VEHICLE AUTONOMY, CONNECTIVITY AND ELECTRIC PROPULSION: CONSEQUENCES ON HIGHWAY EXPENDITURES, REVENUES AND EQUITY

by

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A Thesis

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Master of Science in Civil Engineering

Lyles School of Civil Engineering

West Lafayette, Indiana

May 2022

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To Mr. I.K. and Mrs. L.C. Mbewe,

whose love and support I can never repay,

and whose patience and nurturing has brought me this far.

ACKNOWLEDGMENTS

My sincerest gratitude to my advisor and mentor, Professor Samuel Labi for his guidance and continued support throughout this process. Your wisdom and guidance have been instrumental to my academic success, intellectual growth, and professional development. I also express sincere gratitude my committee members: Olson Distinguished Professor Kumares C. Sinha – Purdue University Lyles School of Civil Engineering, Professor Konstantina Gritza – Purdue University Lyles School of Civil Engineering, Professor Stephen P. Mattingly – University of Texas at Arlington College of Engineering, and Professor Mansoureh Jeihani – Morgan State University School of Civil Engineering. Thank you for spending valuable time to serve on my committee and for the feedback and guidance that were invaluable for improving my work.

Special thanks to my family and friends for the encouragement and support rendered to me throughout my studies. I am grateful to have shared this journey with you all. I am also grateful to my colleagues and schoolmates for the support and feedback that have fostered the development of my academic skills.

Finally, my gratitude to the Center for Connected and Automated Transportation (CCAT) – USDOT Region 5 University Transportation Center (grant no.: 69A3551747105), the Joint Transportation Research Program (JTRP) for the financial support and enumerable resources throughout my studies. I also want to thank the Federal Highway Administration's University Grants and Awards Program (FHWA UG&A) for the award of the Dwight David Eisenhower Transportation Fellowship (DDETF).

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ALM	Axle Load Miles
ATR	Automated Traffic Recorder
AV	Autonomous Vehicle
CAV	Connected Autonomous Vehicle
CRP	Cost Responsibility Percentage
EV	Electric Vehicle
EAV	Electric Autonomous (Automated) Vehicle
ER	Equity Ratio
ESAL	Equivalent Single Axial Load
FHWA	Federal Highway Administration
GVW	Gross Vehicle Weight
HCA	Highway Cost Allocation
HCAS	Highway Cost Allocation Study
HPMS	Highway Pavement Monitoring System
HEV	Hybrid Electric Vehicle
NHS	National Highway System
MPG	Miles per Gallon
MPGE	Miles per Gallon Equivalence
OEM	Original Equipment Manufacturer
PCE	Passenger Car Equivalents
RCP	Revenue Contribution Percentage
V2V	Vehicle to Vehicle
V2I	Vehicle to Infrastructure
V2X	Vehicle to Other (pedestrian, cloud, etc.) communication protocol
VMT	Vehicle Miles Traveled
WIM	Weigh in Motion

ABSTRACT

Asset managers continue to prepare physical infrastructure investments needed to accommodate the emerging technologies, namely vehicle connectivity, electrification, and automation. The provision of new infrastructure and modification of existing infrastructure is expected to incur a significant amount of capital investment. Secondly, with increasing EV and CAV operations, the revenues typically earned from vehicle registrations and fuel tax are expected to change due to changing demand for vehicle ownership and amount of travel, respectively. This research estimated (i) the changes in highway expenditures due to adoption of ECAVs, (ii) the net change in highway revenues that can be expected to arise from ECAV operations, and (iii) the changes in user equity across the highway user groups (vehicle classes). In assessing the changes in highway expenditures, the research developed a model to predict the cost of highway infrastructure stewardship based on current and/ or future system usage.

The results of the research reveal that CAVs are expected to significantly change the travel patterns, leading to increased system usage which in turn results in increased wear and tear on highway infrastructure. This, with the need for new infrastructure to support and accommodate the new technologies is expected to result in increased highway expenditure. At the same time, CAVs are expected to have significantly improved fuel economy as compared to their human driven counterparts, leading to a decrease in fuel consumption per vehicle, resulting in reduced fuel revenues. Furthermore, the prominence of EVs is expected to exacerbate this problem. This thesis proposed a revision to the current user fee structure to address these impacts. This revision contains two major parts designed to address the system efficiency and equity in the near and long term. For the near term, this thesis recommended a variable tax scheme under which each vehicle class pays a different fuel tax rate. This ensures that both equity and system efficiency are improved during the transition to ECAV. In the long term, this thesis recommended supplementing the fuel tax with a distance based VMT tax, applicable to electric vehicles.

1. INTRODUCTION

1.1 Overview

Most basic driving functions currently are either partially automated or greatly enhanced (Blanco, 2020). Many vehicles being sold today come with advanced driver assistance systems including adaptive cruise control, lane-keeping assist (NHTSA, 2020). Several vehicle manufacturers including Tesla, Audi, BMW, and Mercedes Benz are developing or have announced plans to develop autonomous vehicles in the next few years (Madrigal, 2017). As vehicles and driving systems become more sophisticated, it is no longer a question of if but when completely connected and autonomous vehicles will soon become a reality.

Connected and autonomous vehicles (CAVs) are expected to bring about several key benefits to the transportation sector, the most important of which include improved safety, improved fuel efficiency and reduced congestion (Labi et al., 2015; Litman, 2017). For roadway accidents and motor crashes, over 90% of them can be attributed to human factors and errors (Chen et al., 2020; NHTSA, 2008). With the driver removed from the cockpit, AVs will not be prone to the same mistakes as humans and thus likely to have few crashes overall. This will lead to enormous safety benefits and savings, because traffic vehicle crashes are the leading cause of death from people younger than 45 years.

However, critics have argued that AVs may introduce problems of their own which may cause them to have more crashes than we expect, albeit less than, perhaps even close to that of human driven vehicles (Brooks, 2017a, 2017b; Litman, 2017). Some point to the difficulty in proving the safety of autonomous vehicles, given that the algorithms they operate on are harder to test because they rely on non-deterministic statistical techniques (Marshall, 2018). Furthermore, only test tracks and driving simulators, not real roads, are available for testing (Chen et al., 2020). In the short term, the-less-than perfect sensor technology in autonomous vehicles only allows them to operate in fairly standard or controlled environments and fail to handle more extreme situations (Wolmar, 2018). CAVs rely on sensors and connectivity for their operation, therefore, any malfunction of the sensor or connectivity channel may lead to the system disengaging or even worse, a crash. This makes CAVs unable to operate in suboptimal conditions such as in extreme weather or poorly marked or unpaved roads, or in areas where connectivity is unavailable or poor

(Litman, 2017). This is evidenced even more by the metrics currently used to evaluate AV performance, the most common of which measures the number of disengagements per distance driven (Saeed et al., 2021). In some states such as California, AV manufacturers are required to file an accident report for each crash incident that involves an AV, no matter how minor (Marshall, 2018). Even if the sensor technology improves significantly enough to enable AVs to perform in extreme weather conditions, some still consider AVs as pariahs because they are apprehensive of the long-term downsides that AVs and the algorithms that power them may never become '*smart*' enough to understand and adequately replicate human social interactions and the unspoken cues of the road. (Brooks, 2017a, 2017b). Yet still, even the most ardent critics agree that it is not a matter of if, but when AVs will dominate our streets.

Given the growing interest in electric, connected, and automated vehicles, it is imperative that all stakeholders understand the benefits and disbenefits that these technologies will bring to individual livelihoods as well as the profitability of businesses. For the trucking business for example, CAVs may mean reduced operating costs as the need for personnel will be reduced due the automation. Also, for conventional trucks, fuel costs account for a majority of the operating costs (Davis & Figliozzi, 2013). With the benefits of connectivity-enabled platooning however, trucks will be able to reduce the overall aerodynamic drag and save fuel (Abbott et al., 2017). These benefits, combined with potentially reduced vehicle maintenance costs due to improved driving dynamics (including smooth acceleration and braking) that is expected of CAVs (Litman, 2017), companies operating CAVs as part of their fleet can expect to see significant savings. Additionally, because CAVs can operate longer hours, since they do not require scheduled breaks as humans do (Min, 2009; Schubert, 2019), companies can speed up their delivery times.

For most users and many businesses, ECAVs will yield several key benefits and will greatly enhance the road user experience. For planners and transportation agencies however, there is another dimension to the debate that may not be obvious but is also important. ECAVs are likely to cause a paradigm shift in travel patterns and behaviors. From facilitating shared mobility to enhancing equity in mobility (by allowing population segments that are currently unable to or unlicensed to 'drive'), ECAVs will alter the transportation landscape. This is particularly important when viewed from a perspective of highway finance (expenditures and revenues). As discussed in subsequent chapters, highway revenues are derived mostly from user fees and fuel taxes. Fuel taxes are directly tied to travel patterns and total VMT. Similarly, highway expenditures on maintenance and rehabilitation are tied to overall highway use and travel patterns. Thus, changes in travel patterns are likely to affect highway revenues and expenditures. The anticipated dynamics and feedback of the impacts of emerging vehicle technologies are summarized in Figure 1.1 below:

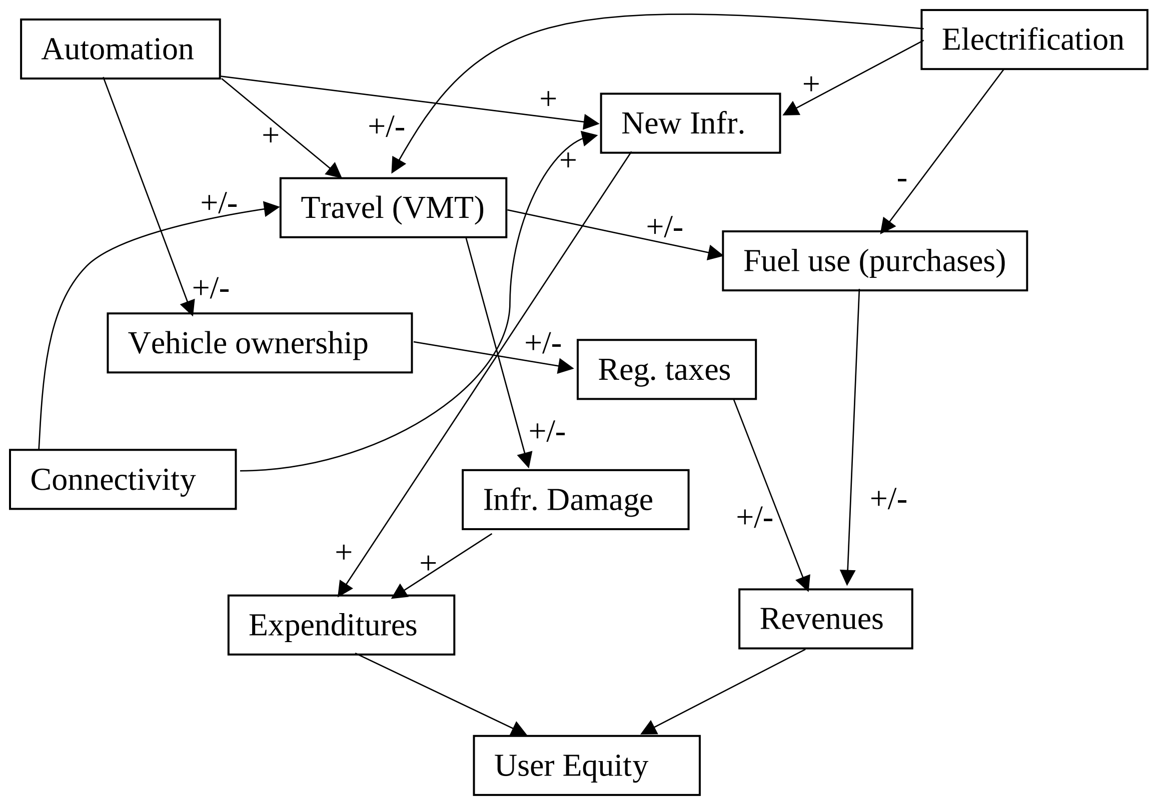


Figure 1.1: System dynamics overview and anticipated impact feedback

1.2 Highway Revenues and Expenditures

Over the past few decades, the total yearly vehicle miles of have increased steadily (FHWA, 2020), along with them, the need for increased expenditure on stewardship of highway assets to accommodate the increased demand. At the same time, new technologies (including forced induction and adaptive cruise control) and stringent regulations have allowed for even greater fuel efficiencies in vehicles (Matsushima & Khanna, 2021). This has resulted in a shortfall in revenues, which is primarily based on motor fuel taxes. As the current tax rate is fixed per gallon while fuel efficiencies continue to improve, this trend is expected to continue (Kile, 2021; Kirk & Mallet, 2020). Research has shown (see Figure 1.2) that the gap is expected to grow even further as alternative fuels become more pronounced and available. The introduction of ECAVs only serves to exacerbate this trend.

Figure 1.2: Annual Revenues, Outlays and Balance of the Highway Trust Fund in CBO's 2021 Baseline Projections (Kile, 2021)

1.3 Study Motivation, Objectives and Scope

1.3.1 Motivation and Problem Statement

Vehicle connectivity, automation, and electric propulsion are likely to become more prominent and this will exacerbate the current highway financing crisis. A study is therefore needed to investigate the changes in the cost responsibility and revenue contribution of highway users regarding the upkeep of the highway infrastructure in response to the emerging vehicle technologies. The costs include expenditures on construction, preservation, maintenance, and operation of the infrastructure and the asset types include pavements, bridges, and safety and mobility assets. Regarding revenues, this consists of user and non-user sources at federal, state, and local. The user sources include fuel tax, motor carrier fuel use tax, driver license fees, motor carrier surcharge tax, vehicle registration fees, taxes on truck and trailer sales, tires, and heavy vehicle use, wheel taxes, and county motor vehicle excise surtaxes. The impacts of electrification, connectivity and automation on highway expenditures and revenues need to be analyzed and documented.

1.3.2 Objectives

The main objectives of this thesis are to estimate, in the era of ECAV operations, the anticipated changes in (i) highway expenditures, (ii) highway revenues, and (iii) user equity. To ensure that the impacts are properly addressed, the users are categorized into highway user groups (vehicle classes), and their contributions to the revenues and expenditures assessed accordingly. While highway users are typically represented by the thirteen Federal Highway Administration (FHWA) vehicle classes (Figure 2.2), portions of this thesis also consider three categories highway users, namely: passenger cars, light duty trucks and heavy-duty trucks.

1.3.3 Study Scope

The study analyzes the impacts of highway expenditures, revenues, and user equity in the era of emerging vehicle technologies. The study duly recognizes the dichotomy between attributable and common costs. This is important because some costs on the highway system are load or size dependent whereas others are not. For example, costs associated with highway safety elements, such as guardrails, signage, and right of way are load independent and must thus be evenly distributed to all highway users based on their VMT contributions. These are referred to as common costs because they are all common to all vehicle classes and only depend on the respective VMT. Other costs however, such as those related to the structural integrity of the pavements and bridges depend on the vehicle weights. Different vehicle weights impose different moments and reactions in the structural elements and consequently different stresses. As a result, the wear-and-tear is different for different loads as heavier vehicles generally cause greater damage. Similarly, bridge widths, vertical and horizontal clearances need to be larger to accommodate larger vehicles. The costs associated with these are therefore high than those of small passenger cars. These costs are attributed to each class based on their weights (and size) and are appropriately referred to as attributable costs. Therefore, for allocating the attributable costs to the vehicle classes, Equivalent Single Axial Loads (ESALs), AASHTO load equivalency factors, and Passenger Car Equivalents (PCEs) are used; for allocating common costs, VMT is used.

Highway cost models used to estimate highway expenditures are developed using highway statistics data for all 50 states published by the FHWA. Assessments of highway expenditures and revenues are carried out only for the state of Indiana for purposes of illustration. The data is adapted from Volovski et al., (2015) which includes information on system usage (VMT, ESAL-miles, PCE-miles, etc.), highway expenditures (pavement, bridges, safety, and mobility, etc.) and highway revenues (fuel, registration tax, taxes on wheels and trailers, usage fees and surcharge taxes, etc.) as detailed in the Section 3.3 of this thesis. The analysis for expenditure and revenue assessments are repeated for each of the several levels of ECAV implementation. This is because a number of researchers have argued that the design of highway infrastructure at any given time to adequately accommodate the new technologies, will be a function of the prevailing levels of vehicle autonomy and market penetration, and the fractional distribution of vehicles across the autonomy spectrum (Labi et al., 2015). The autonomy spectrum ranges from Level 0 (the current practice, where the driver completely controls the vehicle at all times) to Level 5 (where the vehicle performs all safety-critical functions for the entire trip including parking and the driver is not expected to control the vehicle at any time (NHTSA, 2013; SAE, 2018). A summary of the scope and framework used in this thesis is illustrated in Figure 1.3 below:

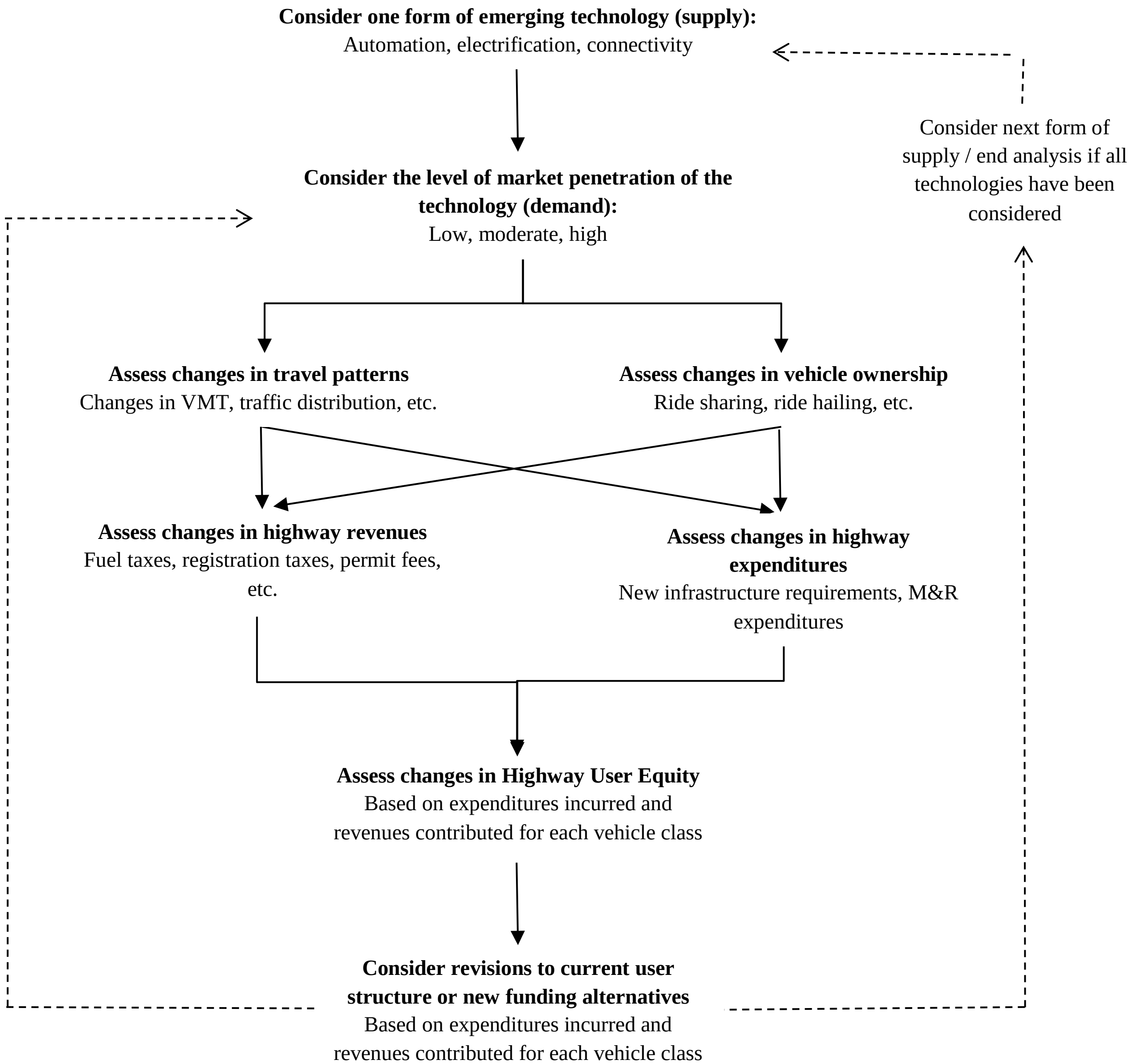


Figure 1.3: Study scope and framework

1.3.4 Assumptions

Analyses of highway revenues and expenditures presented in this thesis rely on some assumptions and simplified frameworks. These include projections of demand and supply of each of the vehicle technologies, the level of synergistic interactions among them, the rate of growth of VMT and system usage, etc. These assumptions are discussed in specific detail in each of the relevant sections and are summarized here.

a) VMT and System Usage

Changes in VMT and travel patterns because of the wide adoption of ECAVs underpin the analysis of the expected changes in highway expenditures and revenues. As these technologies gain sufficient market penetration, it is expected that they will result in changes in travel patterns that may ultimately result in increased overall travel. These patterns may range from shared mobility spurred by vehicle automation to induced travel demand resulting from increased roadway capacities (see Sections 3.5 and 3.6 of this thesis). As the VMT changes, thesis assumes that the overall composition of the traffic stream does not change significantly over the period of analysis. The percentage of vehicles of each highway vehicle class in the stream remains fairly the same over the period of analysis. The percentages used in this thesis represent the average of traffic stream data from 1994 through 2019, based on FHWA highway statistics data (FHWA, 2020).

b) Highway Expenditures and Revenues

The estimates of highway expenditures and revenues presented in this thesis are determined using regression models as detailed in Section 3.2. These estimates are underpinned by an assumption that highway system usage is the primary driver of highway expenditures. Therefore, highway expenditures increase (or decrease) according to the amount of system usage. Because most expenditures on highway systems are for construction works and major repairs, increased system usage necessitates more frequent repairs due to increased wear and tear, and results in the need for construction of new facilities to ease congestion. Furthermore, auxiliary expenditures related to highway systems such as enforcement and management, safety treatments, and research and development can also be assumed to increase with system usage.

Highway revenues are categorized as either fuel or non-fuel revenues (see Section 3.7). Fuel revenues depend on fuel tax rates, vehicle fleet fuel efficiency and amount of fuel consumed. The amount of fuel consumed depends directly on the system (or fleet) VMT. Therefore, for a given fuel efficiency, the amount of revenues generated from fuel use depends directly on the system usage. Therefore, the assumptions employed in determined system usage carry over to revenue estimation. Non-fuel revenues encompass revenues such as vehicle registration fees, heavy vehicle permit fees, motor carries surcharge fees, etc. (see Sections 2.4 and 3.7 of this thesis). The analyses presented in this thesis assume that non-fuel revenues scale linearly with system usage. For example, it can be assumed that revenues from vehicle registration fees double if the number of vehicles double. It is also assumed that the rates and taxes levied stay constant during the period of analysis. Furthermore, the models used to estimate the changes in revenues are calibrated with revenues for the years 2009 through 2012 for the state of Indiana as presented in Volovski et al. (2015). The revenue estimates are presented in 2012 dollars and are not adjusted for inflation.

c) Demand Projection and Market Penetration Rates for ECAVs

Demand projections and rates of market penetration are discussed in detail in Section 3.4 of this thesis. This thesis assumes that the market penetration rates grow following a sigmoid curve (Figure 3.3), slow adoption at introduction due to limited market exposure. Following a critical takeoff point, the market penetration rate accelerates to reach its maximum, following which it slows down as the market reaches saturation. In the analyses presented in this thesis, each emerging vehicle technology (or a combination thereof) is given a market penetration timeline based on demand projections by industry experts and various researchers (see Section 3.4). For example, vehicle electrification can be assumed to have a market takeoff of late 2020s to early 2030s, and follow the sigmoid adoption curve, reaching peak sales around a decade later, and nearing market saturation around the mid-2050s to early 2060s.

1.4 Organization of this thesis

The remainder of this thesis is organized as follows: Chapter 2 presents a review of literature. This covers literature of EVs and CAVs and their prospective impacts on highway expenditures, revenues, and the resulting equity as well as an overview of highway cost allocation studies. Chapter 0 presents the study methodology, including the assumptions employed as well as a description of the data used in the study. The results of this analysis are presented in Chapter 4 with a discussion of the results presented in Chapter 5. The thesis concludes with conclusions and recommendations for future studies in Chapter 6.

2. LITERATURE REVIEW

2.1 Introduction

An assessment of the impacts of CAV adoption on highway expenditures and revenues must be preceded by examining the procedures that scholars and transportation agencies have used to attribute these expenditures and revenues. This includes a review of literature on CAV impact analysis, with respect to the cost and revenues associated with highways. The information also includes demand projections associated with various rates of CAV market penetration. Literature on highway costs allocation methods is reviewed and documented. Sources searched for published material on the subject include journal publications, conference publications, agency reports, and reports from management consultants and technology companies.

