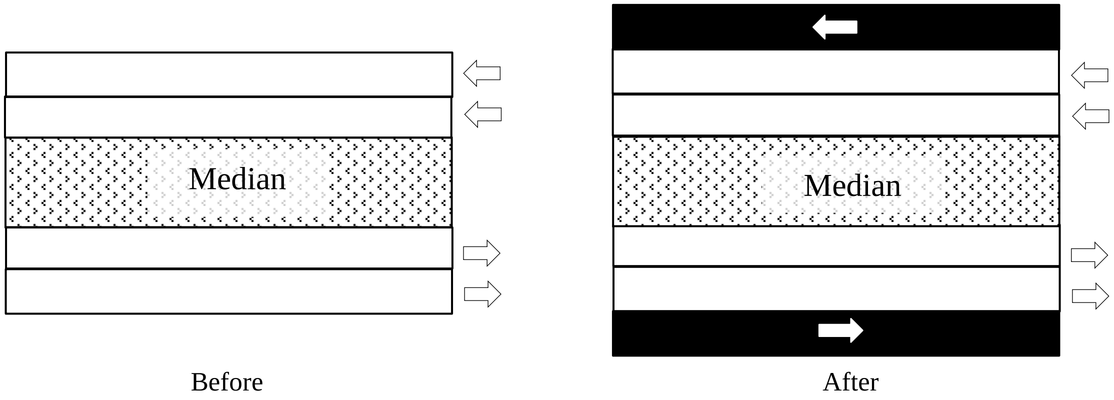
There are two possible states of appropriation:

- Appropriation: TV lanes are existing, SV lanes are appropriated from existing TV lanes, thus, the number of TV lanes reduces. The discussion on lane configuration in the previous section of this chapter (Section 8.3) assumes that lane appropriation takes place.
- No appropriation: TVs are existing lanes, SVs are new lanes. New lanes for SVs may be constructed on land that was formerly the location of the median, shoulders, or green space adjacent to the existing corridor.

Figure 8.2 presents a schema for managed lanes without appropriation of existing lanes. In (a) the road median space is converted into special lanes and the outermost lane(s) are used for the mixed stream (TV and SL). In (b), the existing adjacent right-of-way space is used to build a new dedicated lane for the special vehicles. In some cases, that space is exchanged with the innermost lanes, so that the mixed stream uses the new outermost lanes while the innermost lanes are reassigned to the special vehicles and/or traditional vehicles.



(a) Conversion of road median



(b) Using existing adjacent right-of-way to build new dedicated lane for the mixed stream special vehicles

Figure 8.2. Example schema of managed lane, without appropriation of existing lanes

Figure 8.3 presents a pre-implementation photo of the then-proposed special lanes U.S. 69 in Kansas, from just south of 151st Street to just north of 103rd Street in Overland Park. The corridor was subsequently widened from four to six lanes (three lanes in each direction) as part of the U.S. 69 Modernization and Expansion Project. The existing median and green space were converted to SP lanes. Figure 8.4 presents the pre-implementation and post-implementation sketches for that project (KDOT, 2020).

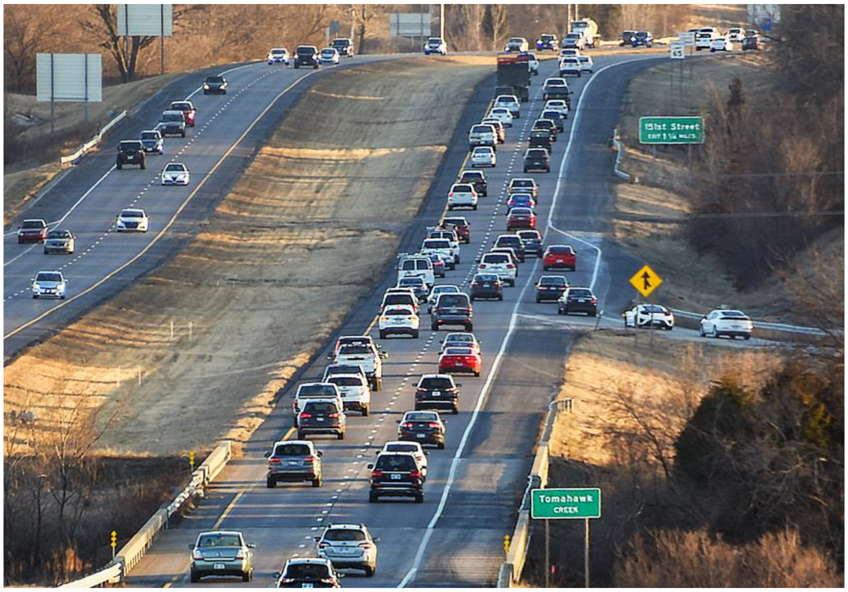
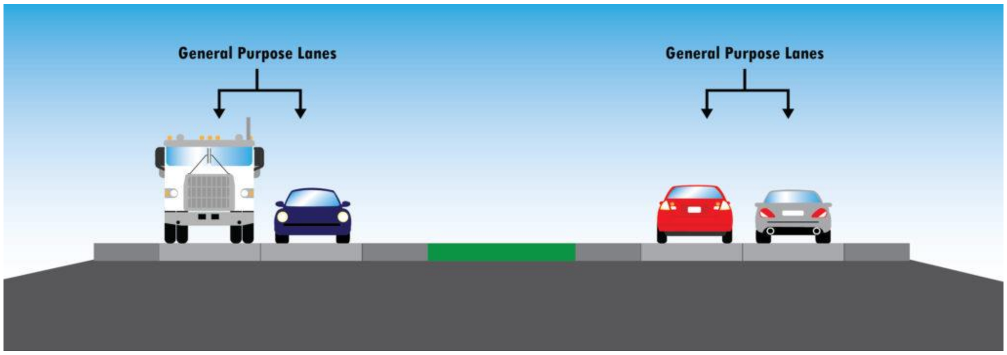
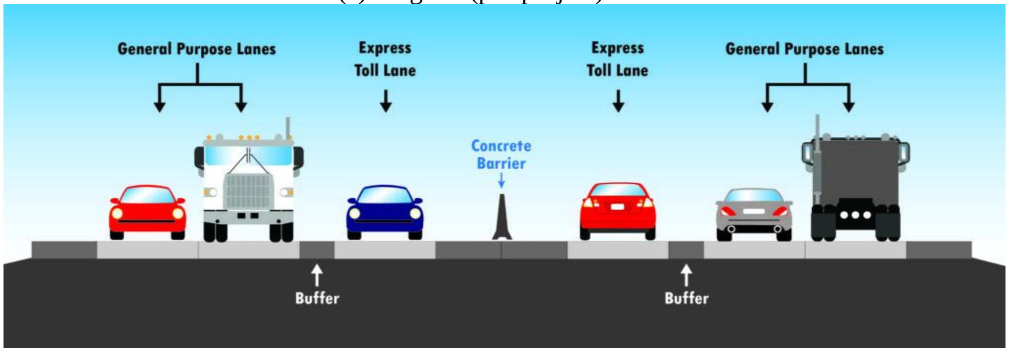


Figure 8.3: Pre-implementation of Special Lanes planned for U.S. 69 in Kansas (KDOT, 2020)



(a) Original (pre-project) status



(b) Post-completion status (no appropriation)

Figure 8.4: Managed Lanes on U.S. 69 in Kansas (KDOT, 2020)

8.5 Enforcement of Managed Lanes

The effective operations of managed lanes for autonomous and connected vehicle road transportation can be enforced through techniques typically used in lane management for other road classes. These include physical design, policy, and incentives such as (Neudorff et al., 2004; FHWA, 2008; Perez et al., 2012):

- Non-dynamic signs and pavement markings
- Lane control signs and signals
- Law enforcement and legal restrictions
- Variable message signs
- Temporary traffic control devices
- Economic incentives and disincentives
- Adequate lighting at access point locations (areas of entry and exit)
- Monitoring of the managed lane corridor as well as its access point locations (transition areas).

Figure 8.5: Example of traffic guidance on managed (truck-only) lanes in New York (Photo: Neudorff et al., 2004)

8.6 Guidelines for the Implementation of AV Managed Lanes

Perez et al's 2012 guide on priced lane management identified and discussed three major barriers to lane management, particularly where a toll is involved: technical, institutional, and public acceptance. The discussion below, which is relevant in prospective implementation of CAV-only lanes, is culled from the Perez et al. (2012) publication and other similar relevant sources.

8.6.1 Technical Barriers

Roads with managed lanes are typically constructed in urban corridors that have severe restrictions on the right-of-way. Secondly, to support the technologies associated with the types of special vehicles in question (EV, AV, toll customers, etc.), these road sections need infrastructure such as electric charging guideways, connectivity stations, roadside units, electronic toll gantries, cameras, and so on. Often, the installation of this infrastructure requires special roadway or roadside designs and management, including exceptions to existing design policies and standards. In addition, the entry points (or transition areas) from traditional lanes to special lanes or vice versa often cause turbulent traffic flow at these access points and, subsequently, a safety hazard (Saad et al., 2018; Abdel- Aty et al., 2020). Thus, special geometric designs or road operation initiatives may be needed to channelize or smoothen traffic flow at these areas (Perez et al., 2012). Other technical challenges of managed lanes include the need to install ITS technologies to monitor and track traffic conditions and in the case of toll roads, establish variable toll prices as and when needed. Also, ITS technologies are needed to disseminate roadway information to road users, prevent lane-use violations, and incident detection and response. Regarding PPP-procured managed-lane projects, the road agency will require expertise in legal and procurement issues. Other technical issues include refinement of analytical models to reliably monitor travel demand and to evaluate the impacts of variable toll prices on travel demand and behavior – including an analysis of the impacts of tolls that vary across time of day and day of the week. Other analytical challenges include the development of project finance and financial feasibility models, particularly where the project will be financed using toll revenues.