2.2 EV and CAV Impacts

Emerging vehicle technologies, particularly, automation, connectivity and electrification are poised to result in numerous impacts which include comfort, convenience, safety, reliability, and security, among others (Du et al., 2020; FHWA, 2017; Labi et al., 2015; Li, Chen, Dong, et al., 2020; Saeed et al., 2020; Talebpour & Mahmassani, 2015). These emerging vehicle technologies hold the promise of making transportation more equitable and accessible to sections of the population that may not be well served by the current paradigm. As such, various stakeholders are investing resources to develop and make the technology safer, more affordable, and accessible to the public. It is anticipated that with increased vehicle automation, individuals who are currently unable to drive (disabled, elderly, children) will be able to use AVs and therefore will become more mobile. Another area that is often discussed as part of vehicle automation is the rise of vehicle-sharing services and the accompanying downward trends in vehicle ownership. Research has shown that AVs will pave way for ride-sharing services (Fagnant & Kockelman, 2018; Fagnant & Kockelman, 2015c), which may lead to further decline in vehicle ownership. However, as Saeed et al., (2020) point out, a majority of people would still prefer to use their own vehicles as opposed to a shared service. In fact, the Saeed et al. study results indicated that given a choice between using a privately-owned traditional vehicle, a privately owned AV and a shared or hired AV, only 2% to 10% of respondents chose the latter while approximately 33% chose the former (Saeed et al., 2020). This suggests that the impacts of these technologies may exhibit greater variability than expected and must therefore be analyzed within the broader context with respect to competing alternatives, individual preferences, and prevailing levels of market penetration.

In parallel with the drive to develop automated vehicles, there is growing concern about the environmental impacts of transportation systems. Therefore, there is a growing push from the public and regulators to transition transportation systems to incorporate environmental sustainability to a greater extent (FHWA, 2014; Mead, 2021; USDOT, 2019). Electric propulsion has emerged as a strong contender among many alternatives, with many legacy and newer vehicle manufacturers alike committing to producing electric vehicles (Deloitte, 2020; McKinsey & Company, 2021). Beyond the obvious environmental benefits of being emissions free, electric vehicles yield other prospective benefits to both the individual owners and their communities. Research has shown that despite currently having a higher purchase cost, electric vehicles have lower operating costs (Sivak & Schoettle, 2018). Furthermore, given the current rate of improvement of battery technology, EVs are likely to be competitive with conventional vehicles on life cycle costs (Ayodele & Mustapa, 2020; Carlsson & Johansson-Stenman, 2003; Delucchi & Lipman, 2001; Lin et al., 2013). Some researchers have also postulated that electric vehicles could prove to be socially beneficial by sharing power with local grids, which could help stabilize electric grids when power demands are high (Kempton & Letendre, 1997).

Many of the outlined benefits of vehicle automation and electric propulsion will only be realized to a significant extent once the technology gains enough market penetration. For the technology to gain enough market penetration however, it must have the supporting infrastructure in place (Engel et al., 2018; Markel, 2010; Wood et al., 2017). For electrification, this entails an accessible network of charging stations, increased power generation capacity across the cities, and other smart supporting infrastructure. For automation, the supporting infrastructure may include cloud computing infrastructure, smart highway and intersection features (signs, lane markings, traffic lights, etc.). The provision of such supporting infrastructure is expected to incur significant expenditures by highway agencies. Additionally, transportation agencies may incur further costs in expanding highway facilities if these new technologies lead to increased travel activity. Furthermore, technologies such as electric propulsion have been determined to negatively impact highway fuel tax revenues (Kirk & Mallet, 2020). These and other impacts are explored in greater detail in subsequent chapters of this thesis.

2.3 Highway Cost Allocation

Several researchers and organizations have conducted studies to ascertain the costs of highway infrastructure upkeep. These highway cost allocation studies (HCAS) highlight methods for allocating infrastructure project costs among the users. This includes the cost of new infrastructure and expansion of existing infrastructure to keep up with growing traffic demand, the cost of maintenance and rehabilitation and other costs such as intelligent transportation systems and safety infrastructure including guard rails. The second part of highway cost allocation studies is highway revenue attribution. Highway revenues including fuel revenues, user fees, and other taxes are attributed to highway users commensurate with their level of contribution. This is often followed by an analysis of the user equity and system efficiency to determine areas of improvement including revisions to the user fee structure and exploring alternative sources of funding when necessary. Figure 2.1 illustrates the highway cost allocation process. This section of the thesis explores past research in each of these areas. Table 2.1 identifies recent studies that studied highway cost allocation, highway financing, and initiatives to address the highway financing crises. This section also reviews available literature on emerging vehicle technologies – connectivity, automation, and electrification – and their anticipated impacts on highway expenditures, revenues, and equity.

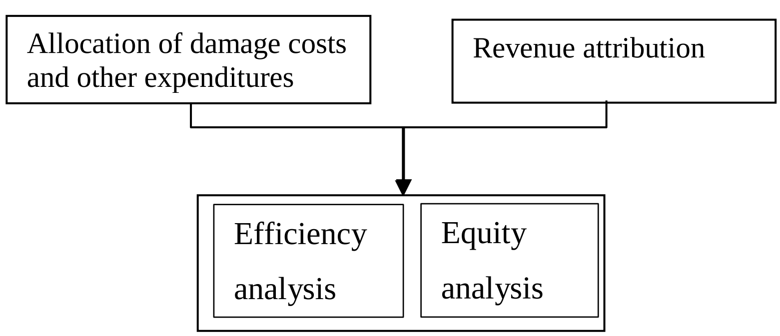


Figure 2.1: Highway cost allocation (HCA) process

Table 2.1: Notable recent studies that explored highway cost allocation and financing.

Study	Cost Allocation	Revenue Attribution	Novel Revenue Alternatives	Impacts of ECAVs
(Agbelie et al., 2016)	✓	✓	✓	✗
(Agbelie et al., 2012)	✗	✓	✓	✗
(Agbelie et al., 2010)	✗	✓	✓	✗
(Oh & Sinha, 2008)	✗	✓	✓	✗
(ECONorthwest, 2014)	✓	✓	✓	✗
(Gupta & Chen, 2012)	✓	✓	✓	✗
(Balducci et al., 2009)	✓	✓	✓	✗
(Kumar Dubey, 2017)	✓	✗	✗	✗

2.3.1 Pavement Cost Allocation

Pavement cost allocation estimates the cost responsibility of individual vehicle classes regarding construction, preservation, and maintenance of highway infrastructure. The estimated costs are attributed to highway users based on recent expenditure levels and patterns, and the highway users are represented by the 13 Federal Highway Administration (FHWA) vehicle classes (Figure 2.2). Previous HCAs involved various methods for estimating highway expenditures based on available information (Balducci & Stowers, 2008; Balducci et al., 2009; ODOT, 1980). This section briefly discusses a few of the common highway cost allocation methods.

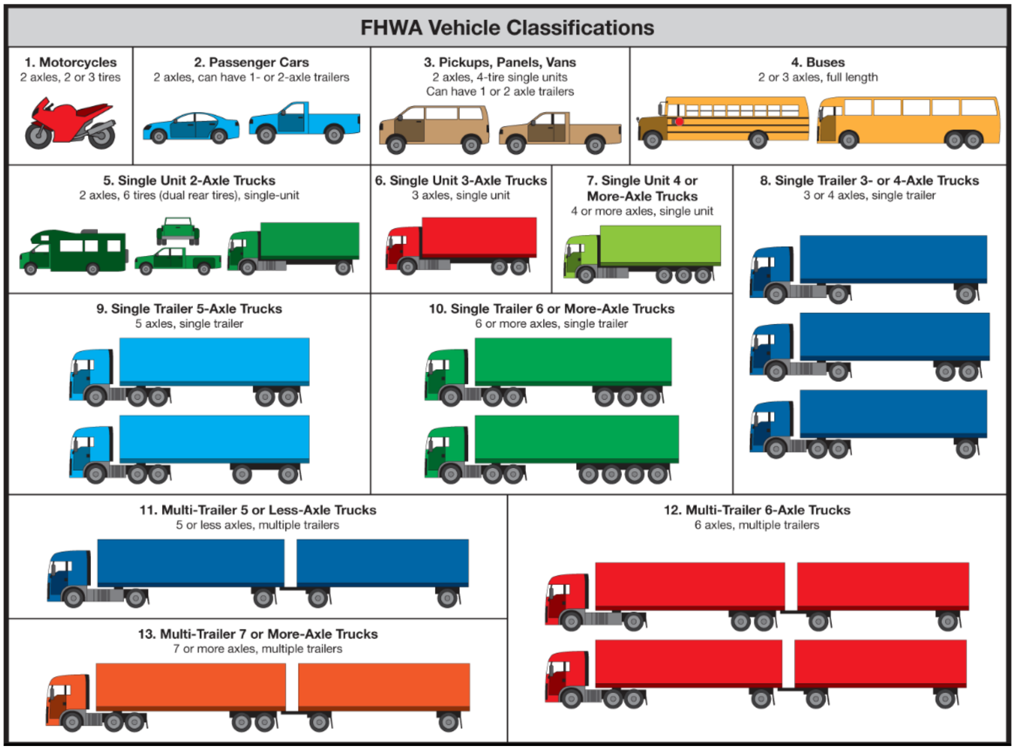


Figure 2.2: FHWA Vehicle classification (Randall, 2012).

In this discussion, it is important to review important and frequently used terminology, including measures of road usage. This is necessary because of the differences in the nature and causes of various expenditure items, such that a single cost estimator cannot be used for all expenditure items. To allow for equitable distribution of costs among vehicle groups, costs are apportioned to vehicle classes in proportion to their responsibility of these costs (Sinha et al., 1984). As such, the costs are defined in two parts: *common costs* and *attributable costs* (Agbelie et al., 2016). Common costs refer to those costs that are shared by all vehicles regardless of their size or weight, whose associated expenditures are due to factors such as weather, climate, and other factors other than the amount of travel. As such, these are attributed to the user groups based on their VMT contributions. Expenditure types under common costs include right-of-way acquisition, safety-and mobility-related treatments. Because some common costs may be related to highway capacity, other studies have proposed the use passenger car equivalent (PCE) miles to allocate common costs as opposed to VMT (Torbic et al., 1997; TRB, 2000). PCE refers to the impacts that a given vehicle class has on traffic compared to a single passenger car (TRB, 2000). Spending that is incurred as a direct result of vehicle weight and dimensional characteristics are referred to as attributable costs. For example, heavy vehicles (trucks) cause more damage compared to automobiles and therefore are responsible for a larger share of the load-related responsibility. To foster equity, these costs are attributed to the various vehicle classes based on their size, weight group, and axle configuration. Further, the load-related costs may be reported based on any of the following metrics (Balducci & Stowers, 2008; Volovski et al., 2015):

- Axle Miles of Travel (AMT): This is the product of VMT and the number of axles.
- Axle-Load-Miles: This is obtained by multiplying the gross load carried by an axle and the distance traveled.
- Ton-Miles: This is the product of the VMT and tonnage.
- ESAL-Miles: An ESAL-mile is defined as the product of a single axle load (ESAL) and the miles travel. One ESAL is the pavement damage caused by a single axle load at 18,000 lbs.

a. Traditional Incremental Approach

This is the simplest method for highway cost allocation. The approach assigns the responsibility for highway costs to each highway user group (vehicle class) by first determining the construction and maintenance cost of the facility to serve only the lightest vehicle class, and then increasing the structural and functional capacity of the facility in increments that meet the next heavier class, repeating this process until the needs of all the classes are met. The incremental method unduly assigns the benefit of scale economies to heavy vehicles, and thus has declined in popularity over the years (Agbelie et al., 2016). Additionally, it has been shown that since equations relating load and pavement thickness are non-linear, changing the order in which vehicles are incrementally added could produce different results (Fwa & Sinha, 1985b).

b. Thickness Incremental Approach for Allocating the Cost of New Construction

As a direct attempt to address the non-linearity issues that arose from the Traditional Incremental Approach, (Fwa & Sinha, 1985b) proposed an alternative to the traditional incremental approach, called the thickness incremental approach. Rather than considering increments of traffic loading (as is the case with the traditional incremental approach), this method considers increments of pavement thickness. Although similar in principle, this method directly incorporates the non-linearity of the thickness cost relationship. This allows it to correct for the bias associated with returns to scale. Consequently, this method is considered advantageous over the traditional incremental approach, as can be seen in Figure 2.3 (Agbelie et al., 2016). A summary description of the thickness incremental approach is presented in (Agbelie et al., 2016) and the full details are presented as part of the Indiana Highway Cost Allocation Study (HCAS) (Sinha et al., 1984) and (Fwa & Sinha, 1985b).

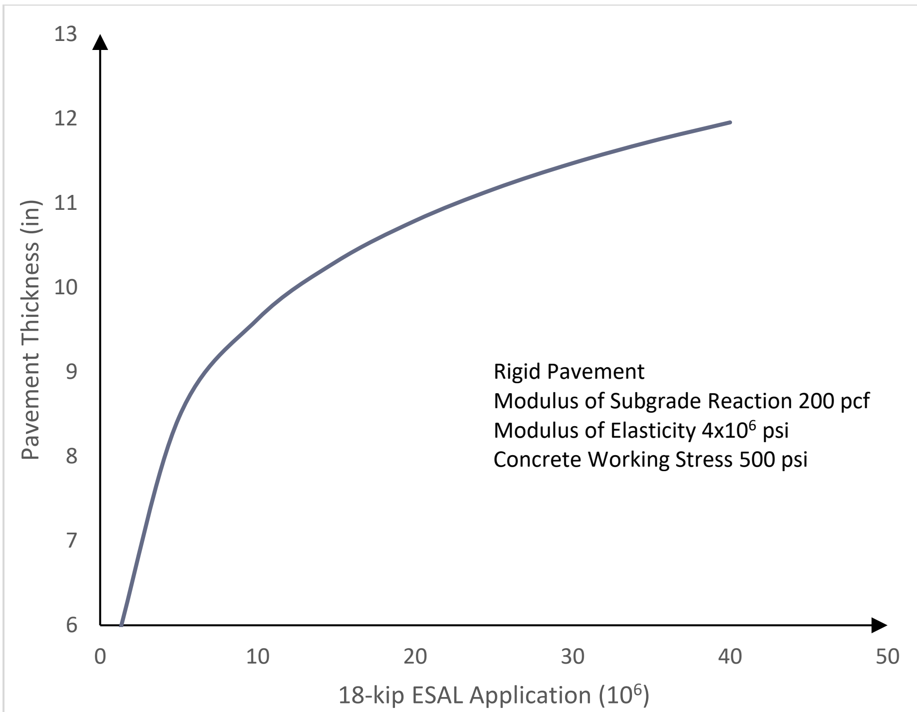


Figure 2.3: Relationship between load application (ESAL) and pavement thickness [adapted from (Fwa & Sinha, 1985b)]

c. Performance Based Approach for Allocating the Costs of Maintenance and Rehabilitation

The 1984 Indiana Highway Cost Allocation Study outlines an aggregate damage model that relates pavement performance to maintenance. This facilitates the allocation of rehabilitation and routine maintenance costs. The metric used is the Present Serviceability Index (PSI), which signifies the Equivalent Single Axle Load (ESAL) loss. This represents the cumulative pavement damage due to loading under different levels of maintenance, including zero-maintenance. The zero-maintenance performance curve is derived by considering actual pavement performance curves and their corresponding maintenance costs as illustrated (Figure 2.4). The zero-maintenance curve represents the total pavement damage caused by the combination of all load-related and non-load-related factors, assuming no maintenance was conducted on the pavement. The region bounded between the no-loss line represents pavement damage caused by load related factors. The no-loss line is an imaginary representation of a pavement kept in its initial state. The design equation curve represents the expected pavement damage based on design criteria (such as AASHTO design guidelines) and the cumulative damage is shown as areas A Figure 2.4. When load and non-load factors, and the interactions between them are considered, the resulting pavement damage is bounded by the field performance curve and represented by area Figure 2.4. The relative responsibilities of the load related and non-load related effects can be estimated using a proportionality assumption as detailed in (Agbelie et al., 2016) and (Fwa & Sinha, 1985b; Sinha et al., 1984). It is worth noting that on average, load related factors typically account for about 70% of the expenditures are attributed on the basis of ESALs while those related to non-load factors are allocated on the basis of VMT (Agbelie et al., 2016; Fwa & Sinha, 1985a).

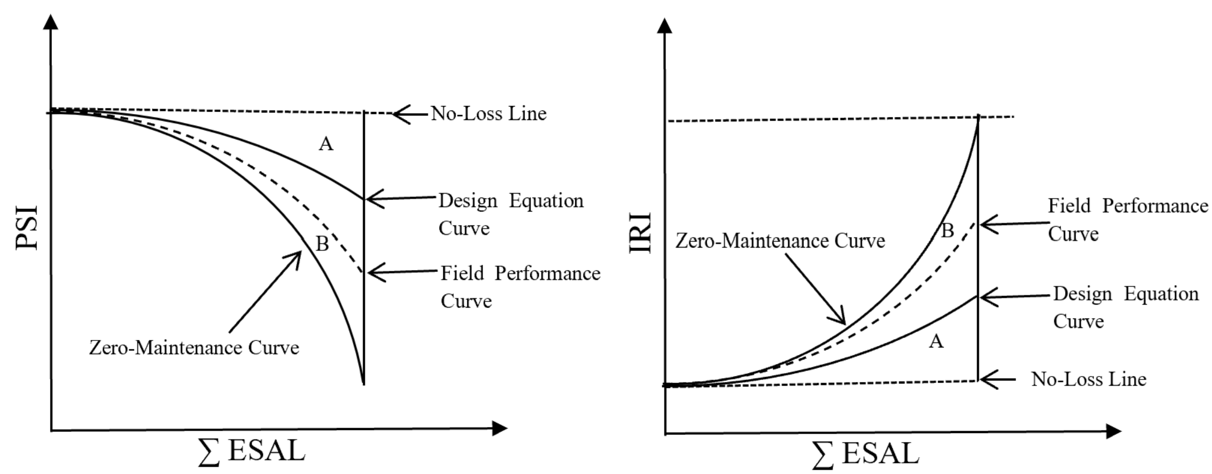


Figure 2.4: The zero-maintenance performance curve (Fwa & Sinha, 1985a)

2.3.2 Bridge Cost Allocation Methods

Bridges tend to make up a significant portion of highway expenditures as they typically account for approximately 16% of new highway systems expenditure and can make up as much as one third of total preservation costs (FHWA & FTA, 2019). Consequently, it is important in any highway cost allocation study to accurately assess and account for these costs. Similar to pavements, bridge costs and expenditures are allocated to highway users represented by FHWA’s vehicle classes. This is necessary because different vehicle classes have different weights and thus induce different loads and stresses on bridges. Heavier vehicles induce larger live loads and moments, resulting in larger stresses in the structural members required to support them (Agbelie et al., 2017). As a result, larger structural members are required to accommodate heavier vehicles, leading to an increase in construction and material costs. Furthermore, heavier vehicles tend to cause more wear and tear on the bridge components, leading to increased repair spending. It is therefore reasonable that each vehicle pays their appropriate share of the cost which should be proportional to the damage inflicted.

Unlike pavements, bridges possess characteristics that exhibit far greater variation, for example, the design requirements including span, type of super structure – suspension, cable stayed, arch, etc. – that determine the mechanism of load transfer. The damage caused to the bridge is associated with the load and the axle configuration of vehicles. Therefore, previous HCAS have tried to categorize vehicles according to their weight groups and axle configuration (Agbelie et al., 2016; Balducci & Stowers, 2008; FHWA, 1997; Sinha et al., 1984; Volovski et al., 2015). The Indiana HCAS of 1984 placed the vehicles in 14 classes (Table 2.2). Nine of these classes were further subdivided based on their gross operating weights in 2.5-kip increments. Other classifications have also been used, for example FHWA (1997) used 20 vehicles which were subdivided into subgroups by 5-kip weight increments (FHWA, 1997).

Table 2.2: Vehicle classification in 1984 HCAS (Sinha et al., 1984).

Vehicle Class	Description
1	Small passenger automobiles
2	Standard and compact passenger automobiles and pickup trucks
3	Buses
4	Two-axle trucks (2S and 2D)
5	Automobiles with one-axle trailers
6	Three-axle single-unit trucks
7	2S1 tractor-trailers
8	Automobiles with two-axle trailers
9	Four-axle single-unit trucks
10	3S1 tractor-trailers
11	2S2 tractor-trailers
12	3S2 tractor-trailers
13	Other five-axle vehicles
14	Vehicles with six or more axles

For each HCAS however, the classification used for cost allocation must be consistent with the requirements of revenue allocation. This becomes a challenge because cost allocation classifications for bridges must also be consistent with AASHTO design standards, as described in the AASHTO bridge specifications (AASHTO, 2002). Cost and revenue allocation classifications however are mostly based on FHWA 13 class vehicle classification. Therefore, there exists a need to establish a correlation between the AASHTO design vehicles and the FHWA vehicle classes. One approach to achieving this is the method of 'equivalent live load moments' which calculates the live load moments as a function of the operating weight for each vehicle class on various bridge types. These moments are then compared with the moments produced by the AASHTO design loadings (FHWA, 1997; Sinha et al., 1984). This method was utilized to produce the 14-vehicle class classification in the 1984 Indiana HCAS, shown in Table 2.2. This classification is however still not consistent with the FHWA 13-vehicle class classification needed for the present study. To remedy this, Agbelie et al., (2016) adjusted the 14-vehicle class classification of the 1984 Indiana HCAS to match the FHWA classification. Details of the adjustments and the methods used are highlighted in Agbelie et al., (2016).

a. The Federal Method of Bridge Cost Allocation

The Federal method was developed by FHWA in 1982 and improved in 1997. This method has grown to largely replace the incremental method, even though it results in heavy vehicles being allocated higher bridge costs compared to the incremental method (Agbelie et al., 2016). The federal method and the incremental method are consistent with regards to new bridge construction costs, and only differ with respect to bridge repair and replacement costs (Agbelie et al., 2016; FHWA, 2000). In the federal method, the initial increment for a new bridge is associated with the cost of constructing the bridge to support its own weight, the weight of the lightest vehicle class, and resist other non-load related forces such as wind and seismic forces (ECONorthwest, 2009). This cost is treated as a common cost and is assigned to all the vehicle classes based on their relative VMT contributions, or in cases where capacity needs to be considered, PCE-miles is used. The additional cost of accommodating the second lightest vehicle group is assessed and taken as the second increment. This cost is allocated to only those vehicles whose gross vehicle weights (GVW) exceed or equal the second lightest weight, based on their relative shares of VMT or PCE-miles, excluding the lightest group. The additional cost of the third increment is assigned to vehicles whose gross vehicle weights (GVW) exceed or equal the third lightest weight, and so on, until all groups are accounted for (Agbelie et al., 2016).

b. Allocation of Bridge Replacement and Rehabilitation Costs

Unlike the incremental approach where the bridge replacement costs are treated in the same way as new bridge construction costs, the federal method uses a more elaborate way of addressing bridge replacement costs. The federal method incorporates the Bridge Sufficiency Rating (Agbelie et al., 2016; FHWA, 2000). For rehabilitation and maintenance, the costs are often analyzed as *load related* and *non-load related* costs. The proportion of costs that are either load or non-load related can be determined by estimating the fraction by which the costs would be reduced if all the vehicles in the highway class are automobiles or other very light vehicles (FHWA, 2000). For example, if the costs for a given program would reduce by 15% if all the vehicles are automobiles (which have little load contribution), then 15% of the costs are load related and 85% are non-load related. In previous HCAS, load related share for bridge repairs have been estimated at 20% for bridge deck repair or replacement, 30% to rehabilitate or replace deck and superstructure and 15% to rehabilitate substructure (FHWA, 1997).

2.3.3 Methods for Allocating the Costs of Highway Safety, Mobility and Other Assets

Highway safety is an essential part of the planning process. While many accidents and crashes can be attributed to factors such as weather, human error etc., studies have shown that engineering treatments and designs help reduce the frequency and severity of accidents (Chen et al., 2019; Harwood et al., 2003; Labi, 2011; Lee & Mannering, 2002; Tang et al., 2018). Engineering treatments and design elements that have been shown to reduce the frequency and severity of crashes include stricter speed limits, guard rails, traffic control elements such as stops signs and traffic lights, separation of travel directions with medians, and crash barriers. The benefits of some of these treatments have been empirically tested and documented as crash modification factors (AASHTO, 2010; Gross & Yunk, 2011; Labi, 2011; Sinha & Labi, 2011; TRB, 2010).

When crashes occur on highways, state property may become damaged and may need repair or replacement. Safety expenditures include the cost of these repairs and replacements and the expenditures on projects that enhance highway safety and mobility. Examples include geometric realignments to ensure that existing horizontal and vertical curves comply with adequate sight and passing distances, redesigning of the highway infrastructure with higher standards to accommodate the movement of larger and heavier vehicles, etc. These and other treatments lead to higher and higher costs on the upkeep of the infrastructure. Further, although some of these treatments may be considered as part of pavement expenditures, and others such as providing extra vertical clearance may be considered as part of bridge expenditures, they still constitute part of safety treatments and requirements. There is no strict definition of where each of the costs should be considered and different HCAS have treated various costs differently (FHWA, 1997; Sinha et al., 1984; Volovski et al., 2015).

In this thesis, expenditures that are meant to enhance highway safety and mobility are being considered together, as they serve a similar purpose: operational effectiveness. Mobility projects may include congestion reduction measures, installation of intelligent transportation system (ITS) features and addition of extra lanes to enhance mobility. Safety and mobility costs are directly tied to highway expenditures as the assets in question serve to enhance highway functions. As such, they are utilized by all vehicle classes on the highways, irrespective of vehicle size or weight. Because safety and mobility treatments are typically not dependent on vehicle weight or axle configuration, this thesis treats them as common costs, consistent with previous studies (Agbelie et al., 2016; Gupta & Chen, 2012; Sinha et al., 1984; Sinha et al., 1989; Volovski et al., 2015). As common costs, safety and mobility expenditures shall be allocated based on each vehicle class' contribution to the VMT (or PCE-miles).