8.6.2 Institutional Barriers

There exist several stakeholders of AV managed-lane development projects. The road agency will need to coordinate with these stakeholders. The goals and objectives of such projects should be consistent with those of the local MPO, and the road agency will need to solicit input from the MPO and other stakeholders not only at the beginning of the project development process but also throughout the phases of construction and operations. According to Perez et al. (2012), the managed-lane project should be consistent or compatible with other infrastructure and transportation planning processes, programs, and initiatives in the city or region, including transit operators, local and state police and emergency response providers.

8.6.3 Public Acceptance Barriers

The long-term success of any major infrastructure project hinges on public support and buy-in. A barrier to successful deployment of managed lane projects could be ineffective public outreach and consensus building. The road agency needs to cultivate the capability to articulate the prospective benefits of the project to all stakeholders, as well as a candid assessment of the construction costs of the project, and the direct and indirect costs to road users and the community.

In addition, where the AV managed lane is intended for tolling, the additional benefits of the project must be clearly laid out and communicated to all stakeholders. This is because AV will already be paying motor fuel taxes, electric vehicle fees, and vehicle license and registration fees, and any road toll could be viewed as double taxation. Further, in AV lane deployment, road agencies will need to address equity because providing such "premium" service only to those who appear more likely to afford it may raise equity issues.

8.6.4 Other Challenges

Table 8.1 presents other perspectives of the challenges facing managed lanes, and attempted solutions (Wood et al. 2020). The subsequent discussion below is culled from Wood et al. (2020) and other sources.

Table 8.1 Managed Lanes: Some Challenges and Recommendations (Wood et al. (2020)

Challenge	Recommendations
Lack of clarity and poor understanding by the public	Educate road users on effective, efficient and safe use of the managed lanes road (FDOT).
Communicating the goals and objectives of the managed lane project	Justify the economic and societal need for the managed lane project. Promote accountability and transparency regarding the use of toll revenue; provide evidence on how revenues were used to support other programs including transit (VDOT, LA Metro). Compare the managed-lane alternative with similar alternatives without managed lanes (NCDOT).
Active engagement with public agencies	Carry out meeting with elected officials and skeptical stakeholders; present a user friendly and accessible toolkit to explain the purpose of the managed lane project (NCTCOG). Create an advisory group (comprising opponents and supporters of the project) (NCDOT).
Operations performance management	Modify road geometric design of shoulders, intermediate access areas, and other geometric elements (WSDOT).
Enforcement	Establish appropriate penalties for violators and particularly, habitual offenders of the managed lane use policies and protocols (WSDOT). Pilot the use of computer technology for reliable enforcement (LA Metro)

8.7 Stakeholders

Neudorff et al's 2004 operations handbook on freeway management and operations provides some useful suggestions on how to identify and engage lane-management stakeholders. It is anticipated that stakeholders involved in managed lanes will include:

- State and local DOTs
- Elected officials
- Transit agencies
- State and local law enforcement agencies
- Private contractors

- Citizens committees
- Trucking companies
- American Automobile Association
- AV developers (manufacturers of vehicles and CAV technology components)
- Technology companies
- Communication agencies at the federal level.

FHWA reports on lane management continue to reinforce the need to drum up the support of the general public and elected officials for managed lane projects. Also, the road agency must identify other stakeholders that are likely to be affected by the managed lane construction and operations. Where the managed lane corridor includes at least one lane with mixed traffic (i.e., the traditional vehicles and the special vehicles use the same lane), stakeholders often express legitimate anxiety regarding the interactions between the traditional and special vehicles. In the case where the special vehicle is an automated and connected vehicle, it is important to protect not only the traditional vehicle from errant CAVs, but also the CAV from reckless traditional vehicles (Dong et al., 2021; Du, 2021). Researchers have opined that such safety continues to represent a thorny issue in freeway management in the CAV era.

Finally, the concept of managed lane operations needs to consider any political sensitivities and ramifications of the different strategies for managed lane operations. Some researchers have recognized that certain lane management policies yield benefits to certain road user classes that are greater than (or, at the expense of) other road user classes, and such disparity (or, in some cases, inequity) could lead to public resistance and public relations problems for the road agency. In addition, if the AV managed lane deployment will be associated with new tolls on traditional vehicles), that could stoke public opposition. In any case, it is highly recommended to involve all stakeholders early in the development of AV managed lane road systems.

9 OVERALL CONCLUDING REMARKS

This chapter summarizes the report, highlights its significance, provides some concluding comments, and suggests directions for future research. Section 9.1 summarizes the research and discusses associated conclusions. Section 9.2 highlights the significance of the research from theoretical and practical perspectives. Section 9.3 discusses possible extensions and directions for future research.

9.1 Research summary

Connected and autonomous vehicles (CAVs) generally provide opportunities to address the problem of growing traffic congestion at urban areas. In this context, the concept of urban road lane management could potentially increase urban mobility in the CAV transition era. Several studies in the literature have explored the impacts of CAVLs on traffic flow at the corridor and network levels. However, there exists a need to study the design and management of CAV lanes (CAVL) in a manner that explicitly addresses the elements of sustainable development: social, environmental, and economic.

First, this report describes a proposed economic design of CAVLs in a traffic corridor. This report investigates the impacts of CAVLs on traffic congestion during the morning peak period at a road bottleneck. First, user equilibrium conditions are formulated as a linear program with complementarity constraints. Then, the existence of a solution and the solution's details in terms of departure rates and queuing delays are demonstrated. It is proven that in any time interval, a CAVL has lower levels of queuing delay compared to a general-purpose lane. The system-optimal condition is formulated to obtain the minimum system cost, including total queuing delay, and early and late arrival costs, by deriving the optimal number of lanes and tolling scheme. Computational experiments suggest that high CAV market penetration could reduce travel costs of HDV commuters. Further, it is shown that CAV technological advancement, which increases lane capacity, can significantly improve traffic flow with an effect almost similar to that of a tolling scheme.

Second, this report describes a proposed framework for environmentally-sustainable design of CAVLs for an urban road network. The framework could help an agency develop a schedule for optimally deploying CAVLs in their road network over an extended time horizon. It accounts for the uncertainty in the forecast of potential CAV market size which is reflected in consumers' willingness to purchase or patronize CAVs. The problem is formulated as a bi-level model. The upper level uses a robust optimization technique that prescribes the number and locations (candidate links) for CAV-dedicated lane deployment such that the worst-case total emissions cost for the entire network is minimized. The analysis also accounts for the relatively smaller CAV lane widths compared to HDVs due to the small lateral wander of CAV tire tracks across the roadway cross-section. By considering lane reallocation captures the prospect of smaller lane widths (for CAV-dedicated lanes), the framework can lead to an overall increased number of lanes at wide road sections. At the lower level, equilibrium and demand diffusion models capture the travelers' route and vehicle type choices (CAV/HDV) along the time horizon of the analysis. The model is solved using an active-set algorithm. The computational experiments, applied to a small network, indicate that the impact of uncertainty in consumers' willingness to purchase CAVs on total emissions costs can be reduced by deploying CAV-dedicated lanes. It is also shown that the lane reallocation policy, considering prospective lane width reductions (12ft to 8ft), can provide at least 6% reduction in vehicle emissions costs.

Third, this report develops a socially sustainable management strategy for CAVLs. The report presents a CAV-enabled travel credit scheme to manage demand. Here, the urban road agency distributes travel credits to travelers in a direct and instantaneous manner using the CAV's A&C features. Then, travelers use their A&C features to pay these credits when they travel to specific locations or times-of-day according to their choices of lane type and routes (links). About supply, the analysis report considers that the road network consists of three lane types: CAV-dedicated, HDV-only, and mixed traffic lanes, and develops a scheme for Travel Demand and Lane Management Strategies in CAV transition era (TLMCAV). The study models the expected travel choices based on user equilibrium concepts at different levels of CAV market penetration and demonstrates the existence and uniqueness of an optimal solution in terms of link flows and the prevailing travel credit price. Then, the study establishes the optimal credit allocation distribution and the credit price that maximize objectives associated with traffic flow and equity.

Finally, the report discusses some implementation issues, challenges, and opportunities associated with managed lanes in general and AV managed lanes in particular. This includes the pricing and motivation (rationale) for managed lanes, the various configurations of managed lanes and their appropriation status, enforcement, implementation challenges, and the stakeholders.

9.2 Research contributions

This report addresses the sustainable transportation system from the three elements of sustainable development: (i) economic (ii) social and (iii) environmental. This report first seeks to develop a framework for managing morning commute congestion, from the aspect of economic sustainability, in a highway bottleneck during transition horizon with a mixed fleet of CAVs and HDVs considering departure time choices of commuters. This is the first study that analyzes the CAVL departure time choices for managing morning commute congestion during the transition horizon. In this context, the linear complementarity problem is developed to determine the equilibrium departure rates of commuters under the CAVL and tolling schemes. The solution's existence, in terms of departure rates, is proven. For example, computational experiments show that CAV technological advancement, which leads to further increased CAVL capacity, can significantly improve mobility with an almost similar effect as a tolling scheme. Further, this report mathematically investigates the lane and departure time choices of CAV commuters and their impacts on their travel costs and travel times for CAVLs and GPLs. It is shown that the CAVL queuing delay is less than or equal to the one for GPL in any time interval. Further, CAV commuters use GPLs in any time interval only if they use CAVLs in that time interval. This implies that the equilibrium cost of CAV commuters is always less than that of HDV commuters. This has social inequity implications in practice as CAVs are mostly afforded by high-income commuters, particularly during the early years of the CAV transition period. Next, the system-optimal design model is developed as a linear problem to determine the optimal tolling scheme which can also be used to identify the optimal number of lanes. Overall, the optimal scheme is associated with the minimum travel cost during the morning peak period.