2.4 Highway Revenue Attribution

Revenue collection is done at all levels of government, federal, state, and local. For transportation and highway revenues, two primary sources are typically considered – user and non-user revenues (FHWA & FTA, 2019; Kile, 2021; Kirk & Mallet, 2020). User sources include fuel tax, vehicle registration fees, international registration plan, motor carrier tax, oversize/overweight permit fees, driver license fees, etc. They are called user revenues because they are generated directly from highway users or user groups. Non-user revenues include funds from other sources such as governments grants and stimulus, general fund transfers, and other miscellaneous sources including property tax, income tax and state court fees (FHWA & FTA, 2017, 2019) as illustrated in Figure 2.5.

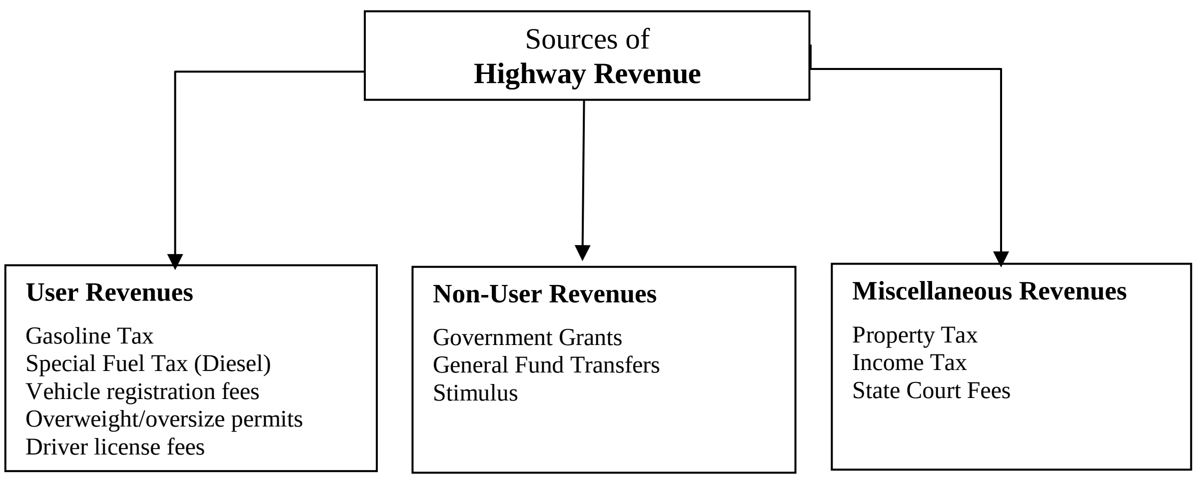


Figure 2.5: Typical highway revenue sources [adapted from (Agbelie et al., 2016)]

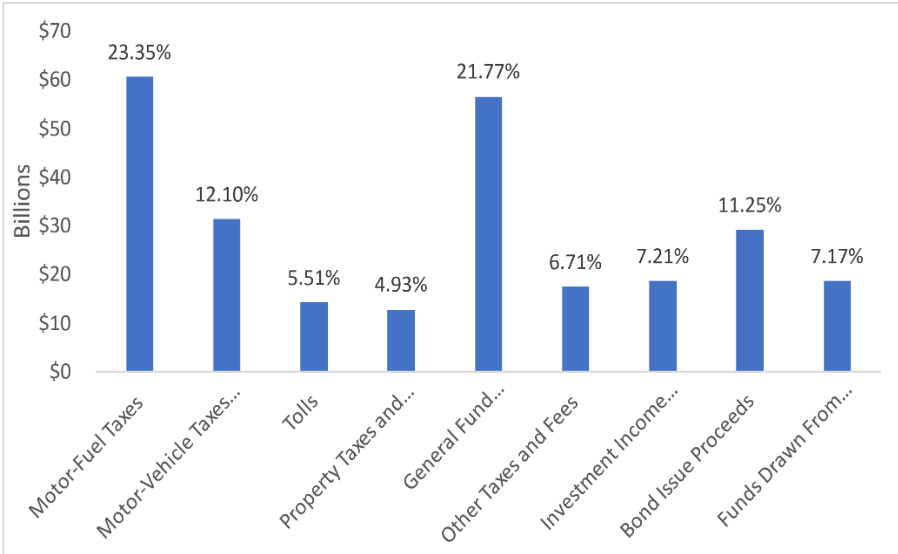


Figure 2.6: Highway revenue contributions by source (FHWA & FTA, 2019)

Across the years, the sources and total funding allocated to highway projects vary depending on the current needs and the government's priorities. Figure 2.6 summarizes the highway revenues for a typical year. Highway projects may be funded from various sources including general fund transfers, property taxes, stimulus from legislative acts in response to current economic and political status, etc. However, these sources are inconsistent and cannot be relied upon year after year to continue funding highway projects. A sustainable, and larger part of the total highway financing in any given year comes from highway user taxes, levied on all motorists for their usage of the highway facilities. As can be seen from Figure 2.6, these comprise nearly half of all highway revenues in any given year. Highway user taxes include taxes on gasoline and special fuels such as diesel, vehicle registration fees, driver license fees, heavy vehicle permits, international registration plan, etc. (Agbelie et al., 2010; Agbelie et al., 2016; FHWA & FTA, 2019; Kile, 2021) as summarized in Figure 2.7.

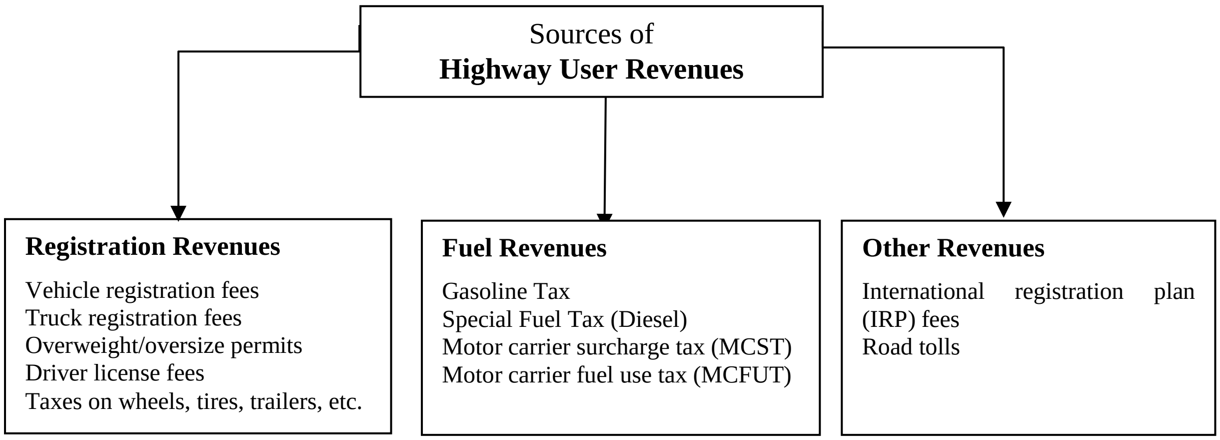


Figure 2.7: Composition of highway user revenues [adapted from (Agbelie et al., 2016)]

2.4.1 Fuel Tax Revenue

The amount of revenues generated from fuel usage depends not only on the tax rates applied to the fuels but more importantly on the total travel rates and fuel usage, which in turn are influenced by socio-economic and demographic factors as well as advancements in technology that enable ever higher fuel efficiencies (Volovski et al., 2015). Thus, to estimate fuel revenues, and expected changes thereof, HCAs analyze economic factors such as per capita income (PCI) and gross domestic product (GDP) which are important indicators and drivers of personal mobility and commodity transportation(Agbelie et al., 2010; Agbelie et al., 2012; FHWA & FTA, 2019). This, together with detailed analyses of driving age populations, passenger and commercial vehicle registration enables researchers to model projections of vehicle miles of travel (VMT) over the given period. Estimations of fleet fuel efficiency are also an essential step in revenue projection and estimation in an HCA study (FHWA, 2020). It is important that fuel efficiencies are estimated as reliably as possible. This is because increasing fuel efficiency due to technological advancements adversely impacts highway revenues. Taxes are a prerogative of the legislature and thus the rates and collection terms are set by the relevant legislative bodies. As of the time of publishing of this thesis, these were 18 cents per gallon for gasoline and 16 cents per gallon for diesel at the state level. At the federal level, the fuel taxes stood at 18.4 cents per gallon for gasoline and 24.4 cents per gallon for diesel (ILSA, 2017). Fuel revenues are computed based on VMT, fuel efficiency and tax rates according to equation (2.1).

$$R_{i,k} = \left(\frac{VMT_i}{e_{i,k}}\right) \times T_k \times p_{i,k} \tag{2.1}$$

where i and k refer to the vehicle class and fuel type respectively, $R_{i,k}$ is the revenue generated from vehicle class i using fuel type k, VMT_i is the VMT for vehicle class i, T_k is the tax on fuel type k in dollars per gallon, $e_{i,k}$ is the fleet fuel efficiency of vehicle class i for fuel type k in miles per gallon and $p_{i,k}$ is the proportion vehicles in class i that run on fuel type k. For a given vehicle class therefore, the fuel revenues can be estimated using equation (2.1), and following the procedure presented in

Figure 2.8.

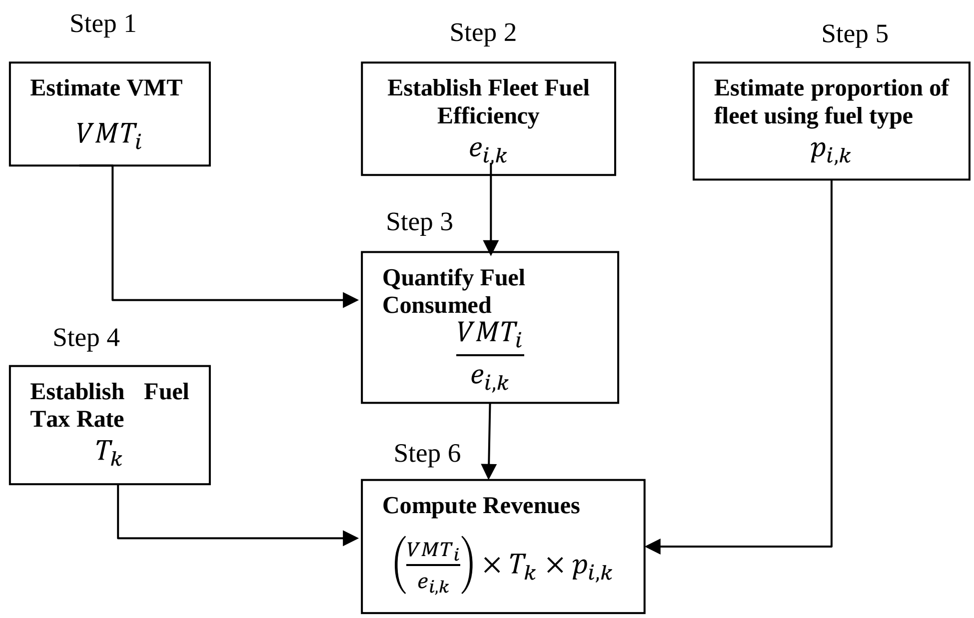


Figure 2.8: Steps to estimate/predict fuel tax revenues.

a. Vehicle Miles of Travel (VMT) Estimation

Vehicle miles of travel (VMT) models are typically based on socio-economic factors such as state (or national) gross domestic product, per capita income of individuals or households and driving age population (Klatko et al., 2016; Volovski et al., 2015). Data on these factors is typically available through government or other public databases or agencies. Estimations of VMT are only accurate to a degree, since they rely on projections of socio-economic factors such as GDP projections, which themselves are only estimates (Volovski et al., 2015). However, VMT can also be estimated from statistical models developed using data obtained traffic count and weigh-in-motion stations (Kim et al., 2016; Rentziou et al., 2012; Wang et al., 2011). Furthermore, the FHWA publishes annual highway statistics that include data vehicle miles of travel, ton-miles of freight, number of vehicle registrations, etc. (FHWA, 2020). This data is publicly available, and researchers can use the data to develop regression models to predict future travel trends.

b. Estimation of Vehicle Fleet Fuel Efficiency

In order to estimate the revenues generated from fuel consumption, we first need to estimate how much fuel is consumed by each vehicle. Estimation of fleet fuel efficiency takes in account several factors including the average age of the vehicles in the fleet, the proportion of vehicles in the fleet that fall within the given age group as well as corporate average fuel economy standards. A common method employed in HCA studies to estimate vehicle fleet fuel efficiency is the age cohort survival approach (Agbelie et al., 2010; Agbelie et al., 2016; Sinha et al., 1984). The general procedure involves three steps. The first step is the determination of the proportion of vehicles in the fleet of the given age cohort. Then, for each age cohort, the relative miles of travel are estimated. Finally, fleet fuel efficiency is estimated for each vehicle age cohort based on the model year efficiencies. CAFÉ standards are used as a basis for model year fuel efficiency, with the relevant adjustments made to reflect real world usage (Agbelie et al., 2012).

c. Quantifying the Amount of Fuel Consumed

The amount of fuel consumed by the fleet in each class can be quantified by dividing the estimated VMT by the estimated fleet fuel efficiency. Because fleet fuel efficiency is measured in miles per gallon (mpg), the amount of fuel consumed in each time is simply the quotient of the VMT and fuel efficiency of the fleet (Agbelie et al., 2012; Davis et al., 2014; Volovski et al., 2015). Amount of fuel consumed can also be obtained from government agency records as well as fuel sales data (CEC, 2017; EIA, 2021b; EPA, 2020; FHWA, 2020).

d. Fuel Tax Rates

Taxes are a prerogative of the legislature. The rates and collection terms are set by the relevant legislative bodies. Legislative entities are the various levels of government levy taxes on the fuels purchased and consumed within their respective jurisdictions. In this thesis, taxes imposed on fuel at the federal and state levels are considered. As of the time of publishing of this thesis, these were 18 cents per gallon for gasoline and 16 cents per gallon for diesel at the state level. At the federal level, the fuel taxes stood at 18.4 cents per gallon for gasoline and 24.4 cents per gallon for diesel (ILSA, 2017).

e. Estimating the Proportion of Vehicle Fleet Using the Given Fuel Type

Proportions of vehicles in the fleet that use a given fuel can be estimated on the basis of a number of factors including the number of registered vehicles of each kind, vehicle composition (VMT mix), and fuel sales data (Vasudevan & Nambisan, 2013; Verma et al., 2015). Government agencies also record and track data on volumes and specifications of vehicles sold. This data is often made available to the public and can be used to model fleet fuel use (Chambers & Schmitt, 2015; EIA, 2021a)

f. Estimating the Fuel Revenues

Using the information provided in steps a. through e. above, fuel revenues can be estimated using Equation (2.1). Amount of revenues generated from each source are also reported by government agencies annually (FHWA, 2020; ILSA, 2017; Kirk & Mallet, 2020).

2.4.2 Revenue Attribution to the Highway User Groups

Revenue attribution is the process by which the highway user revenues are distributed among the highway users (vehicle classes). In many highway cost allocation studies, the users are typically classified according the 13 FHWA vehicle classes. A given source of revenue and a given level of government, the amount of total user revenue is first determined (as per steps a through f above). Then for the given user group, the results are summed up for all the revenue sources and for all the government levels to yield the total revenue attributable to each vehicle class. For each vehicle class, the revenues from vehicle registration fees, commercial vehicle excise tax, wheel tax, motor vehicle excise tax, excise surtax and license fees are typically attributed on the basis of the number of registered vehicles and fees whereas fuel revenues are attributed based on the class VMT and the fleet fuel efficiency (Agbelie et al., 2010; Oh & Sinha, 2008; Volovski et al., 2015)

2.5 User Equity Analysis

In transportation, like any public service, it is important that the distribution of benefits and disbenefits to the system users is as fair as possible. These benefits and disbenefits maybe monetary or non-monetary. From the user's perspective, the monetary costs may include out of pocket expenditures, and the non-monetary costs may include inconvenience, discomfort, and unsafety. Conversely, the benefits may include reduction in the out-of-pocket costs, increased network connectivity, increased accessibility to social and economic centers, improved safety, and reduced delays and higher travel time reliability (FHWA, 2017; Litman, 2002; Sinha & Labi, 2007).

The fairness of the distribution of the costs and benefits among user classes is assessed based on equity. In transportation, equity refers to the fairness in which not only the benefits but also the costs of a transport system are distributed among the current or prospective users (Litman, 2002). User equity analysis is meant to compare the contributions of each user with their share of the cost responsibility, with the goal of achieving parity between the two. In HCAS', user equity analysis is done by comparing the share of revenue contributed and the share of cost responsibility for each vehicle class. At its core, user equity with regard to transportation financing is simply a comparison of the taxes and fees paid by a user compared to the costs incurred by the agency to provide the transportation service to the user (Agbelie et al., 2016; FHWA, 1997; Sinha et al., 1984; Volovski et al., 2015).

Because the costs of building and maintaining transportation infrastructure is borne entirely by the agencies and governments, these expenditures must be made up for through taxes and fees charged to the users. Using user equity ratios, governments can revise their policies and taxation structures and determine other options that can be implemented to achieve equity. This can best be accomplished through a periodic and systematic study of revenue generation mechanisms and attributable costs. This ensures that the tax and fee structure is responsive to changing vehicle technologies, travel patterns, construction materials, and project delivery approaches. State authorities and transportation agencies have used this approach to update their cost estimates and revenue projections. Texas investigated the fairness of the structure of taxes and charges imposed on highway user classes by estimating the share of total revenues from highway user taxes and charges that the class contributes, and compared this with the share of highway system costs contributed by the class (Luskin, 2002; Luskin et al., 2001; Luskin & Walton, 2001). By investigating the state's highway cost allocation how highway user classes, differentiated based on vehicle type and weight category, the state of Nevada was able to make recommendations for tax rate changes in a bid to reduce the disparity between payments and cost responsibilities for each vehicle class (Balducci et al., 2009). And more recently, following a highway cost allocation study, the state of Oregon suggested alternative fee schedules that would minimize cross-subsidization across the vehicle classes to improve equity among vehicle classes (ECONorthwest, 2014).

A desirable ratio is exactly 1.00, which means the given vehicle class is contributing as much to revenue as it is responsible for in costs. An equity ratio greater than unity implies the user is overpaying their share of responsibility, meaning the vehicle class in question is paying more in revenues than it is responsible for in costs, and the reverse is true for an equity ratio less than one. Mathematically, equity ratios can be computed using Equation (2.2) below (Volovski et al., 2015):

$$ER_i = \frac{RCP_i}{CRP_i} \tag{2.2}$$

where ER_i = equity ratio of vehicle class i

RCP_i = percentage revenue contribution of vehicle class i

CRP_i = percentage cost responsibility of vehicle class i

2.6 Chapter Summary

This chapter presented a review of literature on highway cost allocation and anticipated impacts of emerging vehicle technologies. This was necessary because assessment of the impacts of CAV adoption on highway expenditures and revenues must be preceded by examining the procedures that scholars and transportation agencies have used to attribute these expenditures and revenues. The review focused on CAV impact analysis, with respect to the cost and revenues associated with highways. The information also includes demand projections associated with various rates of CAV market penetration. Literature on highway costs allocation methods was reviewed and documented. Sources searched for published material on the subject include journal publications, conference publications, agency reports, and reports from management consultants and technology companies.

Emerging vehicle technologies are poised to result in numerous impacts which include comfort, convenience, safety, reliability, and security, among others (Du et al., 2020; FHWA, 2017; Labi et al., 2015; Li, Chen, Dong, et al., 2020; Saeed et al., 2020; Talebpour & Mahmassani, 2015).

As such, various stakeholders are investing resources to develop and make the technology safer, more affordable, and accessible to the public. Another area that is often discussed as part of vehicle automation is the rise of vehicle-sharing services and the accompanying downward trends in vehicle ownership (Fagnant & Kockelman, 2018; Fagnant & Kockelman, 2015c). However, as Saeed et al., (2020) point out, most people would still prefer to use their own vehicles as opposed to a shared service. This suggests that the impacts of these technologies may exhibit greater variability than expected and must therefore be analyzed within the broader context with respect to competing alternatives, individual preferences, and prevailing levels of market penetration. In parallel with the drive to develop automated vehicles, there is growing concern about the environmental impacts of transportation systems. This has resulted in a growing push from the public and regulators to transition transportation systems to incorporate environmental sustainability to a greater extent (FHWA, 2014; Mead, 2021; USDOT, 2019). Electric propulsion has emerged as a strong contender among many alternatives, with many legacy and newer vehicle manufacturers alike committing to producing electric vehicles (Deloitte, 2020; McKinsey & Company, 2021). Many of the outlined benefits of vehicle automation and electric propulsion will only be realized to a significant extent once the technology gains enough market penetration. This will require the necessary supporting infrastructure including accessible charging networks, and increased power generation for vehicle electrification, and cloud computing infrastructure, smart highway and intersection features (signs, lane markings, traffic lights, etc.) for vehicle automation (Engel et al., 2018; Markel, 2010; Wood et al., 2017). The provision of such supporting infrastructure is expected to incur significant expenditures by highway agencies.

Elements of highway cost allocation covered in this chapter include pavement cost allocation, bridge cost allocation, and revenue attribution. Methods of pavement cost allocation include the traditional incremental method (Fwa & Sinha, 1985b), the thickness incremental approach (Fwa & Sinha, 1985b), and the performance based approach (Agbelie et al., 2016; Fwa & Sinha, 1985a). The traditional incremental approach assigns the responsibility for highway costs to each highway user group (vehicle class) by first determining the construction and maintenance cost of the facility to serve only the lightest vehicle class, and then increasing the structural and functional capacity of the facility in increments that meet the next heavier class, repeating this process until the needs of all the classes are met. The thickness incremental approach considers increments of pavement thickness, rather than increments of traffic loading (as is the case with the traditional incremental approach). This method is considered advantageous because it directly incorporates the non-linearity of the thickness cost relationship, allowing it to correct for the bias associated with returns to scale.

Unlike pavements, bridges possess characteristics that exhibit far greater variation, for example, the design requirements including span, type of super structure – suspension, cable stayed, arch, etc. – that determine the mechanism of load transfer. The damage caused to the bridge is associated with the load and the axle configuration of vehicles. Bridge cost allocation is mostly done using the federal method. Like the incremental method, the federal method assigns costs by weight increments. The first increment for a new bridge is associated with the cost of constructing the bridge to support its own weight, the lightest vehicle weight group, and to resist other non-load related forces such as wind and seismic forces (ECONorthwest, 2009).

Highway revenue attribution and user equity are also explored in this chapter. Revenue collection is done at all levels of government, federal, state, and local. For transportation and highway revenues, two primary sources are typically considered – user and non-user revenues (FHWA & FTA, 2019; Kile, 2021; Kirk & Mallet, 2020). User sources include fuel tax, motor carrier tax, vehicle registration fees, driver license fees, international registration plan, oversize/overweight permit fees, etc. Non-user revenues include funds from other sources such as governments grants and stimulus, general fund transfers, and other miscellaneous sources including property tax, income tax and state court fees (FHWA & FTA, 2017, 2019). User equity analysis is meant to compare the contributions of each user with their share of the cost responsibility, with the goal of achieving parity between the two. In HCAS', user equity analysis is done by comparing the share of revenue contributed and the share of cost responsibility for each vehicle class. At its core, user equity with regard to transportation financing is simply a comparison of the taxes and fees paid by a user compared to the costs incurred by the agency to provide the transportation service to the user (Agbelie et al., 2016; FHWA, 1997; Sinha et al., 1984; Volovski et al., 2015).

3. METHODS

This chapter of the thesis presents the methodology adopted for analyzing the highway revenues and expenditures in the prospective era of new vehicle technologies – automation, electrification, and connectivity. The analysis first considered one form of emerging technology or some combination thereof, then considered a given market penetration of the said technology. For this market penetration, the revenue and highway expenditure impacts were estimated. Then the resulting changes in equity were calculated. The analysis was repeated for the next form of emerging technology and the next level of market penetration as presented in Figure 3.1. This analysis was conducted against the backdrop of an established base case or conventional scenario (where none of the emerging vehicle technologies are adopted to any significant extent). Therefore, all changes in VMT, fuel efficiencies, and travel patterns that would occur would be due to factors other than emerging vehicle technologies. The changes in highway expenditures and revenues are therefore assessed under these assumptions and the resulting figures are used as a basis for comparison to the arising situation with a given level of market penetration of a given vehicle technology. Although the models used in the analysis were developed with the intention of application to any country or state, the case studies presented in the results section of this thesis are only for the state of Indiana.

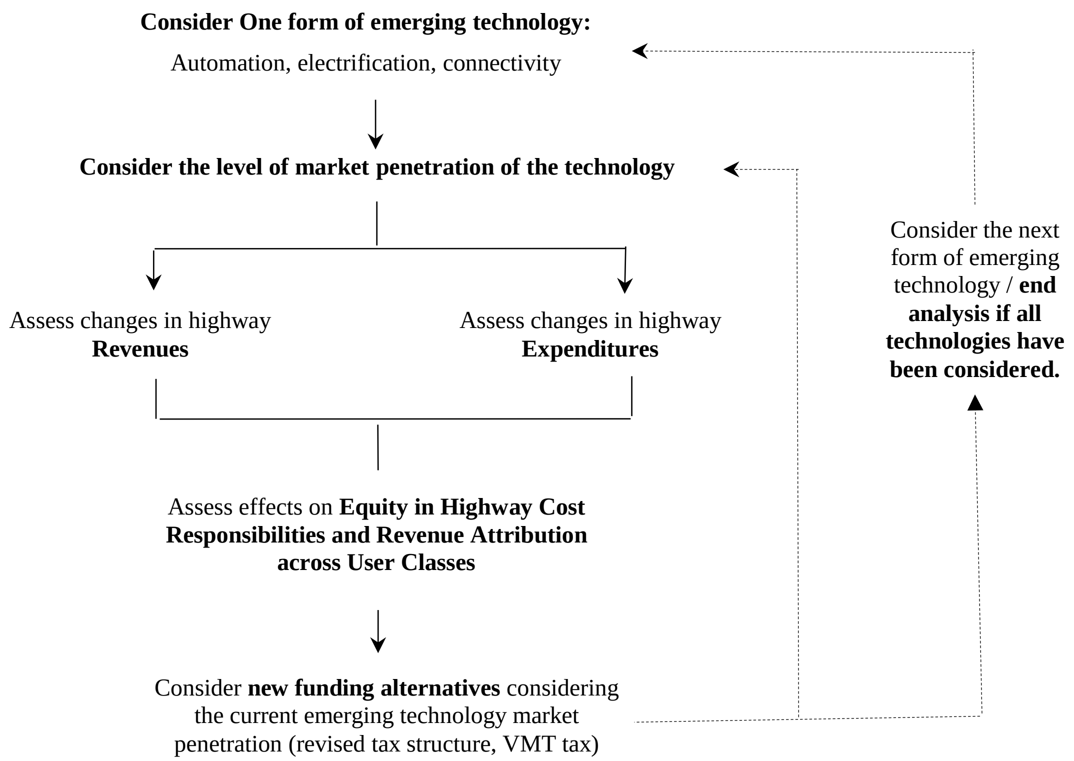


Figure 3.1: Study framework

3.1 Establishing the Base Case (Conventional)

To assess the impacts of emerging vehicle technologies on highway expenditures and revenues, it is important to establish a base case (or conventional) scenario. Anticipated changes resulting from the technologies are then presented in comparison with this base case. This is also necessary because even in the absence of emerging vehicle technologies, VMT and travel patterns fluctuate, causing highway expenditures and revenues to also fluctuate. Therefore, inclusion of the base case provides a control, ensuring that the impacts being assessed are primarily due to emerging vehicle technologies. According FHWA statistics (FHWA, 2020), VMT has increased consistently over the past few decades, except for short periods of plateau during periods of economic recession (Figure 3.2).

Emerging vehicle technologies, as discussed in detail in subsequent chapters of this thesis, will take several years before becoming prominent, affordable, and widely adopted (Bansal & Kockelman, 2017; Litman, 2017). At the same time, the natural trends and increase in VMT will continue, along with it an increase in highway expenditures due to the additional wear and tear resulting from increased system usage. The increased VMT leads to increased revenues in fuel taxes. These changes are accounted for in the established base case scenario.

For simplicity, this thesis does not track the year-to-year variation in traffic distribution across the vehicle classes. Instead, the historical trends in VMT are linearly extrapolated to the year in question. The linear extrapolation used is shown in Figure 3.2 and has a correlation coefficient (R^2) of 0.968. It is assumed that the vehicle distributions across vehicle classes do not change significantly over the period in question. After estimating VMT for the year in question, the revenues, and expenditures (described in Section 3.3) are adjusted based on the new VMT estimates. This represents the base case scenario for the year in question, showing the state of the expenditures and revenues without the impacts of emerging vehicle technologies. The impacts of emerging vehicle technologies, such as additional VMT changes, changes in vehicle ownership patterns, etc. are then analyzed for the given vehicle technology and level of market penetration.

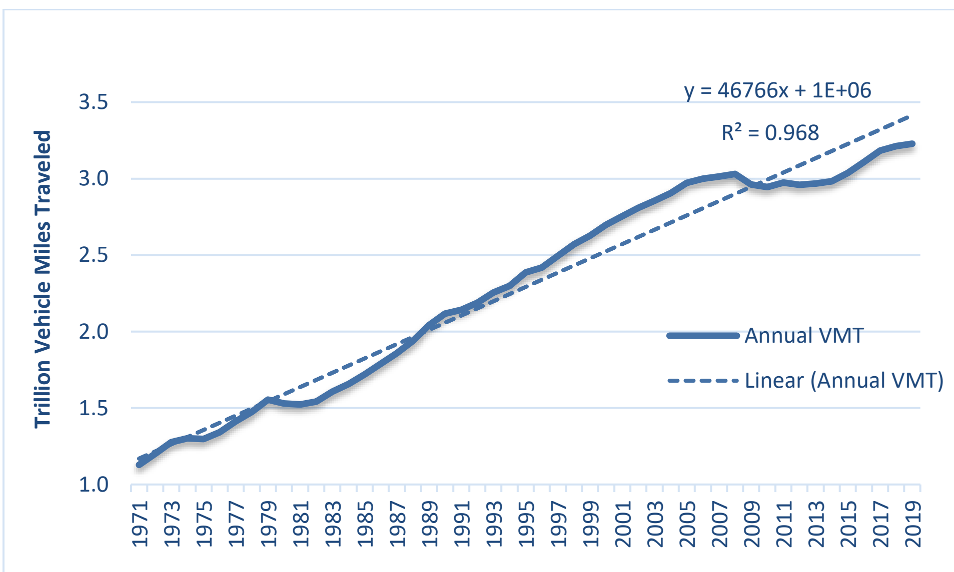


Figure 3.2: Annual Vehicle Miles of Travel (VMT) in US from 1971 through 2019 [adapted from (FHWA, 2020)]

3.2 Estimating the Cost of Infrastructure - Infrastructure Cost Functions

To estimate the impacts of emerging vehicle technologies on highway expenditures and revenues, cost estimates for highway revenues and expenditures were first established. Various HCA studies have approached the topic differently, each with different underlying assumptions that inform the specific methodology, subject to data availability and other applicable conditions (climate, vehicle classification, etc.). In many HCA studies, infrastructure costs have been estimated using an accounting approach where estimates are determined through a perpetual inventory approach, and the costs allocated to the various vehicle classes based on their system usage (Schreyer et al., 2002). Furthermore, HCA studies allocate different percentages of infrastructure investment costs in different repair categories to various classes of vehicles. Specific percentages are drawn from engineering studies and assessments estimating the additional costs for increased road dimension, structural strength, etc. This is reflected in HCA methods such as the thickness-incremental approach (Fwa & Sinha, 1985b), the performance-based approach (Fwa & Sinha, 1985a; Sinha et al., 1984) and the federal method (FHWA, 1997).

Through the accounting approach, transportation agencies and other parties conducting HCAs examine and quantify highway expenditures and revenues of past planning horizons and attribute these to the various vehicle classes in a manner that is commensurate with their respective system usage and damage incurred. This is then followed by a comparison of these revised cost responsibilities with the existing user fee structure, with relevant adjustments as needed (Ahmed, 2012). Although this approach is useful for adjusting the existing user fee structure and improving efficiency, it lacks the forward-looking element that would be necessary to predict changes in highway costs and revenues resulting from evolving transportation system usage and dynamics such as the emergence of new vehicle technologies. Furthermore, the estimation of consistent pavement damage costs (as well as other infrastructure deterioration costs) has remained largely unresolved, and even controversial, despite significant and earnest efforts over the last several decades (Ahmed, 2012). Therefore, there is a need for robust infrastructure cost functions that can not only be used to allocate highway costs to various vehicle classes but can also accurately predict infrastructure costs in the face of evolving transportation system usage and dynamics such as the emergence of new vehicle technologies.

In their 1985 highway cost allocation study, Fwa and Sinha showed that the relationship between pavement loading (ESAL) and required thickness is logarithmic (see Figure 2.3). By relating the pavement thickness with cost, one can establish a direct relationship between pavement loading (ESAL) and pavement cost. In 2002, Schreyer et al. developed a model that approximated such a relationship using data (from 1985 through 1998) from 127 sections on the Swiss road network. The researchers estimated marginal maintenance and rehabilitation costs for different vehicle classes. The costs were estimated on the basis of total vehicle mileage (all vehicles), gross vehicle weight-distance (gross ton-Km) for each vehicle class, and total axle load equivalent kilometers. The axle weights of all vehicles were converted to the standard axle load of 18,000 lbs. Vehicles were classified as cars, light trucks, and heavy trucks. The cost models were developed for infrastructure operation and maintenance, construction and maintenance, and upgrade and rehabilitation (Schreyer et al., 2002).

This thesis adopted the methodology developed by Schreyer et al (2002) and updated it to develop new models for infrastructure cost functions relevant and applicable to the United States environment. The update was necessary because the original models were developed for the Swiss environment and therefore reflected Swiss specific characteristics such as the climate, geographic topology, vehicle weight restrictions, and maintenance schedules. For example, Switzerland has a 20 ton limit for trucks (Schreyer et al., 2002), which means the road construction parameters and traffic characteristics may be different for a country with different weight policies. Furthermore, this may necessitate specific maintenance practices that are deemed as optimal for the design and existing traffic characteristics. Additionally, the topographical and climatic conditions prevailing in Switzerland may vary significantly from those in the Midwest United States.

The new models were developed using US highway statistics data on highway system usage and expenditures from 1994 through 2019 provided by FHWA. The infrastructure cost model function has the general form:

$$\ln(Cost) = \alpha + \beta \ln x \tag{3.1}$$

Where x is a measure of system usage i.e total vehicle distance travelled (vehicle miles of travel) or total vehicle weight-distance or total ESALs by vehicles of all classes; and α and β are model parameters (Schreyer et al., 2002). Two models were developed for the infrastructure cost: one for common costs and the other for attributable costs. As outlined in Section 2.3 of this thesis, common costs encompass costs that do not depend on vehicle size and weight (such as safety treatments, right-of-way acquisition, and highway traffic enforcements). These costs are attributed to the vehicle classes only on their share of the total VMT. Therefore, for common costs, x in Equation (3.1) represents the vehicle miles of travel for each vehicle category. For attributable costs (pavement construction, reconstruction and major rehabilitations, bridge superstructures and substructures, major maintenance, and rehabilitations), the costs are attributed on vehicle weight and size. For this model, the chosen metric is the distance weight (vehicle ton-miles) because it accounts for both relative VMT and vehicle weight. From Equation (3.1), the cost of the infrastructure stewardship can be computed through algebraic manipulation. A general form of the resulting equation is shown in Equation (3.2):

$$Cost = e^{\alpha} x^{\beta} \tag{3.2}$$

Due to lack of granular data for many of the years for which data was available, it was difficult to develop models specific to each infrastructure type or treatment type. Therefore, the developed models envelope the cost of all highway infrastructure undertaken by the individual states in the given year. The data is categorized as either capital expenditures or traffic mobility and services. The capital expenditures encompass the actual construction costs for both new constructions, major reconstructions, rehabilitation, and physical maintenance for both bridges and pavements, and account for load related (attributable) costs in the model. Traffic mobility and services expenditures refer to expenditures on highway safety treatments, traffic control operations, enforcement, general administration, research, and planning, etc., and account for the non-load related (common) costs in the model.

3.3 Data

A major part of a highway allocation study is the determination of the system usage. This is so that the costs incurred, and revenues generated can be attributed to the users of the system based on their system usage. A common way to quantify system usage is through vehicle miles of travel (VMT). Other measures include gross vehicle weight (GVW), equivalent single axle loads (ESAL), and axle load miles (ALM), among others. For this thesis, the data in the model development was obtained online from the Federal Highway Administration Office of Highway Policy Information. The data is published as part of the Highway Statistic Series and includes data on system usage, expenditures, revenues, appropriations and debt obligation for all states and the federal government. The data used in the analysis is adopted from Volovski et al., (2016). The dataset includes AADT data for the years 2009 through 2012 based on traffic counts for state routes and select local routes in the state of Indiana. The data set also contains highway user and non-user data obtained from the Indiana Department of Transportation (INDOT), Indiana Department of Revenue, Annual Operational Reports from counties and cities, and the Indiana Handbook of Taxes, Revenues, and Appropriations and the Highway Statistics series published by the FHWA.

The system usage data used in this thesis were collected from various sources including weigh in motion (WIM) detectors and automated traffic recorders (ATR), and AADT data reported to the Highway Pavement Monitoring System (HPMS). Using this data, traffic distributions were then developed for each vehicle class and highway functional class. Furthermore, spatial distributions of this traffic were determined using the locations of the weighing stations (Agbelie et al., 2016; Volovski et al., 2015). A detailed description of the approach and models used is presented in Volovski et al., (2015). Highway revenues and expenditures used in this thesis represent the amounts for the fiscal year 2009 through 2012 and are presented in 2012 dollars. Highway expenditures include funds spent on new construction and long-term stewardship of highway assets. This includes expenditures on pavements, bridges, highway safety, etc. The revenues include gasoline tax, diesel tax, motor carrier surcharge tax, motor carrier fuel use tax, vehicle registration fees, driver license fees, international registration plan, oversize/overweight permit fees, commercial vehicle excise tax, wheel tax, motor vehicle excise tax and excise surtax, heavy vehicle use tax, tax on sales of trucks and trailers, and tax on tires.

3.4 Evolution of Market Penetration of the Emerging Vehicle Technologies

The rate of development and maturity of novel technology is different from the rate of its market penetration. This is expected because there is lag between the initial introduction of a technology and its mass market adoption. For many new technologies, their mass market penetration rates usually follow a sigmoid curve (Lavasani et al., 2016; Litman, 2017): a slow adoption rate in the beginning, and then accelerating as the technology becomes cheaper and widely available, and then finally slowing down as the market nears saturation. In research, this is modeled using Bass

Diffusion models (Kim & Hong, 2015; Lavasani et al., 2016) and is schematically illustrated in Figure 3.3.

Vehicle automation, electrification and connectivity are each expected to develop at different paces. The rate of their market penetrations, however, can each be expected to follow the Bass diffusion model as explained above. Their impacts on highway revenues and expenditures will vary greatly depending on the mix of technologies, their level of maturity and effective market penetration. Vehicle automation maturity is classified according to the SAE vehicle automation classification on a five-point scale as shown in Figure 3.4. The rate of development and maturity of this technology hinges on advances in sensor and computational technology. This is discussed in greater detail in Section 3.4.2 of this thesis. The rate of development of connectivity hinges on advances in wireless communication protocols as well as the enabling technologies such as network transmitters and receivers, as discussed in section 3.4.1. Electrification hinges on advances in battery technology, particularly, improvements in energy density. In practice, it is likely that there will be different combinations of technology maturity and market penetrations. Each of the different combinations of supply (connectivity, electrification, and automation) and demand (market penetration) will pose a different demand on the kind of infrastructure needed to accommodate that combination. Assuming 5 scenarios of supply and 3 scenarios of demand (low, moderate, and high), this thesis analyzed at least 15 scenarios of supply and demand. This is illustrated in Table 3.1.

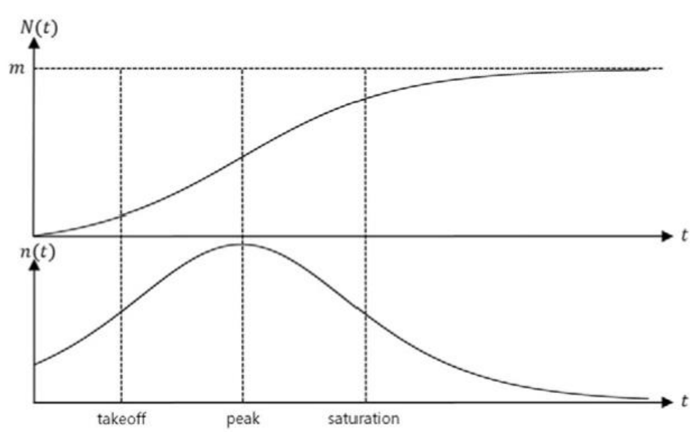


Figure 3.3: Bass model adopter curves: top: cumulative adopter, bottom: non-cumulative adopter (Kim & Hong, 2015).

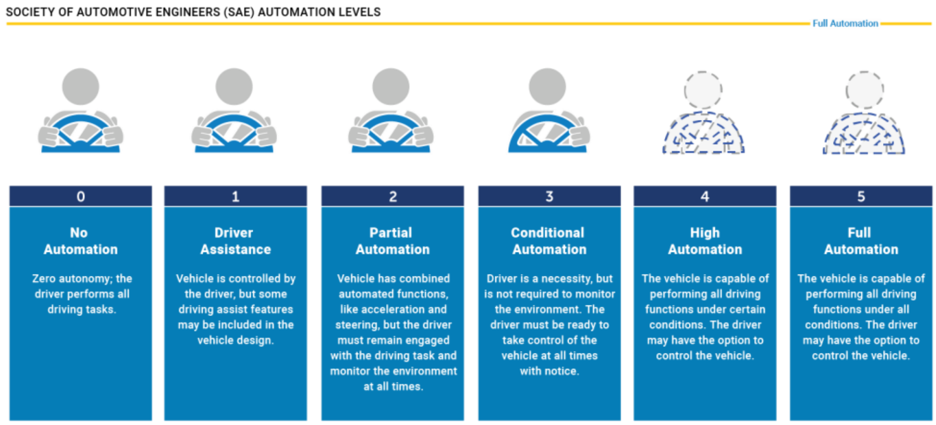


Figure 3.4: SAE automation levels (SAE, 2018)

Some of these scenarios are more likely than others. For example, connected vehicles are already in use to some extent so the supply situation is not at the base level. With regard to the demand side, the AV market penetration rate is currently zero due to restrictive regulation and lack of mature vehicle automation technology, but the market penetration is expected to increase as these constraints are gradually being overcome. At the same time, V2I connectivity is currently rudimentary but is expected to grow rapidly in the next few years. Electric vehicles are currently in use and the supply is expected to increase soon as more manufacturers commit to vehicle electrification. It is expected that ECAV demand will closely follow supply. In other words, ECAV technology will be incremental and evolutionary with increasing market penetration. This section considers these scenarios one at a time. In Table 3.1, the timeline indicates an estimated period when the technology in question is predicted to have the shown market penetration level.

Table 3.1: Scenarios of demand and supply analyzed in this thesis

Scenario	Supply	Demand	Timeline (Year)
1	Connectivity	Low	2020
2		Moderate	2040
3		High	2060
4	Automation	Low	2040
5		Moderate	2060
6		High	2080
7	Electrification without Automation	Low	2030
8		Moderate	2050
9		High	2070
10	Automation and Electrification	Low	2040
11		Moderate	2060
12		High	2080
13	Connectivity and Automation	Low	2040
14		Moderate	2060
15		High	2080
16	Connectivity, Automation, and Electrification	Low	2040
17		Moderate	2060
18		High	2080

3.4.1 Vehicle Connectivity

Today's automotive industry is rapidly adopting connectivity features for various reasons including users' personal convenience, the vehicle's diagnostics and maintenance data and ultimately for improved safety (DOT, 2018; Ha, Chen, Du, et al., 2020). Connectivity features include integrated smart apps, GPS and satellite navigation as well as cellular connectivity. All these features enable the vehicles to communicate with other vehicles (V2V) as well as other infrastructure (V2I). By extension, the enabling technology can also allow vehicles to communicate with the cloud infrastructure (V2N) as well as pedestrians (V2P). Collectively, the different types of enabled vehicle connectivity types have the acronym V2X. Figure 3.5 below illustrates this connectivity. These connectivity features can be classified as: embedded, tethered and integrated / mirrored (Heiden, 2019). Embedded connectivity refers to those where the connectivity devices are built into the car. Examples of these may include inbuilt GPS navigation and satellite connectivity. Tethered solutions rely on a separate mobile device (e.g a smart phone) to be used a modem (connected through Bluetooth or Wi-Fi) to provide the connectivity. Integrated/Mirrored solution is where smartphone applications are integrated or mirrored into the vehicle infotainment system allowing for a safer and more natural interaction with the driver (e.g., Apple Carplay and Android Auto).

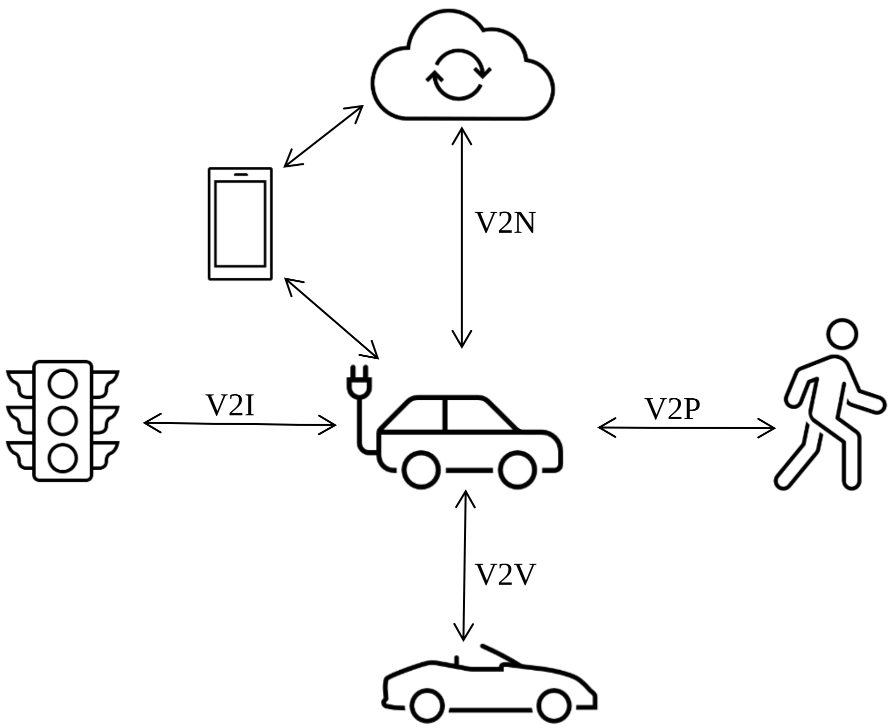


Figure 3.5: Schematic representation of different types of vehicle connectivity [adapted from (Heiden, 2019)].

Vehicle connectivity is poised to bring about numerous benefits including improvements in safety, reduction in congestion, improvements in fuel efficiency and direct and indirect economic returns (Auld et al., 2017; Khondaker & Kattan, 2015). The value of connectivity in automotive applications is dynamic from the perspective of the technology itself, the pace of development of innovative solutions, and the transformational nature of the automotive/mobility market. As such, the questions of how new connectivity-based revenue sources and benefits will be generated and monetized and by whom are currently one of the most critical strategic issues facing the automotive industry (Heiden, 2019). It is well understood however that some of the biggest prospective benefits from vehicle connectivity include potential savings in fuel costs because of improved vehicle efficiency through platooning, as well as increased safety benefits due to the communication abilities of the vehicles.

Literature has shown that vehicle platooning can improve fuel efficiency for heavy vehicles. This can mostly be attributed reduced air resistance faced by vehicles in following positions in the platoon, a phenomenon known as drafting. In addition to improved fuel efficiency, platoons can also increase road capacity by allowing vehicles to drive closer to each other (Zhang et al., 2020). Research is still on going about how many vehicles are required to achieve significant fuel consumption reductions. Furthermore, real world traffic conditions make it harder for platoons to form and be sustained for a significant distance due to variations in composition of traffic and varying terrain. By studying a platooning rate of 1,800 heavy-duty vehicles, Liang et al (2014) analyzed sparse vehicle position data from a region in Europe for one day. Map-matching and path-inference algorithms were used to identify paths taken by the vehicles. The results found that the spontaneous platooning rate is 1.2 %, which corresponds to a total fuel saving of 0.07% compared to the base case (where none of the vehicles platooned) (Liang et al., 2014).

Under more controlled conditions however, such as on track tests, wind tunnel tests and simulations, vehicle platooning has shown significant improvements in fuel economy, anywhere from 3% to 12% depending on the conditions employed. In fact, in homogenous situations, the estimated fuel improvements are even higher. Hussein and Rakha (2020), used empirical data from the literature to develop general power models that capture the impact of a vehicle position, in a platoon of homogeneous vehicles, and the distance gap to its lead (and following) vehicle on its drag coefficient. The model results indicate a significant improvement in the vehicle fuel economy when compared with those based on a constant drag coefficient assumption. Specifically, considering a minimum time gap between vehicles of 0.5secs (which is typical considering state-of-practice communication and mechanical system latencies) running at a speed of 100km/hr, the optimum fuel reduction that is achieved is 4.5%, 15.5%, and 7.0% for light duty vehicle, bus, and heavy-duty truck platoons, respectively. For longer time gaps, the bus and heavy-duty truck platoons still produce fuel reductions in the order of 9.0% and 4.5%, whereas light duty vehicles produce negligible fuel savings (Hussein & Rakha, 2020).

Further, there are several factors that influence the resultant fuel economy in a platoon, including the inter-vehicle spacing, the aerodynamic design and configuration of the vehicles, vehicle mass, etc. The most important of these factors, however, is the inter-vehicle spacing (Zhang et al., 2020). Literature has shown that the average fuel savings from platooning increase as the inter-vehicle spacing is decreased, varying from 11% at 3-4 meters to 8% at 8-10 meters (Browand et al., 2004; Lammert et al., 2014).