Second, the report investigates the design of CAVLs from the aspect of environmental sustainability. Unlike most past similar studies, this study considers uncertainty in the potential CAV market size over several years. This report explores the interaction between the impacts of uncertainty on the CAV-dedicated lane deployment design at different CAV market penetrations. The next contribution is that the report captures the fact that CAVs require a smaller lane width compared to HDVs, and therefore, for wide existing corridors, there exist opportunities to increase the number of road lanes within the overall roadway cross-section. The fourth contribution is the consideration of CAVL deployment specifically to address vehicle emissions. The study demonstrates that CAVL deployment can motivate travelers to purchase CAVs (which are assumed to be electric), consequently leading to reduced vehicle emissions in the network.

Finally, this report develops a bi-level framework for socially sustainable management of CAV-dedicated lane deployment. This report integrates the deployment of CAV links with TCS to enable the urban road agency to realize the network benefits of congestion reduction and social equity. The framework, termed Travel demand and Lane Management in the CAV transition period (TLMCAV), helps prescribe the optimal amount of credit to be allocated and the travel fee, given the specified CAVL links (locations) on the road network. The results demonstrate the extent to which HDV users could suffer increases in travel cost if equity is not considered in the model. The results also show how the road agency could use TLMCAV to keep HDV travel costs to acceptable levels, particularly during early periods of the CAV transition period. Further, the report shows how TLMCAV could be designed to gradually diminish inequity effects so that travelers, in the long term, travelers are motivated to shift patronage to CAVs.

9.3 Study limitations and future research directions

This research can be expanded in several directions. First, the present study assumes that at general purpose lanes where both HDVs and CAVs use the lane, the GPL capacity is independent of the proportion of HDVs and CAVs in traffic flow. However, the CAV share increase in traffic flow on GP lanes could lead to a higher lane capacity. There are studies (e.g., Liu and Song, 2019) that model the lane capacity as a function of the CAV share in traffic flow. Liu and Song (2019) also showed that this could enhance the mobility benefits of CAVs even on GPLs. This could delay the CAVL deployment start year to times of higher CAV market shares compared to the values found in the numerical experiments. This realization and adjustment could be incorporated into the frameworks developed in this study to enhance the practicality of the findings of this study. This report considers only the allocation of existing lanes to CAVs. However, the effect of the addition of new lanes could be considered in future work.

The second limitation of this research is the lack of consideration of induced travel demand due to increased mobility. In this report, the total travel demand is set to be constant and not as a function of travel time. However, the introduction of CAVLs into the system could result in increased travel demand (due to the effect of induced demand) that increases the nonlinearity of the mathematical programs formulated in this study. In future work, the frameworks developed in this study could be extended to capture any induced demand, and the solution algorithms will need modification to address the resulting complexity that will arise due to the expanded formulations.

The third limitation of this study is that it considers the different elements of sustainability disparately (that is, in different chapters). It will be interesting and probably useful to develop a comprehensive framework that addresses simultaneously all possible impacts of the proposed strategies, related to different pillars of sustainability (social, environmental, and economic) through a multi-objective framework and to measure the tradeoffs associated with the pillars.

The fourth limitation pertains to the development of the CAV-dedicated lane design within the planning framework. The developed framework does not account for some practical factors and operational conditions, such as traffic dynamics, instabilities, and densities in the lane-management context. This could be addressed using micro-simulation and cab simulation in the CAV context (Ghiasi et al., 2017, 2020; L. Liu et al., 2021; S. Liu et al., 2021; Yang et al., 2021).

Chapter 5 assumes that CAV and HDV have identical desired arrival times, and early and late arrival penalties. However, in reality, commuters are heterogeneous in terms of their desired arrival times and their early and late arrival penalties. Therefore, the developed framework could be extended to capture such commuter heterogeneity. Second, this chapter proposes a tolling scheme as a synergistic travel demand management strategy for CAVL. To further reduce social inequity, a tradable credit scheme can be used as an alternative to tolling. Under a tradable credit scheme, the road agency could allocate more credits to HDV commuters to compensate for their increased travel costs. Third, CAV and HDV travel demand levels are assumed to be deterministic in this chapter. However, there is significant uncertainty in their travel demand levels because it is rather difficult to forecast CAV penetration. A robust design is needed to decrease the impact of uncertainty on the efficacy and efficiency of the developed lane management strategies.