In addition to the savings resulting from platooning, vehicle connectivity is also poised to yield increased safety benefits. With properly designed control algorithms, connected vehicles can coordinate and potentially avoid otherwise dangerous situations. Literature has shown that vehicle connectivity can result in 10% to 70% reduction in crashes depending on the prevailing circumstances (Yue et al., 2018). Connected vehicles can also help smooth out traffic at intersections by coordinating with other vehicles and infrastructure on approach to determine which vehicle gets the right of way. The result is a much smoother traffic flow without encountering stop-and-go conditions (Kreidieh et al., 2018; Stern et al., 2018). When implemented at roundabouts, vehicle and infrastructure connected has been shown to result in up to 80% reduction in traffic delay and up to 40% reduction in fuel consumption (Zohdy & Rakha, 2013, 2014). Research has shown that more generally, at signalized intersections, vehicle and infrastructure connectivity can result in up to 91% and 75% reduction in total delay and fuel consumption, respectively (Malakorn & Byungkyu, 2010).

a) Implications of Vehicle Connectivity on Highway Expenditures and Revenues

It is widely understood that vehicle connectivity will result in significant benefits in both economic terms and improvements in quality of life. Yet still, quantifying these benefits is challenging. It is anticipated that these benefits will be felt by the public, government entities, and the private sector. The use of connectivity technology such as network equipment, modems etc. and the services that follow will generate economic activity for the entities providing and maintaining the services (Iyer et al., 2019). Majority of these services are likely to be provided by private companies and corporations. The provision of the infrastructure and associated services is expected to generate hundreds of billions of dollars for the stakeholders involved (Heiden, 2019).

It is also likely that public entities will incur significant costs as they provide services to support the connectivity infrastructure. However, the extent of these costs is hard to quantify. Similarly, they are also likely to benefit from reduced crashes. Thus, overall, their expenditure on safety-related highway programs will likely decrease and they will realize the savings. Similarly, the extent of these savings is difficult to quantify. Thus, for purposes of this thesis, highway expenditures on safety-related items will be assumed to increase in tandem with VMT. An additional 10% is assumed for the connectivity infrastructure costs to be borne by the agency. Additionally, it is expected that connectivity will not result in an increase in traffic volume beyond the trend, any more than would normally have been. It is however expected to result in improved fuel efficiency for the connected vehicles, through platooning and adaptive cruise control. For the purpose of this thesis, values of 10% to 15% are assumed to represent the average improvement in fuel efficiency for connected vehicles. This is a rough average estimate meant to reflect the reported improvements highlighted in literature (Browand et al., 2004; Lammert et al., 2014; Zohdy & Rakha, 2013, 2014), which ranges from 4.5%, 15% and 7% for light vehicles, buses and heavy trucks, respectively, in highway cruising to 75% improvements for vehicles at intersections. The true improvements in fuel economy cannot be easily quantified and a representative average is hard to compute without a good idea of the relative proportions of the distances travelled in each circumstance for each vehicle class. Moreover, the results presented in literature are only suggestive as they represent experimental conditions. Real world conditions may vary and potentially yield different results. Hence for simplicity, this research assumes a 10% to 15% improvement in fuel economy across the board for connected vehicles. To realize these benefits and improvements, vehicles should be equipped with at least automated longitudinal and lateral control. As such, it is assumed that connected vehicles have at least level one automation.

Governments and transportation agencies spend funds on several aspects of highway infrastructure. Several of these are directly related to the volume and weight of the vehicles that use the highways. Of all highway expenditures, those on pavements, bridges and mobility components constitute the largest percentage share. They are all related to (and dependent on) VMT and ESAL miles. At significant levels of market penetration, vehicle connectivity may be expected to result in increased road and intersection capacity owing to the coordination resulting from connectivity. This may in turn result in some induced demand and therefore increase in overall VMT. For this analysis, it is assumed that at high levels of market penetration of connected vehicles, VMT may increase up to 10%. Thus, bridge expenditures, load related pavement expenditures, etc. are assumed to grow accordingly.

3.4.2 Automation Evolution and Market Penetration

To date, numerous technological features are available on vehicles including driving assistance features such as adaptive cruise control and even automatic valet parking. Therefore, it is "… no longer a question of if but when autonomous vehicles will hit the road"(Mosquet et al., 2015). Development of autonomous vehicles is gaining momentum across a broad front with multiple stakeholders including vehicle manufacturers, government agencies, academic institutions, and regulatory bodies. For example, all the major vehicle manufacturers including Ford, General Motors, Mercedes Benz, BMW, and VW have either already announced plans, or are in the process of developing or conducting public tests of their autonomous vehicles. (Audi, 2015; Bomey, 2018; Ford, 2020). Additionally, some non-traditional vehicle manufacturers such as Tesla, some mobility companies such as Uber and technology companies such as Google are developing and testing autonomous vehicles (Hawkins, 2019; Tesla, 2021).

It is anticipated that autonomous vehicles will be available for use (or, at least, for testing) on public roads by the early 2020s, with commercial availability by 2025. Further, if the adoption trend follows that of previous vehicle technologies, AVs will be commercially available by 2030 (Litman, 2017). This is however still an optimistic estimate as the early versions are likely to be limited in capability and of excessive purchase cost thus inhibiting mass adoption by the market. Therefore, the market penetration of AVs is likely to be low at first (with only the early adopters and affluent customers) but will grow in the subsequent years as prices decline and/or the technology matures.

There are several challenges to the mass market adoption of AV technology. The obvious ones are the limitations of the technology and the prohibitively high purchase price. In this context, researchers have developed models to forecast the trend of adoption of AVs and their market penetration over the next few decades. These demand models often use approaches that consider adoption rates of previous automotive technologies such as adaptive cruise control (Litman, 2017), other disruptive technologies such as the internet, and cell phones (Lavasani et al., 2016). Demand models typically consider demographic factors and previous vehicle ownership (Bansal & Kockelman, 2017). In all these, the estimates of AV market penetration vary from around the single digit percent in the late 2020s to as high as 90% by 2060 depending on the model employed and the level of automation considered as shown in Table 3.2. Lavasani et. al. (2016) developed a Generalized Bass Diffusion model by considering market size, user adoption behavior and historical data on the penetration patterns of earlier technologies such as cell phones and the internet. The study predicts that cumulative AV sales in the US will follow a sigmoid curve. Assuming an available market cap of 87 million vehicles, the cumulative AV sales will gradually rise from 1.3 million in the late 2020s to 8 million by 2035, and rapidly increase to 36 million by 2040, through 70 million by 2045 and reach market saturation at 87 million sales by 2060. Also, Litman (2017) used the Bass Diffusion model to estimate high and low estimates of AV market penetration and suggested a similar s-curve adoption model, with AVs accounting for 20% of new car sales by 2035, increasing to 60% by 2050 and reaching market saturation by 2070. Ownership and travel follow a similar trend, AVs accounting for 10% and 12% of ownership and travel respectively by 2035, increasing to 30% and 35% by 2050 through 90% and 93% by 2070.

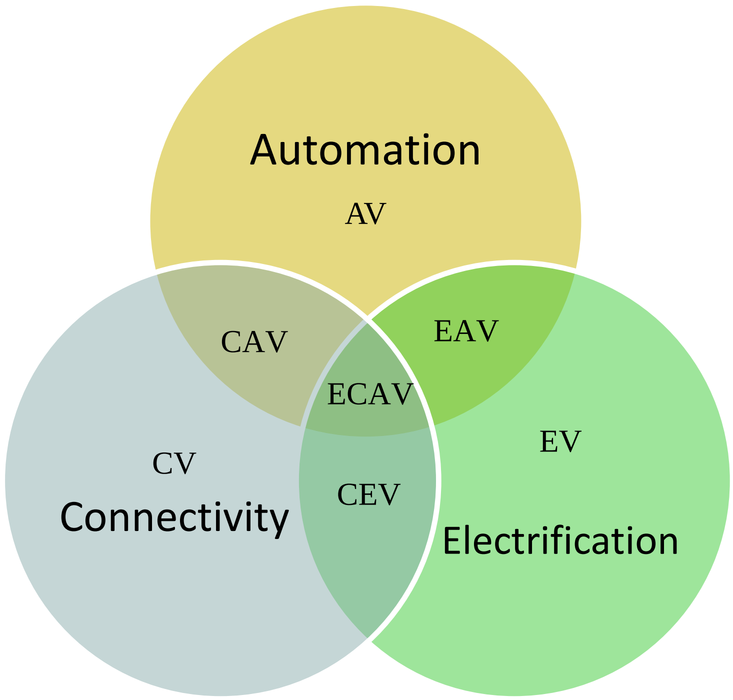
In forecasting autonomous vehicle adoption rates and market penetration, several factors on the demand and supply side must be considered. These include government regulation and incentives, affordability of the technology and its evolution over time, consumer willingness to pay and available levels of automation (Labi et al., 2015; Saeed et al., 2021; Saeed et al., 2020). Technologies such as adaptive cruise control and lane keeping assist have already made their way into current vehicles, although they took several years after their introduction to become commonplace due to their high costs. For example, adaptive cruise control has only achieved a 6 percent market penetration rate globally and in the US (Mosquet et al., 2015) despite being on the market for about a decade.

Table 3.2: AV market penetration forecasts

Reference	Model / Approach	AV / Level of automation forecasted
	Ownership and market penetration	
(Saeed et al., 2020)	Consumers' preference survey	26%-28% of respondents would prefer to use privately owned AVs whereas only 2% - 9% would use shared AVs, at least in the early stages.
(Litman, 2017)	Bass Diffusion Model	15% and 30% of US vehicle fleet will be equipped with L4 AV capabilities by 2040 and 2050 respectively, 80% by 2070.
(Bansal & Kockelman, 2017)	Simulation-based fleet evolution framework	25% Level 4 AV market penetration by 2045 assuming 5% annual price drop and constant willingness to pay (from 2015 onwards) values. 87% AV penetration if assuming 10% annual price drop and 10% increase in WTP.
(Mosquet et al., 2015)	Survey of consumer's willingness to pay	AVs will have a global market share of 15% for partially automated and 10% for fully automated vehicles by 2035.
(Begg, 2014)	Cross-section survey of transportation experts	35% of respondents forecasted level 4 AVs will be on public roads by 2025, and 28% stated level 5 AVs will be available by 2050.
	Sales Forecast	
(Litman, 2017)	Bass Diffusion Model	60% and 70% – 90% of new cars to be AVs by 2050 and 2060, respectively.
(Mosquet et al., 2015)	Survey of consumer's willingness to pay and analysis of previous trends	AVs making up 20% – 40% of new cars sales globally by 2035 – 2040.
(ABI-Research, 2013)	-	50% of new car sales in US to be fully autonomous by 2032.
(Lavasani et al., 2016)	Generalized Bass Diffusion Model	8 million (10%) and 84 million (90%) cumulative AV car sales by 2035 and 2050 in US, respectively.

3.4.3 Vehicle Electrification: Comparing Evolution of Electric Propulsion and Automation

It is generally assumed that autonomous vehicles will be electrically powered, with battery power being the most obvious choice. In fact, almost all the companies developing autonomous vehicles (Tesla, General Motors, Mercedes Benz, etc.) are all developing versions of battery powered EVs (Ford, 2020; Hawkins, 2019; Tesla, 2021). It is important to note however that automation and electrification require different technologies and are not generally dependent on one another. That the two technologies are being pursued and developed in tandem is driven more by a mix of coincidental market forces rather than the inherent interdependency of the technologies in question The push towards electrification is mainly being driven by the rise in climate awareness fueling the move away from fossil fuels (Deloitte, 2020; Engel et al., 2018; Mead, 2021; USDOT, 2019), Automation on the other hand is being driven by advances in computational power and data availability giving way to artificial intelligence (Abbott et al., 2017; Chen et al., 2020; Ha, Chen, Dong, et al., 2020; Ha, Chen, Du, et al., 2020). Vehicle automation relies on advancements in sensor technology and computational power whereas electric propulsion relies on improvements in battery technology or wireless charging. Therefore, it is possible to, for example, have autonomous vehicles that use internal combustions engines or electric vehicles that are not autonomous (as evidenced by the current fleet of electric vehicles). These relationships are illustrated in Figure 3.6.



Legend
AV: Autonomous Vehicle
EV: Electric Vehicle
CV: Connected Vehicle
CAV: Connected Autonomous Vehicle
EAV: Electric Autonomous Vehicle
CEV: Connected Autonomous Vehicle
ECAV: Electric, Connected Autonomous Vehicle

Scenarios
1-3: CV
4-6: AV
7-9: EV
10-12: EAV
13-15: CAV
16-18: ECAV

Figure 3.6: Relationships among the emerging vehicle technologies

Vehicle automation and electric propulsion, even though they rely on different technologies, are being pursued in tandem. Companies that are working on autonomous vehicle technologies are also investing heavily into battery research and electric propulsion. Further, while this might be feasible for small vehicles, it is technologically more challenging for heavy duty vehicles. Road freight transport is the most energy intensive mode (in terms of ton-miles) and runs almost exclusively on fossil fuels (Çabukoglu et al., 2018). This is because fossil fuels have higher energy density compared to their battery counterparts. Some of the best lithium ion batteries have energy densities of just over 700 Wh/kg (Zhang et al., 2010) whereas the conventional diesel fuel has energy density of over 13,700 Wh/kg (EIA, 2020). As a result, battery powered vehicles must dedicate significantly more weight to the batteries, leaving little room for the payload. This is problematic in the case of freight where the goal is to maximize the payload.

In addition to the low energy density, battery powered vehicles must contend with the charging time and electricity usage. Liimatainen et al. (2019) estimated that the potential for electrification of freight transport varies across markets, from as low as 35% in Finland to as high as 71% in Switzerland. This level of electrification, however, comes at the expense of increased electricity usage and potential overloading of local grids near logistic centers and rest stations along routes. Additionally, they noted that this may only be suitable for medium duty trucks (Liimatainen et al., 2019). (Çabukoglu et al., 2018) introduced a data-driven, bottom-up approach to explore the technical limits of electrification using real data from the entire Swiss truck fleet. They found that full electrification increased the total Swiss electricity demand by about 5% (3 TW h per year) over its current level. Consequently, they concluded that the potential of full electrification for trucks would require (1) an allowance to exceed current maximum permissible weight regulations, (2) a high-capacity grid access for charging at the home-base (at least50kW) and (3) a supporting intra-day energy infrastructure, e.g., battery swapping (Çabukoglu et al., 2018). Cabukoglu et al., (2019) proposed the use of hydrogen fuel cells as a potential replacement for gasoline as it appears to solve the weight issue that hinders batteries and can be refueled in just half an hour with proper infrastructure in place. By simulating the entire Swiss truck fleet to run on fuel cell propulsion system, they found that this would draw over 8 TWh of electricity to produce the necessary amounts of hydrogen. Consequently, all the gains that would result from decarbonization of the transportation would immediately be negated by indirect emissions of generation, leading virtually no difference in overall carbon emissions (Çabukoglu et al., 2019). They concluded that while fuel cells are an attractive decarbonization agent for heavy duty vehicles, significant investments would have to be made to ensure that hydrogen production is truly renewable. With the current technology therefore, replacing diesel in heavy duty vehicles seem implausible and thus even with full automation, it is expected that these fleet of vehicles will still operate with internal combustion engines.

For the purpose of this thesis, various scenarios and combinations of electrification and automation are considered for their impacts on the highway infrastructure expenditure and revenues. The scenarios and the accompanying assumptions are discussed in the sections that follow.

a) Electric Propulsion with no Automation

The first scenario considered in the analysis is electric propulsion without automation features. The vehicles considered in this category include battery powered electric vehicles (BEV) and some hybrid electric vehicles (HEV). The lack of automation in these classes of vehicles reflects the current situation where the electric vehicle market consists of vehicles in this category. With the wide availability of driver assistance features in modern vehicles however, it is hardly realistic to assume the complete absence of any automation in current-day electric vehicles. It is expected that at the very least, electric vehicles will be designed with intelligent power and energy management systems to monitor the system power usage and advise the driver of the remaining battery power and recommend changes to driving styles to conserve energy. Additionally, cellular, and other connectivity features to enable the drivers locate charging stations within the network are expected to be present in these vehicles. With these technology features, it is reasonable to expect basic driver assistance features such as cruise control, lane-keeping assist and so on, will be present in electric vehicles. Hence, even though these will be classified as human-driven vehicles, they will possess at least Level 2 automation by SAE automation standards (SAE, 2018).

For purposes of this thesis, electric propulsion is considered for all the vehicle classes at various levels of market penetration. At low market penetration, say 20% to 30%, electrification of vehicles can be expected to have marginal effects on fuel revenues as the amount of gasoline and diesel being consumed decreases. The connectivity features and level two automation features that come with it are not expected to have any significant impact on highway expenditures. At this level of penetration, private parties and governments are not incentivized to invest heavily in supporting infrastructure. Additionally, vehicle platooning and potential increases in road capacity are not expected since at most only 30% of vehicles will have the relevant enabling features (Hussein & Rakha, 2020; Zhang et al., 2020). Thus, at low market penetration, electric vehicles are expected to have a marginal impact on fuel revenues but no significant impact on overall travel patterns and highway expenditures. At moderate market penetrations of 40% to 60%, the impacts on fuel revenues are expected to be significant as about half of all vehicles will be electric and thus will neither purchase nor consume fossil fuels. Simultaneously, the impacts from connectivity and available level two automation features will be significant at this level. Vehicle platooning and coordination will be possible to a significant degree resulting in increased roadway and intersection capacities. Consequently, overall VMT may be expected to increase. For purposes of this thesis, we assume a 5% increase in overall VMT at moderate market penetration of EVs. Finally, at high market penetrations of 70% to 90%, we can expect to see the same effects on travel and VMT as we would from the connected vehicle scenario. These include increased roadway and intersection capacity because of proper vehicle coordination and platooning. As in the case with vehicle connectivity, we assume a 10% increase in overall VMT at this stage. Further, a high market penetration of electric vehicles will have significant impacts on fuel revenues because approximately 10% to 30% of vehicles will consume fossil fuels. Table 3.3 presents a summary of the scenarios, accompanying assumptions, and the expected impacts on highway expenditures and revenues.

Table 3.3: Summary of expected impacts of vehicle electric propulsion

Scenario	**Impact at given Market Penetration**		
	Low	Moderate	High
Total VMT	Minimal / negligible	Marginal 5% increase	Significant 10% higher
Highway Expenditures	Minimal / negligible	Marginal 5% increase	Significant 10% higher
Highway Revenues	Marginal	Significant	Severe impact

b) Automation with no Electrification

The second scenario considered in this thesis is the presence of automation without electric propulsion. This scenario can also be considered a posible scenario because electric propulsion and vehicle automation rely on different technologies which are developing at different paces. While electrification relies mostly on advances in battery technology, automation relies mostly on improvements in sensor technology and computational capacity and control algorithms. It is not necessary that these two technologies develop together or necessarily depend on one another. Thus, it is possible and realistic to have fully automated vehicles that operate on internal combustion engines.

Similar to the previous scenarios considered, this scenario explores three levels of AV market penetration: low, moderate and high. Vehicle automation is expected to have significant impacts on overall travel patterns and VMT, and consequently on highway expenditures. This is in part because much of the highway expenditures are as a result of infrastructure deterioration resulting from traffic loading. Thus, expenditures on new infrastructure and maintenance and rehabilitation are expected to increase with VMT and ESAL miles.

The precise implications of automation on overall VMT are hard to ascertain. Scholars have offered contending views on the subject, some arguing for an overall increase in VMT while others argue the opposite. Those that argue for a decrease in overall travel point to the possibility of ride sharing which is expected to be enabled by automation. Ride sharing, they argue, reduces the need for every person to make a separate trip or even own a vehicle and therefore results in overall decrease in the total VMT (Fagnant & Kockelman, 2018; Litman, 2017). Those that argue for an increased VMT resulting from automation cite among other things, induced demand that may result from an apparent increase in road capacity as a result of automation at high market penetration levels (Cervero, 2001; Gucwa, 2014). In addition, at low market penetration, pent-up demand by early adopters and automation enthusiasts will drive up overall VMT (Fagnant & Kockelman, 2015a). Furthermore, ride sharing may not have enough of a market share to offset the increase in VMT stemming from other competing effects.

For this analysis therefore, an overall VMT increase because of automation is assumed. Using similar reasoning and assumptions as Fagnant and Kockelman (2015), a 10% increase in VMT due to automation at low market penetration, and subsequently 15% and 20% increase at moderate and high market penetrations, respectively, are assumed. As highway expenditures depend on vehicular volumes and loadings, one can expect these to increase with VMT and ESAL miles. By and large, automation will require some degree of connectivity for its full benefits to be realized. However, expenditures on related infrastructure such as network equipment and cloud infrastructure are expected to be borne by private entities. Government agencies may increase their expenditure to modernize or upgrade some of the existing infrastructure such as traffic lights at intersections, traffic detectors and lane markings. However, these expenditures are expected to account for only a small fraction of the overall expenditure. This scenario assumes the use of internal combustion engines in the AVs. Therefore, revenues will grow with the VMT as expected. However, due to assumed connectivity and changes in driving patterns expected with automation, fuel economy (and hence consumption of the AV fleet), will likely be much higher compared with conventional vehicles. Therefore, overall fuel revenues will decrease compared with a fully human-driven fleet at similar VMT levels.

c) Electrification with Automation

This scenario examines the combined effects of electric propulsion with vehicle automation on highway expenditures and revenues. Electric propulsion is not expected to impact overall very significantly. In fact, as shown in Table 3.3, VMT is expected to increase up to 10% at high market penetration rates. Therefore, the effects on highway expenditures of electric propulsion are expected to be of similar magnitude. The effects on highway revenues, however, are expected to be significant due to the sharp decline in fuel consumption. Vehicle automation is expected to result in increased overall VMT. The prospective increase in overall VMT corresponds to an increase in vehicular loading on infrastructure, leading to faster deterioration. This implies that more frequent maintenance (and ultimately, increased expenditures) overall. However, automation alone is not likely to impact revenues significantly because the vehicles are still expected to run on internal combustion engines, meaning they will still purchase and consume fuel, thus still contribute their share to the revenues. Consequently, under this paradigm, revenues (as well as expenditures) are expected to grow in with the VMT. Thus, the equity ratios are not expected to change significantly under this scenario.

The combination of automation and electrification, however, is expected to significantly impact both revenues and expenditures. Automation will drive up expenditures while electrification will drive down revenues. The resulting combination is expected to produce an inequitable arrangement, where most vehicle classes are expected to contribute far less in revenue than their share of repair costs. It is however a matter of conjecture whether the combined effect will simply be a sum total of the separate effects of the two scenario or a synergistic outcome (where the combination has a greater impact than that of the sum total of its parts). For the simplicity of analysis, the former scenario is assumed, even though the reality may indeed contain synergistic characteristics. Since there is not exact way to model the extent to which that may occur, a sum total of the impacts is assumed for this analysis.

When discussing electric propulsion in vehicles, their efficiency is usually quoted in equivalent miles per gallon (MPGe). This is for the ease of comparison with conventional internal combustion engine powered vehicles. For passenger cars, equivalent fuel efficiencies can range from 150 mpge to 120 mpge, and pickup trucks and SUVs may range between 90 to 110 mpge (Loveday, 2018) and electric buses fuel efficiency is about 17 mpge (Eudy & Jeffers, 2018), as detailed in Table 3.4. While this works well for easy comparison of electric vehicle with conventional vehicle efficiencies, it cannot be used for fuel revenue analysis. Consider the extreme case where all vehicles in the fleet at electric, then no fuel would be consumed and the fuel revenues in that case would be zero. However, looking at equivalent fuel consumption equivalents would suggest that fuel is being consumed, albeit significantly less than conventional vehicles, yet still in contradiction with the already established premise. Thus, MPGe numbers should only be used for efficiency comparison and not for fuel revenue computations.

To compute fuel revenues in the electric vehicle paradigms, electric vehicles are simply excluded from consideration. Hence, if we have 50% market penetration of electric vehicles, these are simply excluded from the fuel revenue computation and only the remaining 50% are assumed to contribute to the fuel revenues. The electric vehicles do still contribute their share of non-fuel revenues such as registration taxes, wheel taxes, heavy vehicle surcharge tax and so on. With this approach, all possible scenarios, including edge cases (0% or 100% market share) are accurately accounted for. If 100% of the vehicles are electric, then fuel revenues would be zero, and if 0% of the vehicles are electric, then the revenues would be computed as conventionally done, and all cases in between are accounted for accordingly.

For lighter vehicle classes (FHWA classes 2 – 7), full or hybrid electric propulsion is likely. For heavier vehicle classes, more concerns still exist on the viability on electric propulsion, particularly for freight transportation (Çabukoglu et al., 2018, 2019; Davis & Figliozzi, 2013; Feng & Figliozzi, 2012). For the purpose of this thesis, it is assumed that all AVs in these categories shall be electrically powered. Equivalent fuel efficiency figures for the various vehicle user groups vary based on vehicle size and manufacturer specifications. The equivalent fuel efficiency figures for the various classes of vehicle user groups are summarized in Table 3.4.

Table 3.4: Average Gasoline and Diesel fuel efficiency and equivalent average fuel efficiency for EV [data sources: (EnergySage, 2021; EPA, 2021; Volovski et al., 2015)]

Vehicle Class	Average Fleet Fuel Efficiency - Gasoline (MPG)	Average Fleet Fuel Efficiency - Diesel (MPG)	Average EV equivalence (MPGe)
1	42.50	N/A	42.50
2	23.30	23.30	130.00
3	17.18	17.18	130.00
4	7.20	7.20	17.30
5	9.37	13.80	20.00
6	6.34	8.55	18.00
7	6.34	8.55	17.00
8	5.36	6.06	15.00
9	5.36	6.06	15.00
10	5.36	6.06	15.00
11	5.36	6.06	15.00
12	5.36	6.06	N/A
13	5.36	6.06	N/A

3.5 Estimating VMT Changes Due to CAV Introduction in the Market

A large percentage of vehicle trips are made by persons who do not derive direct personal benefits from the trip but undertake the trip so that others can benefit (Labi et al., 2015). Examples include drivers who drive children to school, and the infirm to hospitals or other activity centers. Considering that some of these classes of passengers could be put in a CAV and sent to their destinations without a driver at the wheel, CAVs can be expected to cause an increase in travel. However, the notion that CAV operations will increase travel is debatable, as certain CAV proponents have sought to link driverless vehicles with reduced travel.

This section discusses the overall net effect of CAV on VMT because a reliable assessment of system usage is a prerequisite element of highway cost allocation. It is also used to forecast the revenue generated from user-based fees and taxes such as fuel tax and tolls. The system usage was quantified in terms of VMT for each vehicle class which was then be used to allocate the pavement and bridge costs to the users. A baseline for the current system usage was adopted based on the work of Agbelie et al. (2016), developed based on available data sources (video, Weigh in Motion, automated traffic recorders, and so on). The baseline VMT was then be adjusted using the available information (see Section 3.1 of this thesis) and earlier established assumptions on the level of CAV penetration.

It is hard to accurately ascertain whether adoption of CAVs will result in an overall VMT increase or decrease because there are competing factors at play. By granting mobility to sections of the population that are currently unable to drive or are otherwise unlicensed, CAVs may increase the overall VMT. However, the advent of shared AVs may likely reduce the total VMT. This is because people may use the same vehicle for travel and share trips rather than everyone taking their own car and increasing the overall VMT. This could reduce the total vehicle ownership and consequently the VMT (Litman, 2017). This is consistent with the results found by Fagnant and Kockelman (2018) in an agent-based simulation analysis of a shared AV fleet in Austin, Texas. The simulation showed that AV ghost trips fell by 4.5% and net VMT fell slightly when demand for the shared AV fleet rose and ride sharing was permitted (Fagnant & Kockelman, 2018). It is worth noting however that such a scenario is only feasible in very dense urban environments where most of the trips made are commuter-style trips of only a few miles in length. It may not be applicable to sparsely populated areas where longer trips are made.

A general view is that in era of CAV, total VMT will increase rather than decrease. Fagant and Kockelman (2015) argue that early adopters of AVs will have pent up demand than later buyers, which could lead to an increase in VMT at lower AV market penetrations, say 10%. Further, at higher market penetrations, say 90%, many benefits of CAVs such as increase in lane and intersection capacity due to the autonomy and connectivity of CAVs may lead to induced demand resulting increased VMT (Fagnant & Kockelman, 2015a). It may be difficult to ascertain which of these competing demands may be dominant. However, the reduction in total VMT may only be realized if shared AVs are adopted on a mass scale, for which there seems to be no indication, judging from trends of current use of shared rides and public transit. Further, Saeed et al., (2020) showed that only a small percentage of users (2% - 9%) would prefer to use a shared AV service in rural and urban areas, respectively. Induced demand however may arise due to realized benefits from CAV adoption, such as reduced congestion (Ha, Chen, Dong, et al., 2020), increased safety (Du et al., 2020), smoother traffic flow (Li, Chen, Dong, et al., 2020), etc. Increase in lane capacity, for example, can be thought of as having the same effect as adding additional lanes to an existing road. Analyses have shown that adding more lanes to an existing corridor has the effect of inducing demand over the long term (3 to 6 years) with an elasticity ranging between 0.47 – 1.0 with an average regional elasticity of 0.74 (Cervero, 2001). This implies that for every 1% increase in lane miles, the induced demand increases by an average of 0.74%. A network approach, however, may not yield the same result because not all links in a network are congested and thus the increase in capacity may not affect all the links in the same way. Furthermore, some networks may have congestion pricing schemes in place that may further curb the induced demand.

The third factor of consideration is the changes in the value of travel time (VOTT) that will come about with CAVs as individuals will now be able to work or relax during their commutes. A simulation by Gucwa (2014) showed that increasing road capacity while reducing travel time values resulted in a 4% to 8% increase in total VMT (Gucwa, 2014). Taking these considerations into account, Fagnant and Kockelman (2015) prognosticated a 20% increase in VMT at 10% AV market penetration and 20% at 90% AV market penetration, across the entire system, applying to shared AVs, personally-owned AVs and AVs used for shipping and freight. For the present study, a modified version of the aforementioned set of assumptions are used. The study assumes a 10% overall VMT increase at low CAV market penetration, 20% at moderate levels and 30% VMT increase at high CAV market penetration levels.

3.6 Anticipated Changes in Highway Expenditures due to CAV Operations

3.6.1 Pavement Expenditures

The expenditures associated with new pavement construction include pavement-related items, grading and earthwork, shoulder, right-of-way (ROW), drainage, and erosion control, and miscellaneous expenditures. Some of these expenditures can be expected to change in the CAV era. These are treated as common costs and are therefore allocated to the vehicle classes based on their post-CAV VMT contributions. The pavement-related expenditures consist of the expenditures of a base facility and that of the remaining facility. The base facility forms the base 'platform', upon which the remaining facility is built. The remaining facility provides strength to carry the expected traffic loading over the pavement's service life. In this thesis, the base facility expenditures are attributed to vehicle classes based on VMT and those on the remaining facility are attributed based on ESAL-miles.

For allocating pavement rehabilitation costs, the several expenditure categories are considered including grading and earthwork expenditures, drainage and erosion control expenditures, pavement-related expenditures, and shoulder expenditures. Because pavement damage is caused by both traffic loading and other factors such as climatic conditions, a portion of the pavement-related expenditures is attributed to load (traffic) using FHWA's NAPCOM models and the remaining attributed to non-load and therefore, will be allocated to the road users (vehicle classes) based on their respective VMTs.

Expenditures that are due to non-load related items, such as roadside work and facilities, ITS, and mobility enhancements are considered common costs. Common costs allocated among the vehicle classes based on their VMT contributions. Figure 3.7 is a simplified version of Figure 1.3 and presents the overall approach taken to evaluate the impact of new vehicle technologies on highway expenditures and revenues.

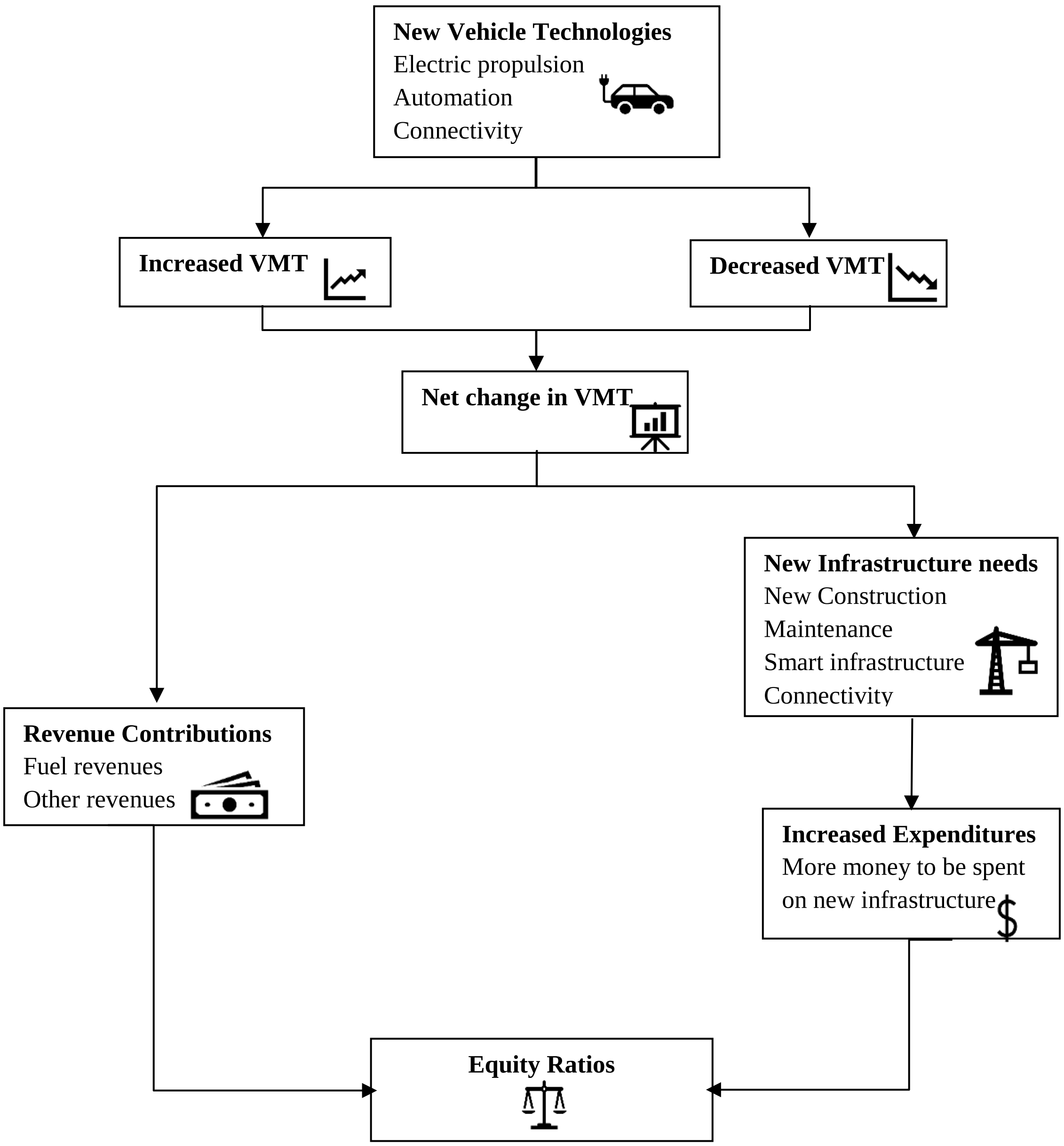


Figure 3.7: Evaluating the impacts of new vehicle technologies on highway revenues, expenditures, and equity.

3.6.2 Bridge expenditures

Bridge expenditures can be expected to change in the era of CAV operations as changes in overall VMT resulting in different vehicular loading on the bridge infrastructure. Different vehicle class have different weights and therefore result in different loading on bridges. As the vehicle weight increases, it exerts larger moments on the structural elements, inducing higher stresses in the members. Consequently, stronger, and larger load bearing members are required to support these loads. Therefore, bridge construction becomes more expensive when heavier vehicles must be accommodated. Furthermore, heavier vehicles tend to cause more wear and tear during the service life of the bridge. Each vehicle class must therefore pay its share of the costs incurred to accommodate the stress corresponding to its weight.

As the bridges are designed according to AASHTO design vehicles, the correlation between AASHTO vehicles and the FHWA vehicles is a key issue in the analysis. The incremental method is used in the research to allocate the costs of new bridge construction. This procedure is explained in Volovski et al. (2016).

For allocating bridge replacement costs, the bridge sufficiency rating formula is used. The sufficiency rating of a bridge is reduced when the bridge has inadequate load-bearing capacity or other problems such as inadequate width. Vehicles whose loading regimes exceed the bridge load-bearing capacity, the fraction of costs to be allocated is calculated as the ratio of the partial sufficiency rating reduction (that is, arising from lowered load-bearing capacity) to the total sufficiency rating reduction.

Unlike new bridge construction, the ratio of load to non-load expenditures in bridge rehabilitation cannot be determined in a straightforward manner. HCAS' use different percentages determine empirically. For example, the 1997 FHWA study and 1999 Oregon study used the following breakdown: deck overlay – 70%, other superstructure rehabilitation – 30%, substructure rehabilitation – 15%, bridge painting – 0%. Cost allocation for bridge rehabilitation is the same as for new construction (load related allocated based on ESALs and common costs allocated based on VMT).

3.6.3 Safety, mobility, and other Assets

Highway safety treatments, mobility enhancement projects and ITS programs all constitute common expenditures. They are therefore allocated based on VMT. However, certain expenditure items such as mobility and right-of-way, can be considered as being related to vehicle size. In such cases, size weighted measures, such PCE-weighted VMT or PCE-miles are used to allocate the costs to account for vehicle size.

3.7 Anticipated Changes in Highway Revenues due to CAV Operations

Highway revenues represent funds used to fund the construction, reconstruction, rehabilitation, and maintenance of state and local roads. In this thesis, the revenue sources are categorized as user and non-user sources (Figure 3.8). The user sources include gasoline tax, diesel tax, motor carrier surcharge tax, motor carrier fuel use tax, vehicle registration fees, driver license fees, international registration plan, oversize/overweight permit fees, commercial vehicle excise tax, wheel tax, motor vehicle excise tax and excise surtax, heavy vehicle use tax, tax on sales of trucks and trailers, and tax on tires. The non-user sources include General Fund transfers, and other miscellaneous taxes such as property tax, income tax, and state court fees.

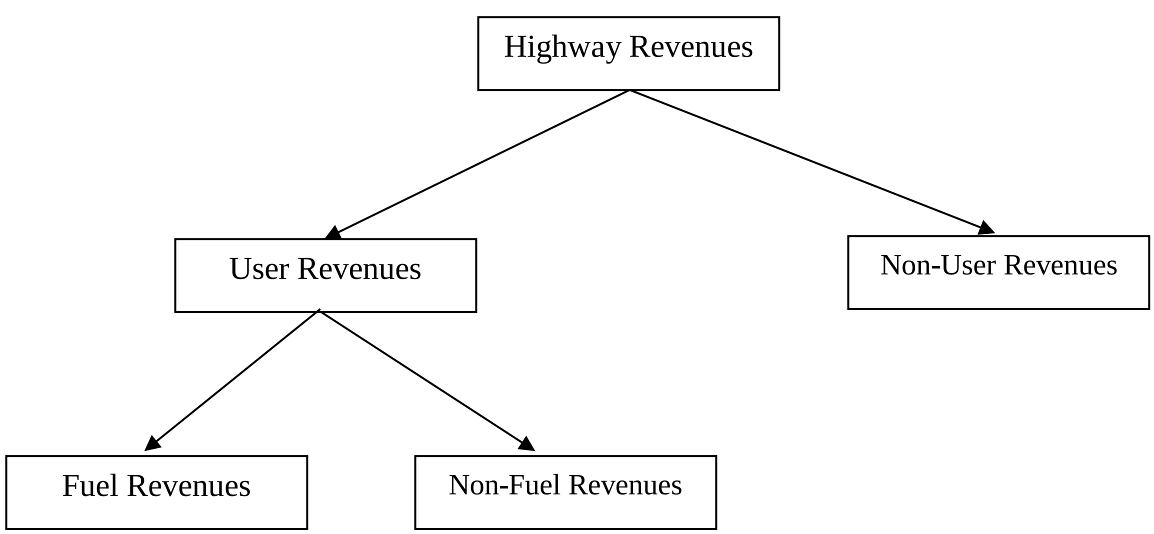


Figure 3.8: Breakdown of highway revenues

Like highway cost allocation, highway revenues generated from a given source are attributed to highway users commensurate with their level of contribution. This is called revenue attribution. Revenue attribution is carried out by determining how much revenue is generated from each user group (vehicle class), for each given source or level or government. Then, for a vehicle class, the results were summed up for all revenue sources and for all levels of government to yield the total revenue that was attributed to each vehicle class.

Building upon the results presented in Agbelie et al. (2016), adjustments were made for changes in VMT and fleet fuel efficiency due to changes in vehicle characteristics – automation, connectivity, and electric propulsion. The revenues are considered in two parts, namely fuel revenues and non-fuel revenues. Non-fuel revenues are adjusted in tandem with changes in VMT and overall travel trends. This is because they depend only the number of vehicles on the road and the prevailing tax rates. Registration, heavy vehicle surcharge, wheel taxes and so on all apply to all vehicles according to their class and regardless of their technological characteristics. Thus, if the number of vehicles increases by 10%, it is expected that the non-fuel revenues generated from those vehicle groups will also grow 10%. Fuel revenues on the other hand, are more susceptible to (and thus more influenced by) a vehicle's technological characteristics. This is because a vehicle's technological characteristics affects its fuel efficiency and ultimately the revenues contributed by that user group. The potential impacts of the different technologies on highway revenues are summarized in Table 3.5.

Table 3.5: Assumed Impacts of vehicle technologies on highway revenues

Technology	**Fuel Revenues**	**Non-Fuel Revenues**
Connectivity	Marginal	Marginal
Electrification	Significant decrease	Increase with VMT
Automation	Moderate decrease	Increase with VMT

Highway revenues are categorized as shown in Figure 3.8. This thesis does not address non-user revenues as these are affected by emerging vehicle technologies. For user revenues, non-fuel revenues change with VMT. Fuel revenues are computed using VMT and fuel efficiency numbers developed by Agbelie et al. (2016) and adjusted accordingly to reflect the technological scenario under consideration – connectivity, automation, or electrification. Highway fuel revenues for each user group are computed directly from the effective fuel tax rate, the fleet VMT and effective fuel efficiency of the fleet using Equation (3.3) below:

$$R_{i,k} = \left(\frac{VMT_i}{e_{i,k}}\right) \times T_k \times p_{i,k} \tag{3.3}$$

where i and k refer to the vehicle class and fuel type respectively, $R_{i,k}$ is the revenue generated from vehicle class i using fuel type k, VMT_i is the VMT for vehicle class i, T_k is the tax on fuel type k in dollars per gallon, $e_{i,k}$ is the fleet fuel efficiency of vehicle class i for fuel type k in miles per gallon and $p_{i,k}$ is the proportion vehicles in class i that run on fuel type k.

3.8 Chapter Summary

This chapter established the approach taken to analyze the impacts of emerging vehicle technologies on highway expenditures, revenues, and equity. The chapter first established the base case scenario, relative to which the impacts are analyzed. The base case scenario is established by extrapolating the trends in VMT over the last two decades (Section 3.1). The VMT obtained from this linear extrapolation is then used to compute the cost of infrastructure stewardship using cost functions developed in Section 3.2. This chapter also outlines projections of expected market penetration rates of the emerging vehicle technologies. It is expected that there will be lag between the initial introduction of the vehicle technologies and their mass market adoption. For many new technologies, their mass market penetration rates usually follow a sigmoid curve (Lavasani et al., 2016; Litman, 2017): a slow adoption rate in the beginning, and then accelerating as the technology becomes cheaper and widely available, and then finally slowing down as the market nears saturation. In research, this is modeled using Bass Diffusion models (Kim & Hong, 2015; Lavasani et al., 2016).

Anticipated impacts of emerging vehicle technologies on highway expenditures, revenues, and equity are also outlined in this chapter. A general view is that in era of CAV, total VMT will increase rather than decrease. Fagant and Kockelman (2015) argue that early adopters of AVs will have pent up demand than later buyers, which could lead to an increase in VMT at lower AV market penetrations, say 10%. Further, at higher market penetrations, say 90%, many benefits of

CAVs such as increase in lane and intersection capacity due to the autonomy and connectivity of CAVs may lead to induced demand resulting increased VMT (Fagnant & Kockelman, 2015a). These changes in VMT, along with the nee for increased investment in infrastructure to support the emerging vehicle technologies are expected to result in increased highway expenditures. At the same time, improvements in fuel efficiency can be expected from CAVs. This is expected to result in a decrease in fuel revenues. Furthermore, electric vehicles will not fuel. Therefore, they will not contribute to the fuel revenues and will therefore exacerbate the problem.

4. RESULTS

4.1 Introduction

This chapter presents the results of the analyses on the impacts of emerging vehicle technologies on highway expenditures and revenues. The resulting changes in equity ratios from these impacts are also presented. The results are presented for each of the scenarios (Table 3.1 and Figure 3.6) representing the various combinations of the three technologies (vehicle automation, electrification, and connectivity) at given market penetration levels of each technology. Each scenario has different revenue implications and infrastructure requirements and will require different levels of investment in supporting infrastructure from the public and agencies for successful operation. Furthermore, each scenario will have different impacts on the amount of travel and vehicle ownership, which will in turn affect the rate of deterioration of highway infrastructure. Consequently, expenditures on highway projects such as maintenance and rehabilitation and construction of new facilities will be impacted. Furthermore, the expected changes in travel patterns, coupled with potential changes in fuel economy (or lack of fuel use in the case of electrification) will impact fuel tax revenues. For each scenario, the extent of these impacts within the assumptions established in chapter 4, are presented in this section. This chapter also presents the modeling results for the infrastructure cost functions developed in Section 3.2 of this thesis. The models were used to estimate the infrastructure cost for each scenario based on estimated system usage. Detailed information and parameter specifications are provided in the next section (Section 4.2).

4.2 Infrastructure Cost Models

Section 3.2 of this thesis establishes the motivation and framework for developing infrastructure cost functions that can be used to estimate the cost of stewardship of the highway infrastructure based on the estimated system usage. Using the modelling process described in Section 3.2, this section presents the results of the developed models. The infrastructure cost models were developed for two cost categories: common costs and attributable costs. Common costs encompass expenditures that are not directly load related, and therefore include expenditures on right-of-way acquisition, safety treatments, treatments that address weather-related defects, highway administration and enforcement, and other expenditures. Because these expenditures are not load related, they are attributed to the various vehicle classes based only on their share of VMT. The second cost category is load-related or attributable costs. These are costs that are directly related to vehicle size and weight and are associated mostly with capital expenditures such as new highway or bridge construction, major structural rehabilitation and maintenance, and reconstruction. Because the intensity, and hence cost of these projects are mostly load dependent, they are attributed to the vehicle classes based on the relative weights of the vehicle classes. In this model, the chosen metric was the vehicle ton-miles. This was chosen because it encompasses both the relative vehicle miles of travel as well as the relative vehicle weight for each vehicle class. As established in Section 3.2, the general form of the cost functions is as shown in equation (4.1).

$$ln(Cost) = \alpha + \beta ln x \tag{4.1}$$

Where C is the cost of highway infrastructure stewardship, x is a measure of system usage, and α and β are model parameters to be estimated. For common costs, x represents VMT and for attributable costs, it represents vehicle ton-miles. Highway expenditure and system usage data used to fit and calibrate the models was obtained from the FHWA highway statistics (FHWA, 2020).

The model presented in equation (4.1) can be fitted using any standard statistical technique (OSL, PanelOLS, GLS, etc.) depending on the nature of the available data. This thesis employed machine learning models using the Support Vector Regression (a subset of the support vector machines algorithm) from the Scikit Learn Machine Learning Library (Pedregosa et al., 2011). The regression algorithm was implemented with the Radial Basis Function (RBF) kernel. The RBF kernel uses a nonlinear mapping that transforms that parameter space into an infinite dimension hyperspace, allowing it to fit a higher dimensional hyperplane to otherwise non-linear data. The RBF kernel generally results in a better fitting model than a linear kernel. However, due to its nonlinear nature, it is not possible to report the linear coefficients of the model as would be the case with an ordinary statistical algorithm such as OLS. Implementation details of the SVR algorithm are presented in Appendix A of this thesis.

4.3 Impacts of Emerging Vehicle Technologies on Expenditures, Revenues and User Equity

This section reports the anticipated and estimated impacts of the emerging vehicle technologies on highway expenditures and revenues. The impacts are assessed for each scenario and for different levels of maturity and market penetration (low, moderate, high). The impacts on highway expenditures are first reported, followed by impacts on revenues. Based on these impacts, user equity, and the changes thereof, are reported.

The impacts of the technologies are reported against the backdrop of an established base case scenario as detailed in Section 3.1. The impacts and infrastructure requirements maybe different for each of the technologies at various market adoption levels. Therefore, they are assessed at different levels of market penetration from low to high. Each of these market adoption levels takes place at different points in time. By extrapolating the historical trends, highway system usage, expenditures and revenues can be estimated for any given year. This forms the base case scenario for that given year. These expenditures and revenues are then adjusted for the vehicle technology in question, using the predicted changes in highway travel patterns, fuel economy, etc. and accompanying assumptions as presented in earlier chapters. A comparison is then made between the status of the expenditures under the base case and the vehicle technology in question at the specified market penetration level. User equity is then analyzed for the scenario in question and any changes (with respect to the base scenario) reported.

4.3.1 Connected Vehicles (CV)

A detailed analysis of the anticipated impacts of vehicle connectivity on highway expenditures and revenues is presented in Section 3.4.1. In summary, vehicle connectivity, in and of itself, is not expected to yield significant changes in travel patterns and volume. However, due to the connectivity, and assumed level two automation features that are expected to accompany this technology, traffic flow may be expected to be smoother at intersections and highway cruising may be slightly enhanced. Consequently, a slight increase in overall travel may be expected, and a slight improvement in fuel economy may result from this technology. This thesis assumed an up to 10% increase in overall travel and up to 10% improvement in fuel economy at high levels of market penetration of the technology. The estimated impacts on highway expenditures and revenues are reported herein:

a. Expenditures

Vehicle connectivity is expected to be widely available in many cars starting in the 2020s to early 2030s (Heiden, 2019; Litman, 2017). Currently, almost all new cars being sold come equipped with connectivity, be it cell phone mirroring (Apple Carplay, Android Auto) or in-vehicle GPS navigation, etc. This technology can be expected to gain widespread market acceptance and use as the years go by. Therefore, this thesis assumes a low market penetration rate (20% to 30%) of this technology around the year 2030. Subsequently, a moderate (40% to 60%) and high (70% to 90%) market penetration can be assumed by the years 2040 and 2050, respectively. The results reported in Table 4.1 and Figure 4.1 are based on these assumptions.