Chapter 6 can be extended in several directions. First, this research assumes uncertainty in the forecast of only the potential CAV market size over the planning horizon. However, given the long-term nature of the planning horizon, there could be uncertainty in the forecast of aggregate travel demand for CAVs and HDVs, due to changes in economic and demographic conditions over time. Future studies could develop robust optimization models that account for uncertainty in aggregate travel demand. Also, the present study assumes that travelers have an identical value of time in their route choice. However, in practice, travelers have different values of time, and HDVs and CAVs have different values of time. Therefore, future studies could formulate the lower-level model as multi-class equilibrium conditions that capture the different values of time of travelers.

Chapter 7 can be extended in several directions. First, CAVs can potentially provide several benefits to the road network, including safety and emissions. This chapter focused only on minimizing the total travel time to mitigate traffic congestion. In future research, the problem could be formulated as a multi-objective problem where the decision factors include total system travel time, traffic crashes, and vehicle emissions. Second, this chapter considers discrete sets of travelers in terms of their value of travel time. In reality, travelers possess different values of time that could be captured in future work using the continuous probability distributions. Third, this chapter assumes that the road agency has perfect information about future travel demand. In reality, however, forecasts of travel demand, particularly in the long term, are characterized by significant uncertainty and could be addressed in future work through robust TLMCAV design. Finally, this chapter carries out the optimal design of TLMCAV on the premise that the prospective CAVL locations are known. In this respect, it would be insightful to investigate the simultaneous design of CAVL locations based on candidate sets of locations, coupled with TLMCAV. Doing this could further increase the reliability of the final solution.

CHAPTER 10 SYNOPSIS OF PERFORMANCE INDICATORS

10.1 USDOT performance indicators I

During the 1-year study period for this project, three (2) transportation-related courses were offered that were taught by the PIs. One of the courses had a teaching assistant who is also associated with this research project. Three graduate students and a post-doctoral researcher participated in the research project during the study period. During the study period, one (1) transportation-related advanced degree (doctoral) program and one (1) transportation-related M.S. program utilized the CCAT grant funds from this research project to support the three graduate students in those programs. The fourth graduate student was a self-funded M.S. student who worked on this project for one year. The Ph.D. student graduated in August 2022, and the two MS students are set to graduate in May 2023. The self-funded M.S. student will graduate in August 2023. The Ph.D. student was selected by Frontiers Journal as a coordinator of the Rising Stars in Connected Mobility and Automation (2022) program and is currently an NSF post-doctoral fellow at University of Buffalo, New York. The post-doctoral researcher was appointed as a faculty member at the Illinois Institute of Technology in Chicago.

10.2 USDOT performance indicators II

Research Performance Indicators:
So far, two (2) journal articles and five (5) conference presentations have been produced from this project. The research from this advanced research project was disseminated to 725 people in attendance (from industry, government, and academia) through 5 conference presentations, including 1 poster session. These include the Transportation Research Board's 101st and 102nd Annual Meetings held in Washington, D.C. in 2022 and 2023 respectively. At the time of writing, the researchers are still working on developing a specific product (new technologies), procedures/policies, and standards/design practices based on the results of this research project.

Leadership Development Performance Indicators:
This research project generated 3 academic engagements and 2 industry engagements. The PIs held positions in 2 national organizations that address issues related to this research project. One of the CCAT students who worked on this project holds a membership position in an ASCE committee related to the subject of this study.

Education and Workforce Development Performance Indicators:
The methods, data, and/or results from this study are being incorporated into the syllabus for the Fall 2022, Spring 2023, and Fall 2023 versions of the following courses at Purdue University: (a) CE 561: Transportation Systems Evaluation, a mandatory graduate level course at Purdue's transportation engineering graduate programs (average 10 students at each course offering), (b) CE 299: Smart Mobility, an optional undergraduate level course at Purdue' civil engineering B.S. program, (average 12 students), and (c) CE 398: Introduction to Civil Engineering Systems, a mandatory undergraduate level course at Purdue University's civil engineering program, (average 85 students at each course offering). These students will soon be entering the workforce. Thereby,

the research helped enlarge the pool of people trained to develop knowledge and utilize at least a part of the technologies developed in this research, and to put them to use when they enter the workforce. Based partly on his contributions in this study, the post-doctoral researcher on this project earned a tenure-track faculty position at the Illinois Institute of Technology.

Collaboration Performance Indicators:
There was collaboration with other agencies, and one (1) agency and at least four (4) institutions provided matching funds.

The outputs, outcomes, and impacts are described in Chapter 11.

CHAPTER 11. STUDY OUTCOMES AND OUTPUTS

11.1 Outputs

11.1.1 Publications, conference papers, or presentations

(a) Journal Papers

- Seilabi, S.E., Pourgholamali, M., Correia, G.H., Labi, S. (2022). Robust design of CAV-dedicated lanes considering CAV demand uncertainty and lane reallocation policy, Transportation Research Part D: Transport & the Environment.
  DOI: https://doi.org/10.1016/j.trd.2023.103827
- Pourgholamali, M., Miralinaghi, M., Ha, P.Y., Seilabi, S.E., Labi, S. (2023). Sustainable Deployment of Autonomous Vehicles Dedicated Lanes in Urban Traffic Networks, Sustainable Cities and Society, 104969.
  DOI: https://doi.org/10.1016/j.scs.2023.104969

(b) Conference Presentations

Pourgholamali, M., Miralinaghi, M., Ha, P., Seilabi, S.E., and Labi, S. (2022). "Sustainability considerations in deploying exclusive highway lanes for autonomous vehicles", *Transportation Research Board 101st Annual Meeting*, Washington, D.C.