At the low market penetration, the expenditures are only slightly higher for connected vehicles than the base case. This difference can mostly be attributed to the increase in expenditures for provision of connectivity equipment, as well as the slight improvement in fuel economy for the connected vehicles. At moderate market share of CVs, the disparity is even wider as these effects are exacerbated. At high market penetration levels when most vehicles are equipped with connectivity, the need for investments in (and maintenance of) connectivity infrastructure is greater. Furthermore, by leveraging this connectivity, vehicles can better coordinate at intersections and during cruising on highways. This can lead to increases in roadway capacity, and possibly, induced demand resulting in highway overall travel, and ultimately, possible increase in highway expenditures compared with the base case, as shown in Figure 4.1.

Table 4.1: Annualized Highway Expenditure Estimates in the era of CVs from low market penetration (2020s) through high market penetration / saturation (late 2050s)

	Annualized Total Highway Expenditure for CVs			
Year	**Base Case**	**CV Lower estimate**	**CV Average**	**CV Upper Estimate**
2020	$2,381,994,219	$2,381,994,219	$2,381,994,219	$2,381,994,219
2021	$2,407,171,270	$2,407,247,974	$2,407,286,325	$2,407,324,677
2022	$2,432,211,804	$2,432,399,886	$2,432,493,923	$2,432,587,959
2023	$2,457,111,769	$2,457,457,179	$2,457,629,873	$2,457,802,561
2024	$2,481,867,471	$2,482,430,428	$2,482,711,878	$2,482,993,308
2025	$2,506,475,576	$2,507,334,140	$2,507,763,353	$2,508,192,520
2026	$2,530,933,097	$2,532,187,357	$2,532,814,335	$2,533,441,211
2027	$2,555,237,392	$2,557,014,228	$2,557,902,331	$2,558,790,225
2028	$2,579,386,153	$2,581,844,461	$2,583,072,997	$2,584,301,122
2029	$2,603,377,400	$2,606,713,534	$2,608,380,437	$2,610,046,563
2030	$2,627,209,472	$2,631,662,497	$2,633,886,888	$2,636,109,864
2031	$2,650,881,019	$2,656,737,153	$2,659,661,476	$2,662,583,299
2032	$2,674,390,991	$2,681,986,430	$2,685,777,731	$2,689,564,749
2033	$2,697,738,630	$2,707,459,756	$2,712,309,621	$2,717,152,352
2034	$2,720,923,460	$2,733,203,384	$2,739,326,008	$2,745,437,075
2035	$2,743,945,277	$2,759,255,826	$2,766,883,772	$2,774,493,517
2036	$2,766,804,138	$2,785,642,803	$2,795,020,253	$2,804,369,844
2037	$2,789,500,352	$2,812,372,442	$2,823,746,101	$2,835,078,332
2038	$2,812,034,467	$2,839,431,645	$2,853,039,944	$2,866,588,410
2039	$2,834,407,262	$2,866,784,564	$2,882,846,253	$2,898,824,041
2040	$2,856,619,734	$2,894,373,815	$2,913,077,373	$2,931,666,679
2041	$2,878,673,087	$2,922,124,551	$2,943,619,805	$2,964,963,890
2042	$2,900,568,726	$2,949,950,809	$2,974,343,867	$2,998,542,413
2043	$2,922,308,239	$2,977,763,064	$3,005,115,071	$3,032,223,362
2044	$2,943,893,389	$3,005,475,646	$3,035,805,201	$3,065,836,925
2045	$2,965,326,107	$3,033,012,866	$3,066,301,377	$3,099,234,256
2046	$2,986,608,476	$3,060,313,122	$3,096,512,034	$3,132,295,204
2047	$3,007,742,722	$3,087,330,777	$3,126,369,570	$3,164,931,585
2048	$3,028,731,207	$3,114,036,078	$3,155,830,072	$3,197,086,617
2049	$3,049,576,412	$3,140,413,641	$3,184,870,929	$3,228,731,599
2050	$3,070,280,935	$3,166,460,094	$3,213,487,241	$3,259,861,047
2051	$3,090,847,476	$3,192,181,405	$3,241,687,805	$3,290,487,327
2052	$3,111,278,827	$3,217,590,298	$3,269,491,246	$3,320,635,521
2053	$3,131,577,866	$3,242,703,972	$3,296,922,638	$3,350,338,977
2054	$3,151,747,545	$3,267,542,249	$3,324,010,759	$3,379,635,702
2055	$3,171,790,884	$3,292,126,140	$3,350,785,997	$3,408,565,629
2056	$3,191,710,958	$3,316,476,821	$3,377,278,843	$3,437,168,666
2057	$3,211,510,893	$3,340,614,932	$3,403,518,878	$3,465,483,380
2058	$3,231,193,857	$3,364,560,131	$3,429,534,137	$3,493,546,188
2059	$3,250,763,050	$3,388,330,856	$3,455,350,764	$3,521,390,916

The trend is clearer when shown graphically, as can be seen in Figure 4.1. For each of the vehicle classes, the early years following the introduction of the technology, the expenditures are close to the base case scenario, because not enough cars are equipped with the technology to have significant impacts. However, as the market penetration increases, the need for provision of additional infrastructure to support the technology as well as the increase in travel resulting from the technology, the cost begins to rise higher than the base case. This disparity increases with time, as the market penetration increases. Furthermore, the range between the lower and upper estimate also grows with time. This is because the estimates are based on projections of travel, fuel consumption and market penetration, which become less reliable the longer the timeline.

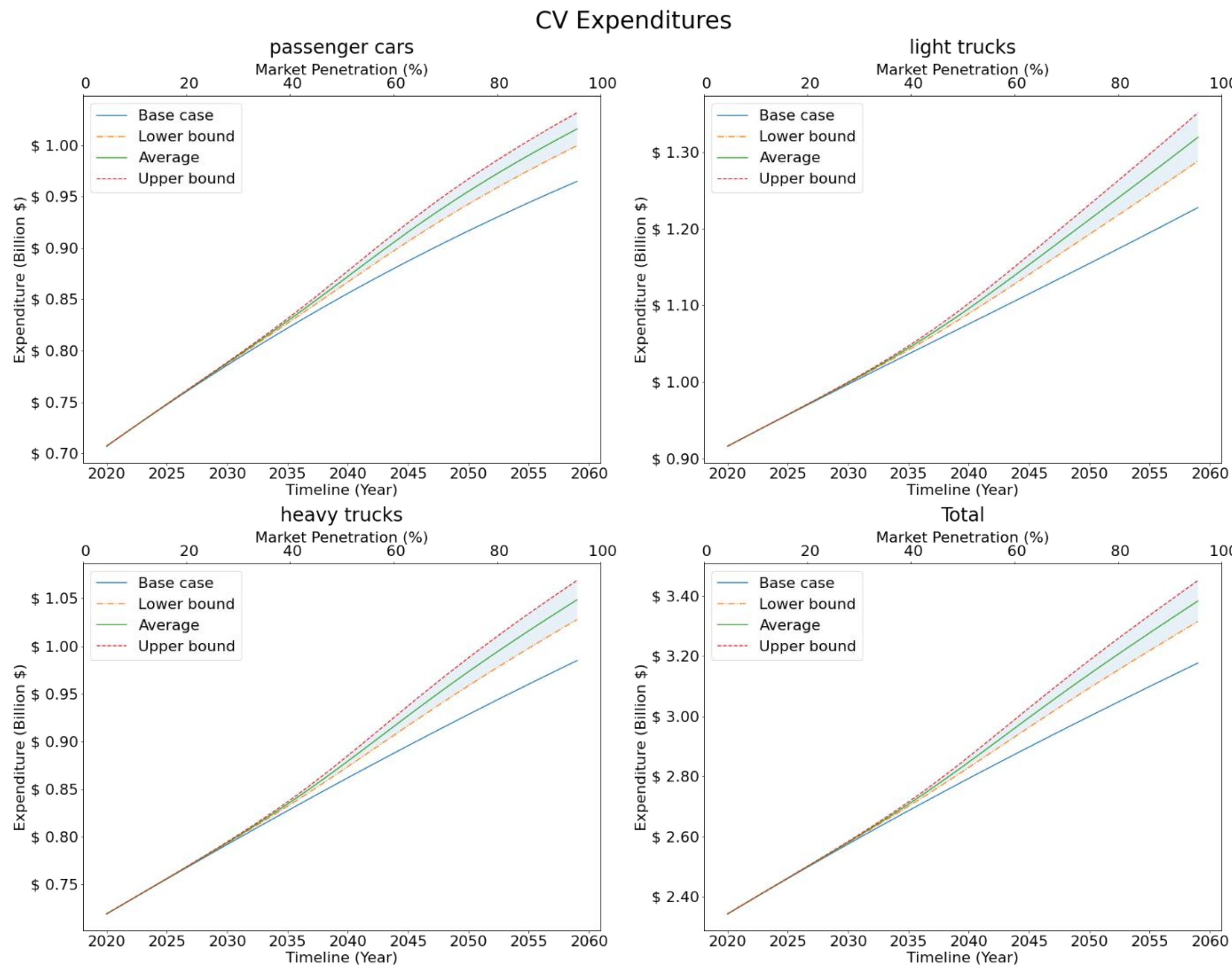


Figure 4.1: Annualized Total Highway Expenditures for the CV scenario from low to high market penetration

b. Revenues

While vehicle connectivity does not directly influence travel patterns and overall VMT, it could however result in marginal gains in fuel economy for vehicles. This is in part due to the benefits of better traffic coordination resulting from the connectivity. This enables smooth traffic flow, eliminating intermittent driving conditions that often result in increased fuel consumption. Additionally, connected vehicles are expected and assumed to contain at least level two automation features. This enables automatic longitudinal control of the vehicle, allowing it to accelerate and decelerate based on information it receives about prevailing traffic conditions, as discussed in Section 3.4.1a). As a result, a 10% to 15% increase in fuel efficiency is assumed for the revenue analysis and the results are presented in Table 4.2 and Figure 4.2 below:

Table 4.2: Annualized Highway Revenue Estimates in the era of CVs from low market penetration (2020s) through high market penetration / saturation (late 2050s)

	Total Annualized Revenue			
Year	**Base Case**	**Lower estimate**	**Average**	**Upper estimate**
2020	$2,309,096,506	$2,309,096,506	$2,309,096,506	$2,309,096,506
2021	$2,330,606,539	$2,330,601,272	$2,330,616,382	$2,330,631,492
2022	$2,352,116,573	$2,352,103,592	$2,352,140,851	$2,352,178,110
2023	$2,373,626,607	$2,373,602,648	$2,373,671,473	$2,373,740,298
2024	$2,395,136,641	$2,395,097,402	$2,395,210,251	$2,395,323,100
2025	$2,416,646,675	$2,416,586,552	$2,416,759,732	$2,416,932,913
2026	$2,438,156,709	$2,438,068,494	$2,438,323,123	$2,438,577,752
2027	$2,459,666,743	$2,459,541,288	$2,459,904,411	$2,460,267,534
2028	$2,481,176,777	$2,481,002,637	$2,481,508,491	$2,482,014,345
2029	$2,502,686,811	$2,502,449,906	$2,503,141,283	$2,503,832,659
2030	$2,524,196,845	$2,523,880,174	$2,524,809,814	$2,525,739,451
2031	$2,545,706,878	$2,545,290,361	$2,546,522,250	$2,547,754,132
2032	$2,567,216,912	$2,566,677,434	$2,568,287,833	$2,569,898,219
2033	$2,588,726,946	$2,588,038,699	$2,590,116,692	$2,592,194,657
2034	$2,610,236,980	$2,609,372,180	$2,612,019,477	$2,614,666,716
2035	$2,631,747,014	$2,630,677,037	$2,634,006,799	$2,637,336,450
2036	$2,653,257,048	$2,651,953,970	$2,656,088,475	$2,660,222,773
2037	$2,674,767,082	$2,673,205,496	$2,678,272,609	$2,683,339,353
2038	$2,696,277,116	$2,694,436,031	$2,700,564,633	$2,706,692,602
2039	$2,717,787,150	$2,715,651,685	$2,722,966,439	$2,730,280,154
2040	$2,739,297,184	$2,736,859,775	$2,745,475,809	$2,754,090,202
2041	$2,760,807,217	$2,758,068,132	$2,768,086,278	$2,778,101,940
2042	$2,782,317,251	$2,779,284,328	$2,790,787,542	$2,802,287,131
2043	$2,803,827,285	$2,800,514,980	$2,813,566,332	$2,826,612,585
2044	$2,825,337,319	$2,821,765,268	$2,836,407,652	$2,851,043,098
2045	$2,846,847,353	$2,843,038,716	$2,859,296,105	$2,875,544,340
2046	$2,868,357,387	$2,864,337,225	$2,882,217,120	$2,900,085,272
2047	$2,889,867,421	$2,885,661,301	$2,905,157,893	$2,924,639,791
2048	$2,911,377,455	$2,907,010,379	$2,928,107,959	$2,949,187,554
2049	$2,932,887,489	$2,928,383,174	$2,951,059,416	$2,973,714,066
2050	$2,954,397,523	$2,949,777,991	$2,974,006,848	$2,998,210,214
2051	$2,975,907,556	$2,971,192,980	$2,996,947,059	$3,022,671,482
2052	$2,997,417,590	$2,992,626,310	$3,019,878,696	$3,047,097,014
2053	$3,018,927,624	$3,014,076,285	$3,042,801,843	$3,071,488,690
2054	$3,040,437,658	$3,035,541,407	$3,065,717,636	$3,095,850,287
2055	$3,061,947,692	$3,057,020,399	$3,088,627,922	$3,120,186,787
2056	$3,083,457,726	$3,078,512,203	$3,111,534,987	$3,144,503,820
2057	$3,104,967,760	$3,100,015,967	$3,134,441,341	$3,168,807,254
2058	$3,126,477,794	$3,121,531,022	$3,157,349,557	$3,193,102,905
2059	$3,147,987,828	$3,143,056,855	$3,180,262,166	$3,217,396,341

At all three levels of market penetration of the technology, the differences in revenues between the base and the technology level in question is not minimal. For passenger vehicles, the connected vehicles scenarios result in increased revenues compared with the base case. This is primarily due to an increase in overall VMT, which is enough to offset the increase in fuel efficiency, resulting in an overall increase in revenues generated from this vehicle class. Light and heavy-duty trucks on the other hand do not see them same increase in VMT, in part because they make up a smaller portion of the overall VMT compared to passenger cars. Consequently, their revenue contributions see a slight decline due to improvements in fuel efficiency, compared with the base case. Overall, even though the overall VMT increases with the adoption of the technology, this increase is accompanied by a similar improvement in fuel efficiency. Consequently, the total revenues in the CV scenario are comparable to the base case.

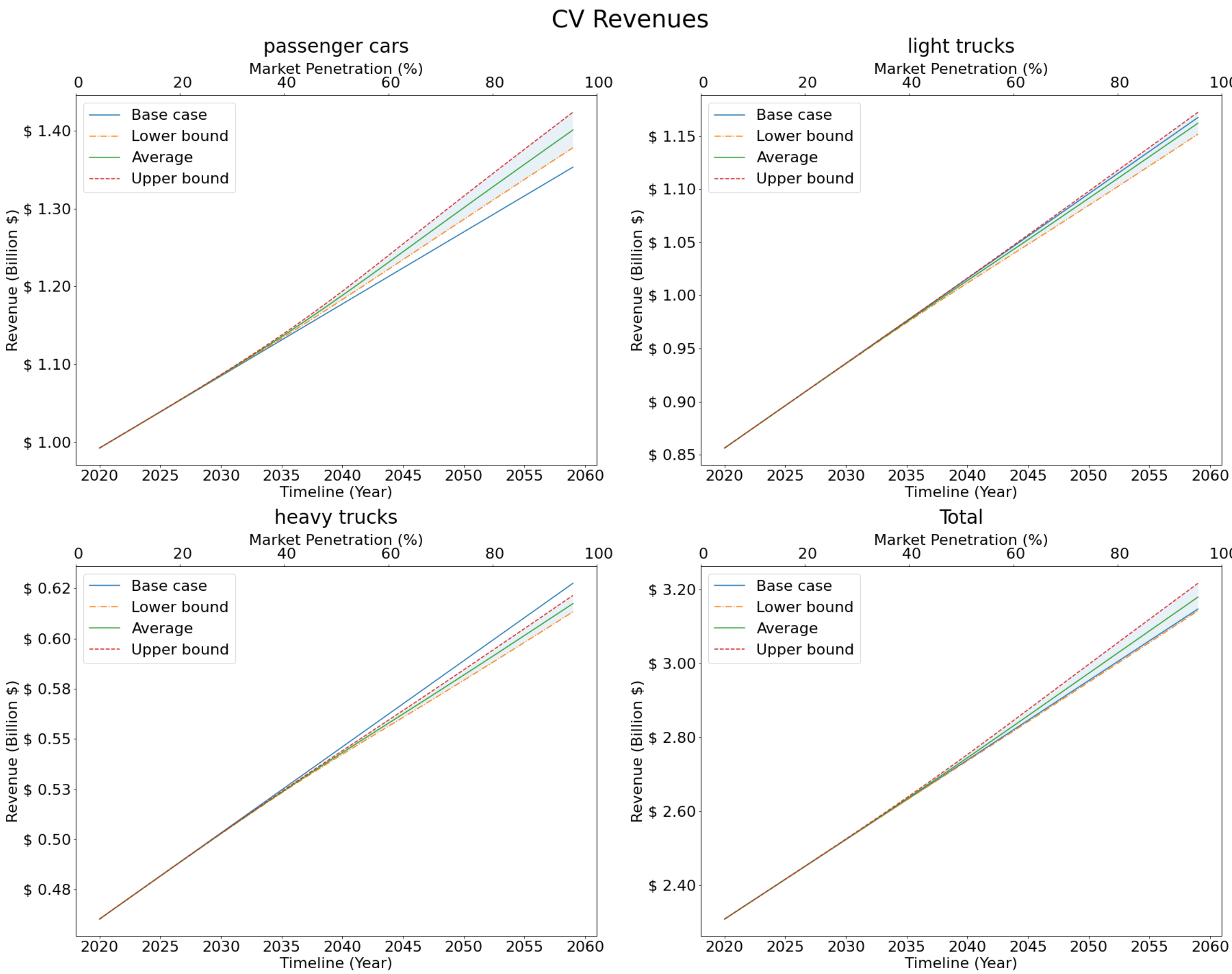


Figure 4.2: Annualized Total Highway Revenues for the CV scenario from low to high market penetration

c. User Equity Analysis

Equity ratios relate the share of revenue contributed by a given user group (vehicle class) to its cost responsibility. These revenues contributed and cost responsibility of each vehicle class are expressed as percentages of the total values across all vehicle classes. Consequently, changes to expenditures or revenues ultimately reflect as changes in equity ratios. Revenues and expenditures depend on travel volumes and patterns. In the connected vehicles environment, marginal changes are expected in the overall travel patterns and volumes, and therefore, only marginal expenditure increases on connectivity infrastructure and ITS devices are expected. Because of the expected integrated technology, connected vehicles are assumed to be equipped with at least level two automation features. This implies that they will enjoy some benefits of automation such as smooth acceleration and deceleration, better intersection coordination and throughput due to anticipated communication with other vehicles and infrastructure, etc. With these benefits, connected vehicles are expected to have a 5% to 15% improvement in fuel efficiency depending on the prevailing circumstances.

The slight increase in VMT and the resulting need for ITS infrastructure to support vehicle connectivity results in marginally increased expenditures. Revenues, on the other hand do not increase by the same amount and see a slight decrease due to improved fuel efficiency. Consequently, equity ratios decline with increased market penetration rates of connected vehicles. For passenger cars, the increase in VMT and the improved fuel efficiency influence expenditures and revenues differently at different levels of market penetration, but ultimately appear to balance out each other (Figure 4.3). This results in the equity ratio declining at first, then increasing with higher market penetration rates. For light and heavy-duty trucks, the equity ratio does not increase to the same degree, in part because these classes experience a less dramatic shift in VMT compared with passenger cars. In all cases however, the equity ratio in the connected vehicles scenario is less than the base case at all levels of market penetration.

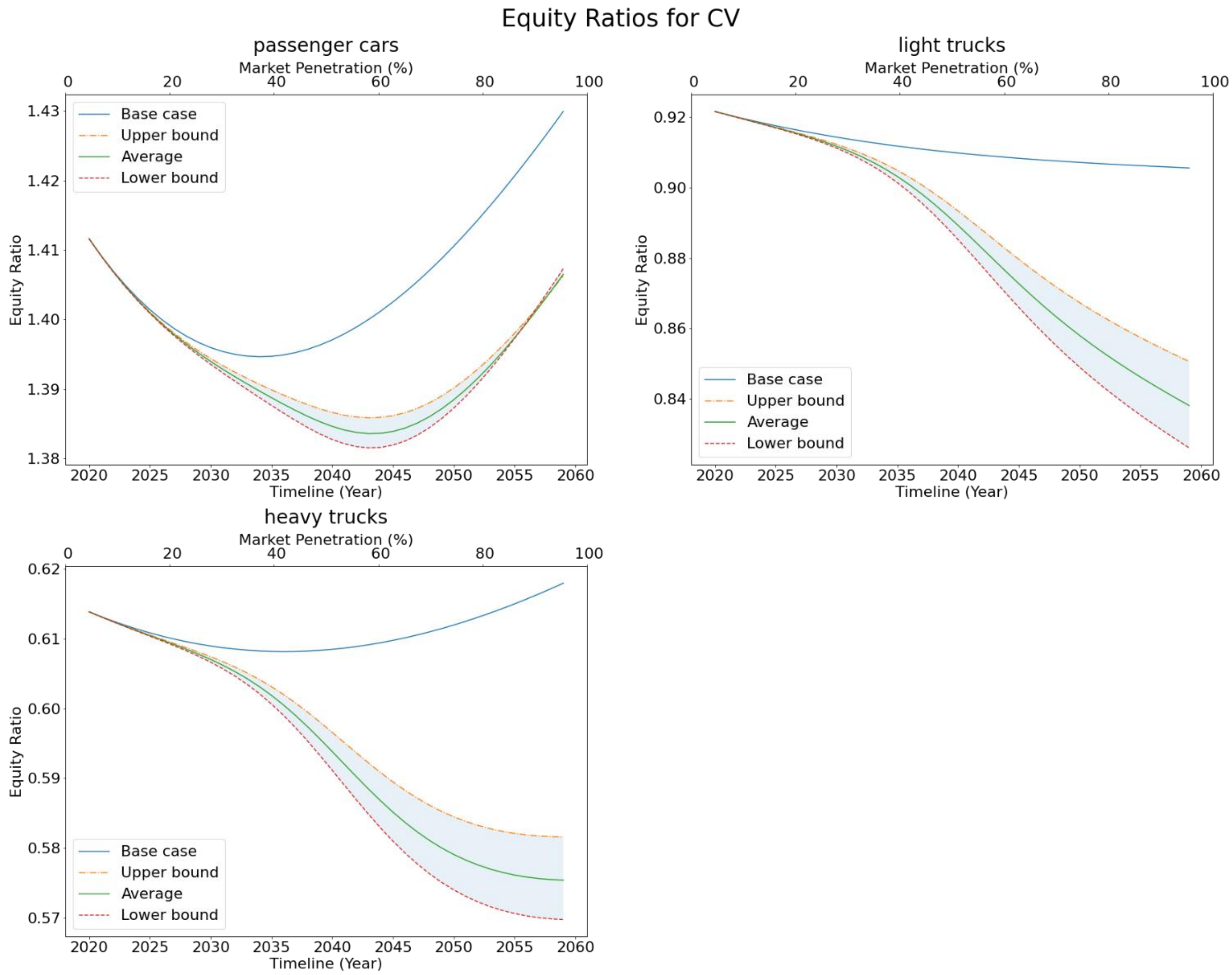


Figure 4.3: Equity Ratios for Connected Vehicles scenario from the low through high market penetration

The overall decline in revenue contributions of each vehicle class is manifested by the results (decreases in equity ratios) across the classes. Across the various levels of market penetration of vehicle connectivity, the light and heavy-duty vehicle classes seem to be underpaying their share of the cost responsibilities compared with the base case. The equity ratios in each case show significant levels of inequity in the system. In all cases, the passenger-car class overpays its share of the cost responsibility. Also, light-duty trucks are underpaying their share of the responsibility, albeit much less severe compared to the heavy-duty truck class. In all cases, the heavy-truck class only pays a fraction of the proportion in revenue compared to their share of the cost responsibility, with equity ratios less than 0.6 in all cases. There is therefore a need to revise the user fee structure to reduce inequity in the highway5 system.