Seilabi, S.E., Pourgholamali, M., Miralinaghi, M., Correia, G., and Labi, S. (2022). "Robust design of CAV-dedicated lanes considering CAV demand uncertainty and lane reallocation policy", *Transportation Research Board 101st Annual Meeting*, Washington, D.C.

Seilabi, S.E. (2022). "Managing travel demand and lane use and other aspects of sustainable CAV era road planning," Presented at the Doctoral Student Workshop, *Transportation Research Board 102nd Annual Meeting*, Washington, D.C.

Seilabi, S.E. (2022). "Robust design of CAV-dedicated lanes considering CAV demand uncertainty and lane reallocation policy," presented at the 4th International Symposium on Infrastructure Asset Management (SIAM4), Northwestern University, Evanston, IL.

Seilabi, S.E., Pourgholamali, M., Correia, G., He, X., Miralinaghi, M., and Labi, S. (2023). "Managing dedicated lanes for connected and autonomous vehicles to address bottleneck congestion considering morning peak commuter departure choices," Presented at the *Transportation Research Board 102nd Annual Meeting*, Washington, D.C.

11.1.2. Other outputs

This report addresses the issues associated with lane management in the era where the market shares of CAVs will be high enough to warrant the deployment of CAV dedicated lanes. The outputs of the study are largely decision support framework that can be used by highway agencies for making decisions regarding the deployment of dedicated lanes for CAVs. Some of these involve traffic flow at the corridor level, and others address traffic flow at the network level Specifically, the new methodologies, technologies and techniques developed in the study are:

- A framework that can be used by highway agencies to make decisions regarding the deployment of dedicated lanes for connected and autonomous vehicles along a **road corridor** with bottleneck traffic conditions, considering the impacts on traffic congestion during the morning peak period of commuter travel.
- A decision-support framework for urban road agencies to make “where and when” decisions regarding the deployment of dedicated lanes for connected and autonomous vehicles in an urban **road network**, considering environmental sustainability. The decisions involve where (which highway link in the corridor) and when (which year) to deploy a dedicated CAV link (lane) considering uncertainties in the forecast of potential CAV market share.
- A framework that can be used by agencies to develop a travel marketplace (managed by the urban road agency) where travelers can buy or sell travel credits, as part of initiatives by the agency to reduce travel demand and congestion in the **road network**. This scheme will be facilitated by the connectivity features of the CAVs and can be modified easily to account for the equity consequences of the tradable credit scheme.

Other products of this research are as follows:

- Frameworks, models, and data to be used in CAV-related instruction, in the Fall 2022, Spring 2023, and Fall 2023 versions of the following courses at Purdue University:
    - CE 561 (Transportation Systems Evaluation), a mandatory graduate level course at Purdue’s transportation engineering M.S. and Ph.D. programs,
    - CE 299 (Smart Mobility), an optional undergraduate level course at Purdue’ civil engineering B.S. program, and
    - CE 398 (Introduction to Civil Engineering Systems), a mandatory undergraduate level course at Purdue University’s civil engineering program
    - CE 597 (Next-generation Transportation), a Purdue graduate course that will be offered in Fall 2024, and annually thereafter.
- Research material and datasets to support future research related to the sustainable (economic, environmental, social) deployment of not only CAV dedicated lanes but also any new technology in transportation.

11.2 Outcomes

This project produced outcomes that could influence road transportation system design or operational policies. These are:

- Increased understanding and awareness of the impacts of growing demand of CAVs on the infrastructure to support these and other next-generation transportation technologies.
- Consideration of the frameworks developed in this study for their long-term infrastructure needs and planning functions.

- More reliable and robust long-term infrastructure planning (by urban road agencies) that accounts for vicissitudes on the highway transportation terrain including the emergence of advanced technologies including vehicle automation and connectivity.
- Enhanced overall infrastructure adequacy and road-users' travel efficiency at large urban networks in the prospective era of CAVs.

11.3 List of impacts

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

- Enhanced equity among road users. The decision-support framework is designed to be flexible in that it accounts for the extents of equity that the decision maker wishes to achieve in the operational policies of the CAV dedicated lane. The framework helps the decision maker (the road agency) assess the extent to which HDV users suffer an increase in travel cost if equity is not considered in the analysis.
- Reduced congestion in road corridors or a network. The decision support frameworks are geared primarily towards (as much as possible) reducing the travel time of the road users in the CAV dedicated lanes as well as those in the general-purpose lanes.
- Reduced adverse impacts on the environment. One of the three developed framework explicitly accounts for environmental impacts by considering roadway emissions in its objective function.
- Improved efficiency of transportation facility uses, and reduced demand for travel. The tradable credit scheme incorporated in the third framework helps to reduce travel demand and traffic congestion by providing travelers the capability to trade (buy or sell) travel credits. As such, this encourages travel by those who really need to travel.
- It is anticipated that this research will provide strong justification for highway agencies to make investments towards preparations for the CAV era. The need for investment in the deployment not only of CAV-only lanes but also other ITS infrastructure in road corridors, can be justified. We expect that the research will provide proof that such infrastructure investments can and will greatly benefit the entire society in terms of the social, economic, and environmental impacts of this new generation of vehicles.
- The three graduate students that worked on this project will enter the workforce in 2023 to help support the workforce that will implement new technologies such as those developed in this study.
- The project had some impact on education, as parts of the research outcomes were incorporated in two undergraduate and one graduate level courses at Purdue University. These students, who will soon be entering the workforce, benefitted from the outcomes of

this research through these academic platforms. This helps enlarge the pool of people trained to develop knowledge and utilize the technologies developed in this research, and to put them to use when they enter the workforce.

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APPENDIX

CCAT Project: Lane Management in the Era of CAV Deployment

Published Related Work

Seilabi, S.E., Pourgholamali, M., Correia, G.H., Labi, S. (2023). Robust design of CAV-dedicated lanes considering CAV demand uncertainty and lane reallocation policy, Transportation Research Part D: Transport & the Environment.
DOI: https://doi.org/10.1016/j.trd.2023.103827

Reduced headways in prospective connected and automated vehicle (CAV) traffic streams provide opportunities to address persistent urban traffic congestion and attendant environmental adversities. Previous researchers have alluded to the potential efficacy of the CAV-dedicated lane concept in this regard. During the CAV transition period, CAVs and human-driven vehicles (HDVs) will share the roadway space either directly as mixed traffic and/or via dedicated lanes. In preparation for CAV deployment, highway agencies need to develop long-term plans that schedule the deployment of CAV-dedicated lanes (CAVDL) at their road network links while accounting for inherent uncertainty in CAV demand. To help agencies do this, this paper presents a bi-level optimization model that captures CAV market size uncertainty. The upper level determines the links (and number of lanes) for CAVDL deployment such that emissions are minimized. The model accounts for the relatively smaller lane widths for CAVs compared to HDVs due to smaller lateral wander of CAV tire tracks across the pavement cross-section. Therefore, the model considers lane reallocation policies that account for the prospect of smaller width of CAV-dedicated lane, thereby increasing the total number of lanes at wide highway sections. At the lower level of the optimization model, equilibrium and demand diffusion models capture travelers' route and vehicle-type choices. The bi-level model is formulated as a min-max mathematical program with equilibrium conditions and solved using the cutting-plane scheme and active-set algorithm. To demonstrate applicability and replicability of the model, it is applied to a test network via a computational experiment, and it is shown that it is feasible to solve the problem, that is, design an optimal deployment schedule for CAV lanes. The analysis indicate that the robust plans have superior performance compared to the deterministic plan under pessimistic cases. On the other hand, the deterministic plan outperforms the robust plan under optimistic cases. Further, it is illustrated that lane reallocation policy implementation leads to total emissions costs being concentrated on the lower values under uncertainty of consumers' willingness.

Pourgholamali, M., Miralinaghi, M., Ha, P.Y., Seilabi, S., Labi, S. (2023). Sustainable Deployment of Autonomous Vehicles Dedicated Lanes in Urban Traffic Networks, Sustainable Cities and Society, 104969.

DOI: https://doi.org/10.1016/j.scs.2023.104969

Autonomous vehicles (AVs) show promise for increasing roadway safety and capacity. During the AV transition era, which will be characterized by a mixed fleet of AVs and human-driven vehicles (HDVs), it is expected that the allure of these prospective benefits will motivate road agencies to allocate AV-dedicated lanes. This paper proposes a sustainability-driven AV-dedicated lane and pricing policy (SALP) framework that addresses the three pillars of sustainable development—social, environmental, and economic. The framework is formulated as a bi-level problem where the upper-level model yields decisions on the timing, location, and quantity of AV-dedicated lanes and tolling levels to minimize total travel time, emissions, and electricity consumption costs (that is, the economic and environmental pillars). To alleviate potential inequity (the social pillar), two considerations are proposed: revenue neutrality to compensate for the increase in travel costs of travelers and an equity constraint to limit the exacerbation of HDV travel costs. At the lower level, travelers react to the decisions made at the upper level by choosing their vehicle type (AV vs. HDV) and routes. The SALP is solved using Genetic and Frank-Wolfe algorithms. The results of the numerical experiments suggest that the proposed SALP addresses all three pillars, as it yields significant reductions in total travel time, emissions, and electricity costs.