4.3.2 Automated Vehicles (AV)

In the section, we discuss vehicle automation with regard to its impacts on overall VMT and ESAL distribution among the 13 FHWA vehicle classes, herein reconstituted as three vehicle classes: passenger cars, light-duty trucks and heavy-duty trucks. The VMT changes consequently impact the cumulative damage and deterioration rates of the pavements, bridges, and other highway assets, and therefore directly impact highway expenditures. On the other hand, the VMT changes also directly impact the highway revenues raised from the highway users. Thus, both highway revenues and expenditures are sensitive to VMT changes. This section reports the impacts of vehicle automation on highway expenditures and revenues, and the resulting equity ratios. For this analysis, high automation levels (SAE levels 4 and 5) are assumed across the vehicle classes because they require no human intervention in driving and can therefore be expected to realize the full benefits of automation.

a. Highway Expenditures

For scenarios involving automated vehicles, this section considers only gasoline-fueled automated vehicles. Scenarios involving electric propelled automated vehicles are reported in Section 4.3.3b) of this thesis. Vehicle automation technology is assumed to be mature enough (levels 4 and 5) by around the 2040s, with mass market adoption taking place in the 2050s (Section 3.4, Table 3.2). Therefore, the analysis of vehicle automation impacts is conducted assuming low market penetration by 2050, moderate market penetration by 2060 and finally, high market penetration by 2070. The results of these analyses are presented in Table 4.3 and Figure 4.4.

Table 4.3: Annualized Highway Expenditure Estimates in the era of AVs from low market penetration (2040s) through high market penetration / saturation (late 2070s)

	Total Annualized Highway Expenditures for AV			
Year	**Base Case**	**Lower Estimate**	**Average**	**Upper Estimate**
2040	$2,856,619,734	$2,856,619,734	$2,856,619,734	$2,856,619,734
2041	$2,878,673,087	$2,878,832,119	$2,878,911,632	$2,878,991,143
2042	$2,900,568,726	$2,900,957,478	$2,901,151,835	$2,901,346,179
2043	$2,922,308,239	$2,923,020,141	$2,923,376,030	$2,923,731,877
2044	$2,943,893,389	$2,945,050,610	$2,945,629,055	$2,946,207,390
2045	$2,965,326,107	$2,967,086,716	$2,967,966,638	$2,968,846,304
2046	$2,986,608,476	$2,989,174,832	$2,990,457,198	$2,991,739,022
2047	$3,007,742,722	$3,011,371,021	$3,013,183,549	$3,014,995,000
2048	$3,028,731,207	$3,033,741,946	$3,036,244,237	$3,038,744,483
2049	$3,049,576,412	$3,056,365,301	$3,059,754,128	$3,063,139,225
2050	$3,070,280,935	$3,079,329,419	$3,083,843,755	$3,088,351,527
2051	$3,090,847,476	$3,102,731,663	$3,108,656,825	$3,114,570,795
2052	$3,111,278,827	$3,126,675,185	$3,134,345,263	$3,141,996,824
2053	$3,131,577,866	$3,151,263,726	$3,161,061,327	$3,170,829,182
2054	$3,151,747,545	$3,176,594,352	$3,188,946,675	$3,201,252,604
2055	$3,171,790,884	$3,202,748,429	$3,218,118,878	$3,233,419,109
2056	$3,191,710,958	$3,229,781,710	$3,248,656,730	$3,267,428,690
2057	$3,211,510,893	$3,257,714,943	$3,280,586,509	$3,303,311,517
2058	$3,231,193,857	$3,286,526,851	$3,313,871,945	$3,341,015,244
2059	$3,250,763,050	$3,316,151,271	$3,348,410,509	$3,380,400,839
2060	$3,270,221,699	$3,346,479,685	$3,384,037,740	$3,421,248,993
2061	$3,289,573,048	$3,377,369,268	$3,420,539,646	$3,463,276,980
2062	$3,308,820,355	$3,408,655,320	$3,457,671,371	$3,506,163,390
2063	$3,327,966,882	$3,440,165,929	$3,495,178,857	$3,549,576,402
2064	$3,347,015,893	$3,471,736,298	$3,532,819,746	$3,593,200,707
2065	$3,365,970,641	$3,503,220,531	$3,570,380,335	$3,636,759,096
2066	$3,384,834,369	$3,534,499,483	$3,607,686,685	$3,680,026,384
2067	$3,403,610,302	$3,565,484,350	$3,644,609,494	$3,722,835,319
2068	$3,422,301,641	$3,596,116,507	$3,681,063,554	$3,765,075,601
2069	$3,440,911,561	$3,626,364,596	$3,717,003,308	$3,806,687,977
2070	$3,459,443,202	$3,656,220,023	$3,752,416,168	$3,847,655,553
2071	$3,477,899,670	$3,685,691,862	$3,787,315,037	$3,887,994,135
2072	$3,496,284,029	$3,714,801,902	$3,821,731,095	$3,927,742,935
2073	$3,514,599,300	$3,743,580,286	$3,855,707,460	$3,966,956,419
2074	$3,532,848,455	$3,772,061,945	$3,889,294,019	$4,005,697,654
2075	$3,551,034,416	$3,800,283,852	$3,922,543,462	$4,044,033,193
2076	$3,569,160,052	$3,828,283,037	$3,955,508,401	$4,082,029,365
2077	$3,587,228,173	$3,856,095,229	$3,988,239,415	$4,119,749,742
2078	$3,605,241,534	$3,883,753,999	$4,020,783,815	$4,157,253,534
2079	$3,623,202,826	$3,911,290,282	$4,053,184,945	$4,194,594,688

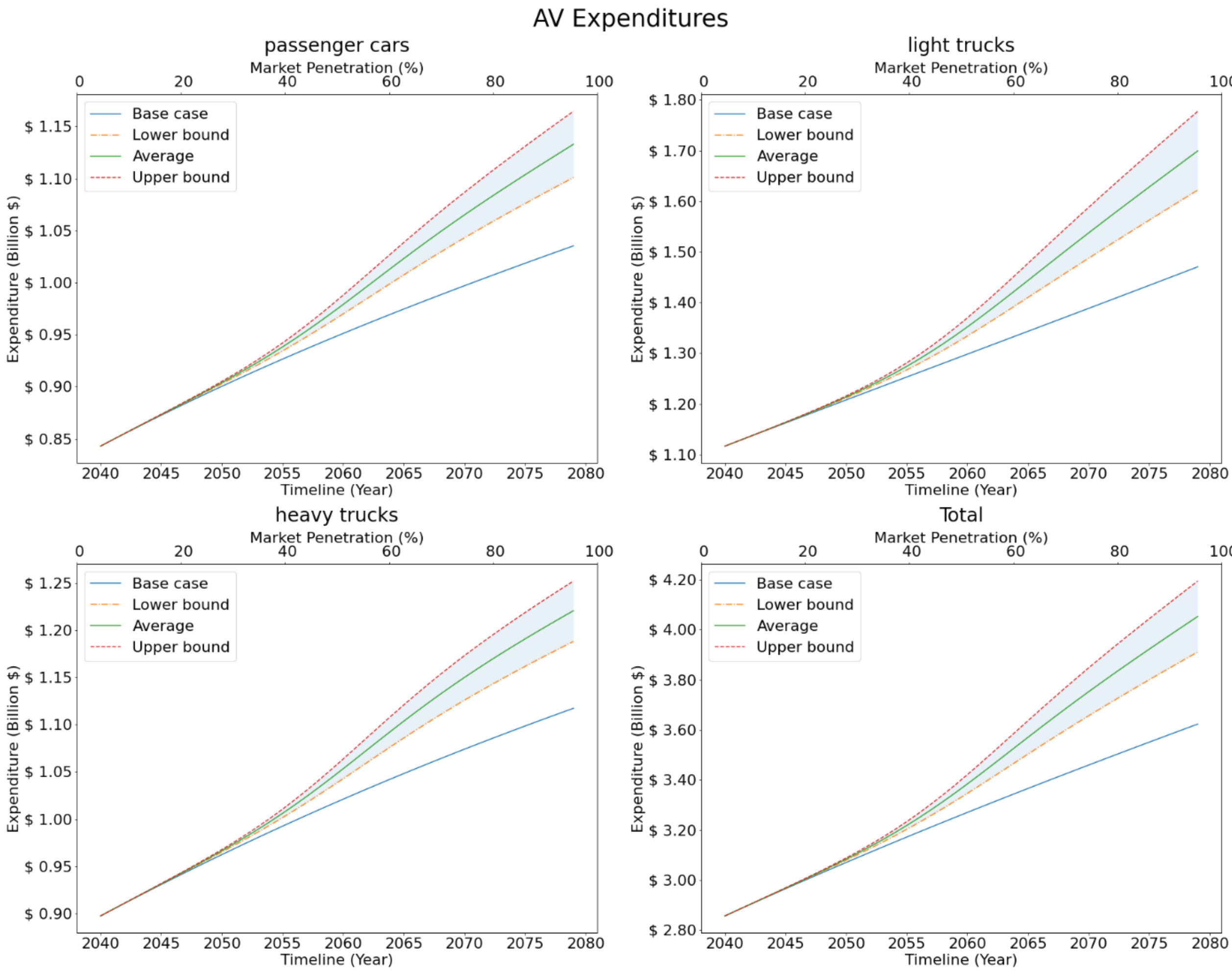


Figure 4.4: Annualized Total Highway Expenditures for AV scenario

The disparity in highway expenditures between the automated vehicle paradigms and the base case are significant in at all levels of market penetration. This disparity grows with the increasing level of market penetration. This can be attributed in part to the increased overall travel that is to be expected with vehicle automation as detailed in Section 3.4.2. This increase in system usage results in faster deterioration of the infrastructure which will then require more frequent maintenance. Furthermore, the increase in overall travel demand necessitates investments in new infrastructure to support the growth. Additionally, investments in connectivity and other smart infrastructure to support the automation functionality adds to the increased expenditure.

b. Highway Revenues

This section considers automated vehicles that use fossil fuels. This means that they contribute to the fuel revenues which is by far the dominant source of highway finance. Their fuel economy, however, is slightly better than non-automated vehicles with similar features. For this analysis, improvements in fuel economy of 10%, 15% and 20% are assumed across the low, moderate, and high market penetration levels, respectively. This section reports the results of highway revenue estimation in the era of automated vehicles (Table 4.4 and Figure 4.5).

Similar to the case for highway expenditures, revenues in the era of vehicle automation deviate from those estimated for the base case. The revenues are higher for automated vehicles across all levels of market penetration. Like the case for expenditures, the revenues disparity is significant and grows with increasing levels of market penetration. The difference in revenues generated between the base case and the automated vehicles case can be attributed to the increase in VMT that is expected to accompany automation. The anticipated improvement in fuel efficiency of automated vehicles which results in lower fuel revenues. The overall VMT increases with increasing market penetration levels, and with it the non-fuel revenues such as registration taxes, heavy vehicle surcharge, etc. Consequently, this increase is enough to offset the decline in fuel revenues arising from the improved fuel economy. Therefore, the total highway revenues generated under automated vehicles are higher compared with the base case, at all levels of market penetration.

Table 4.4: Annualized Highway Revenue Estimates in the era of AVs from low market penetration (2040s) through high market penetration / saturation (late 2070s)

	Total Annualized Revenues			
Year	**Base Case**	**Lower Estimate**	**Average**	**Upper Estimate**
2040	$2,739,297,184	$2,739,297,184	$2,739,297,184	$2,739,297,184
2041	$2,760,807,217	$2,760,878,813	$2,760,914,611	$2,760,950,409
2042	$2,782,317,251	$2,782,493,532	$2,782,581,672	$2,782,669,813
2043	$2,803,827,285	$2,804,152,431	$2,804,315,004	$2,804,477,577
2044	$2,825,337,319	$2,825,869,664	$2,826,135,836	$2,826,402,008
2045	$2,846,847,353	$2,847,663,091	$2,848,070,960	$2,848,478,829
2046	$2,868,357,387	$2,869,554,977	$2,870,153,772	$2,870,752,567
2047	$2,889,867,421	$2,891,572,676	$2,892,425,304	$2,893,277,932
2048	$2,911,377,455	$2,913,749,246	$2,914,935,142	$2,916,121,037
2049	$2,932,887,489	$2,936,123,842	$2,937,742,018	$2,939,360,195
2050	$2,954,397,523	$2,958,741,743	$2,960,913,853	$2,963,085,963
2051	$2,975,907,556	$2,981,653,787	$2,984,526,902	$2,987,400,018
2052	$2,997,417,590	$3,004,914,982	$3,008,663,678	$3,012,412,374
2053	$3,018,927,624	$3,028,582,089	$3,033,409,321	$3,038,236,553
2054	$3,040,437,658	$3,052,710,065	$3,058,846,269	$3,064,982,472
2055	$3,061,947,692	$3,077,347,450	$3,085,047,328	$3,092,747,207
2056	$3,083,457,726	$3,102,531,052	$3,112,067,715	$3,121,604,378
2057	$3,104,967,760	$3,128,280,627	$3,139,937,060	$3,151,593,494
2058	$3,126,477,794	$3,154,594,470	$3,168,652,808	$3,182,711,145
2059	$3,147,987,828	$3,181,446,939	$3,198,176,495	$3,214,906,051
2060	$3,169,497,862	$3,208,788,695	$3,228,434,112	$3,248,079,529
2061	$3,191,007,895	$3,236,549,923	$3,259,320,937	$3,282,091,951
2062	$3,212,517,929	$3,264,646,165	$3,290,710,283	$3,316,774,401
2063	$3,234,027,963	$3,292,985,757	$3,322,464,654	$3,351,943,550
2064	$3,255,537,997	$3,321,477,562	$3,354,447,345	$3,387,417,127
2065	$3,277,048,031	$3,350,037,749	$3,386,532,608	$3,423,027,467
2066	$3,298,558,065	$3,378,594,720	$3,418,613,048	$3,458,631,376
2067	$3,320,068,099	$3,407,091,853	$3,450,603,730	$3,494,115,607
2068	$3,341,578,133	$3,435,488,165	$3,482,443,181	$3,529,398,197
2069	$3,363,088,167	$3,463,757,369	$3,514,091,970	$3,564,426,571
2070	$3,384,598,201	$3,491,885,883	$3,545,529,724	$3,599,173,566
2071	$3,406,108,234	$3,519,870,352	$3,576,751,410	$3,633,632,469
2072	$3,427,618,268	$3,547,715,100	$3,607,763,515	$3,667,811,931
2073	$3,449,128,302	$3,575,429,804	$3,638,580,555	$3,701,731,306
2074	$3,470,638,336	$3,603,027,524	$3,669,222,119	$3,735,416,713
2075	$3,492,148,370	$3,630,523,146	$3,699,710,534	$3,768,897,922
2076	$3,513,658,404	$3,657,932,215	$3,730,069,121	$3,802,206,026
2077	$3,535,168,438	$3,685,270,113	$3,760,320,950	$3,835,371,788
2078	$3,556,678,472	$3,712,551,512	$3,790,488,032	$3,868,424,552
2079	$3,578,188,506	$3,739,790,045	$3,820,590,815	$3,901,391,585

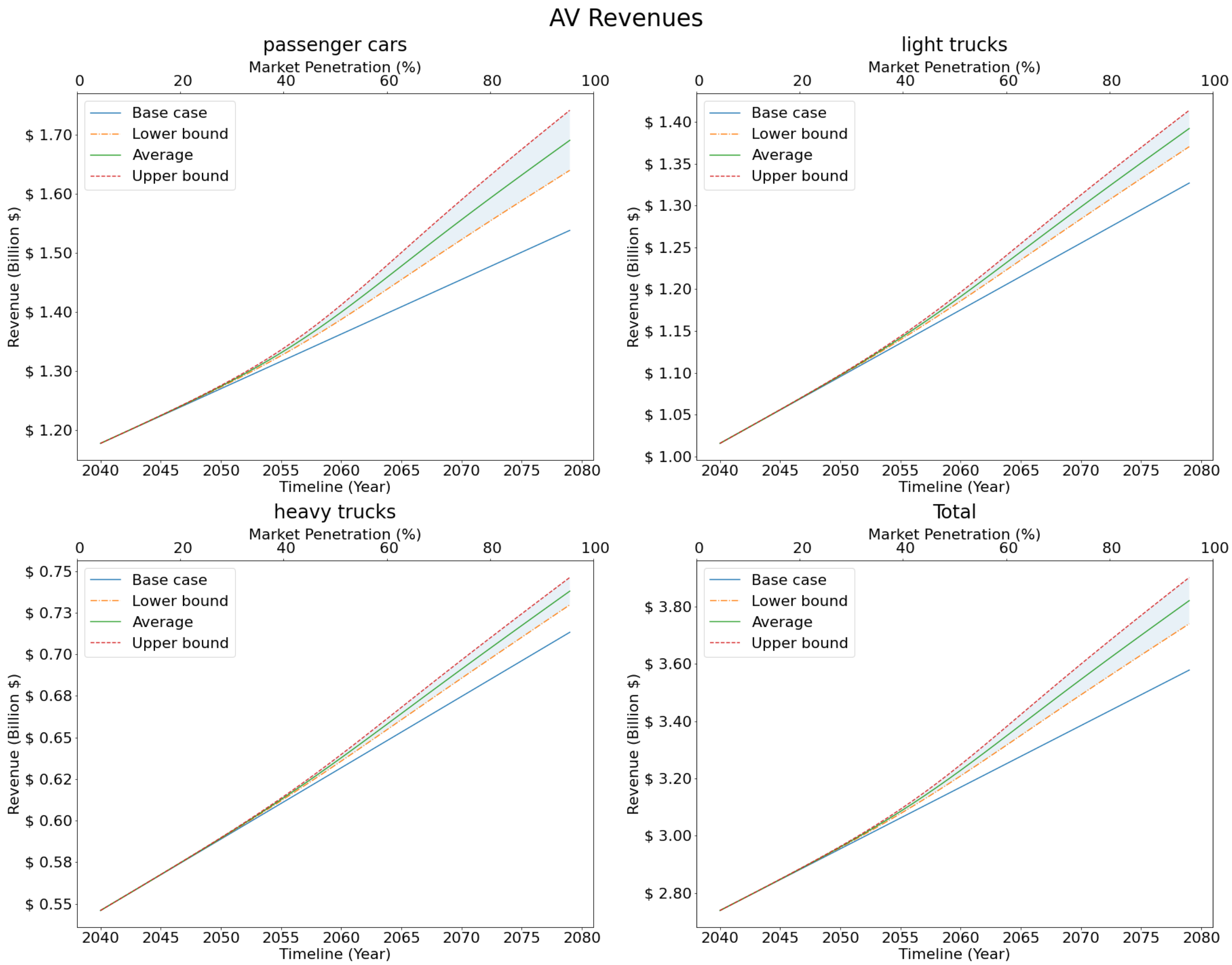


Figure 4.5: Annualized Total Highway Revenues for the AV scenario from low to high market penetration

c. User Equity Analysis

This section reports the equity ratios in the era of vehicle automation, and the changes thereof, based on the reported changes in expenditures and revenues reported in the previous section. These are summarized in Figure 4.6. The results indicate that across the various levels of market penetration, passenger cars are overpaying their share of the cost responsibility whereas light-duty trucks and heavy-duty trucks are underpaying. Of the two classes that underpay their share, heavy-duty trucks severely underpay, contributing a much smaller share of their revenues compared with their share of their cost responsibility. The trend worsens with increasing levels of market penetration. The consistent underpayment of trucks can be attributed in part to their relative lower travel amounts (mileage) compared with passenger cars. Even though trucks cause more damage to pavements and bridges due to their weight than passenger cars, there are far more passenger cars on the road compared with trucks. Therefore, where revenues are concerned, passenger consume and therefore pay more in fuel taxes than trucks. This is reflected in trucks incurring a significant share of the cost but only contributing a relatively small share of the revenues. The user fee structure needs to be adjusted to account for this disparity and restore equity to the system.

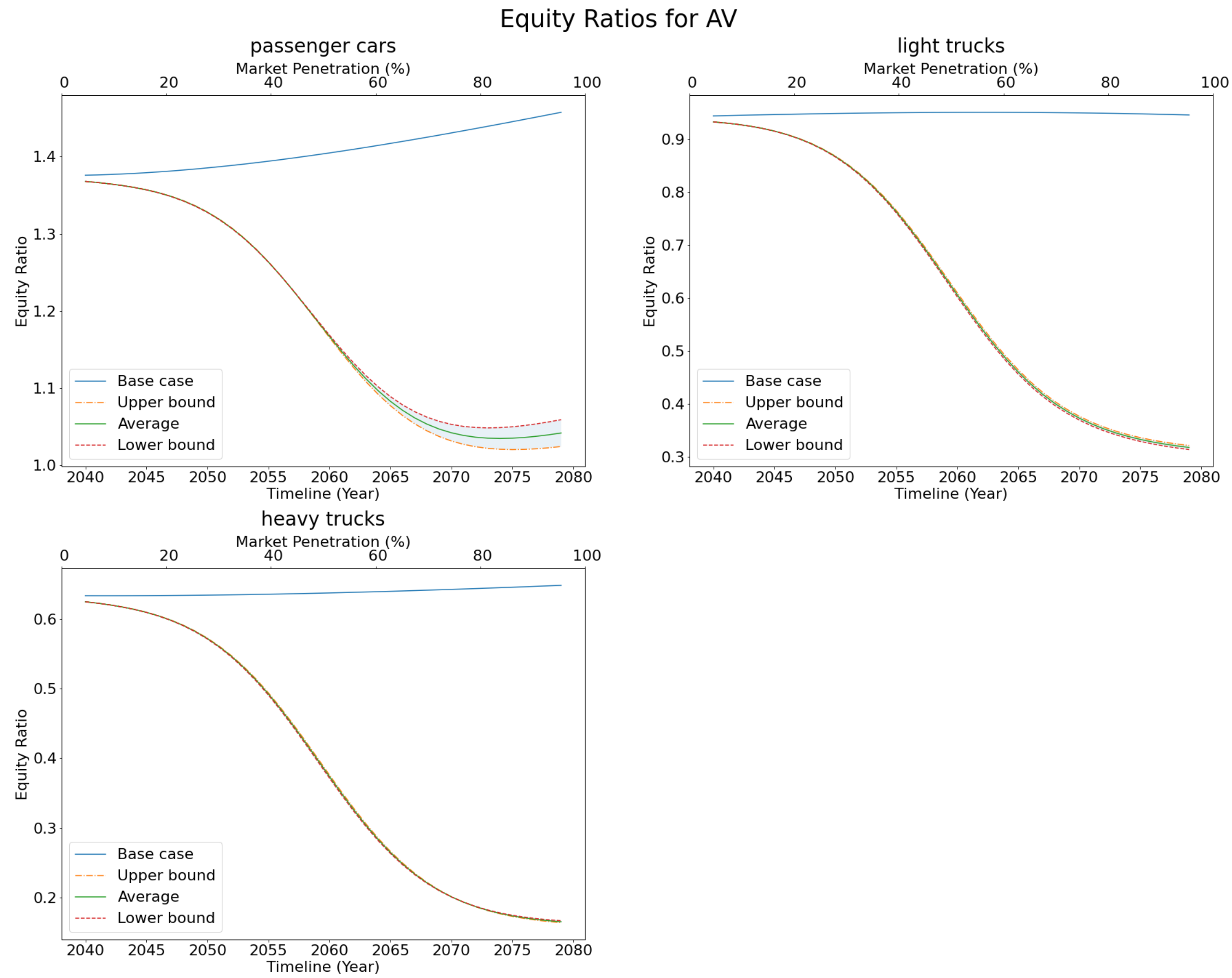


Figure 4.6: Equity Ratios for Automated Vehicles scenario from the low through high market penetration

4.3.3 Electric Vehicles (EV)

Vehicle electrification, and its impacts on highway expenditures and revenues are analyzed in two scenarios: automated electric vehicles and non-automated electric vehicles. Non-automated electric vehicles are already on the road today. In addition, although their costs are still prohibitively high for mass market adoption, the costs have been steadily reducing (Ayodele & Mustapa, 2020) and will continue to do so as the technology matures more, and the manufacturing process scales up (Deloitte, 2020; McKinsey & Company, 2021). As a result, their market adoption is expected to proceed much faster compared to their automated counterparts. The impacts of both automated and non-automated electric vehicles are reported in this section.

a) Non-Automated Electric Vehicles (Human-Driven EVs)

As described in Section 3.4.3a), the human-driven electric vehicle is being considered for analysis even though vehicle electrification and automation are expected to develop in tandem. The reason for this consideration is the difference in the technologies that drive automation and electrification. Indeed, at present, no fully autonomous vehicles are available for public use, yet a significant number of fully electric vehicles have been available on the market for several years. Thus, it is warranted, even if just as an academic exercise, to consider the impacts of electric human-driven vehicles on highway expenditures and revenues. The scenarios and their expected impacts on highway travel patterns, expenditures and revenues are highlighted in Table 3.3 are the results of each are reported herein.

i. Highway Expenditures

Vehicle electrification in and of itself is not expected to significantly affect individual travel patterns. There is no reason to expect that people will travel more or less than usual simply because they own or operate an electric vehicle. Highway expenditures, however, are expected to increase because growing adoption of electric vehicles will necessitate the provision of supporting infrastructure such as charging stations. Furthermore, some connectivity features (and assumed level two automation) are expected to be present in electric vehicles which will further increase the expenditures associated with supporting infrastructure. Overall travel can be expected to increase only slightly because in response to vehicle connectivity and low-level automation features. The impacts of electrification on highway expenditures are reported herein:

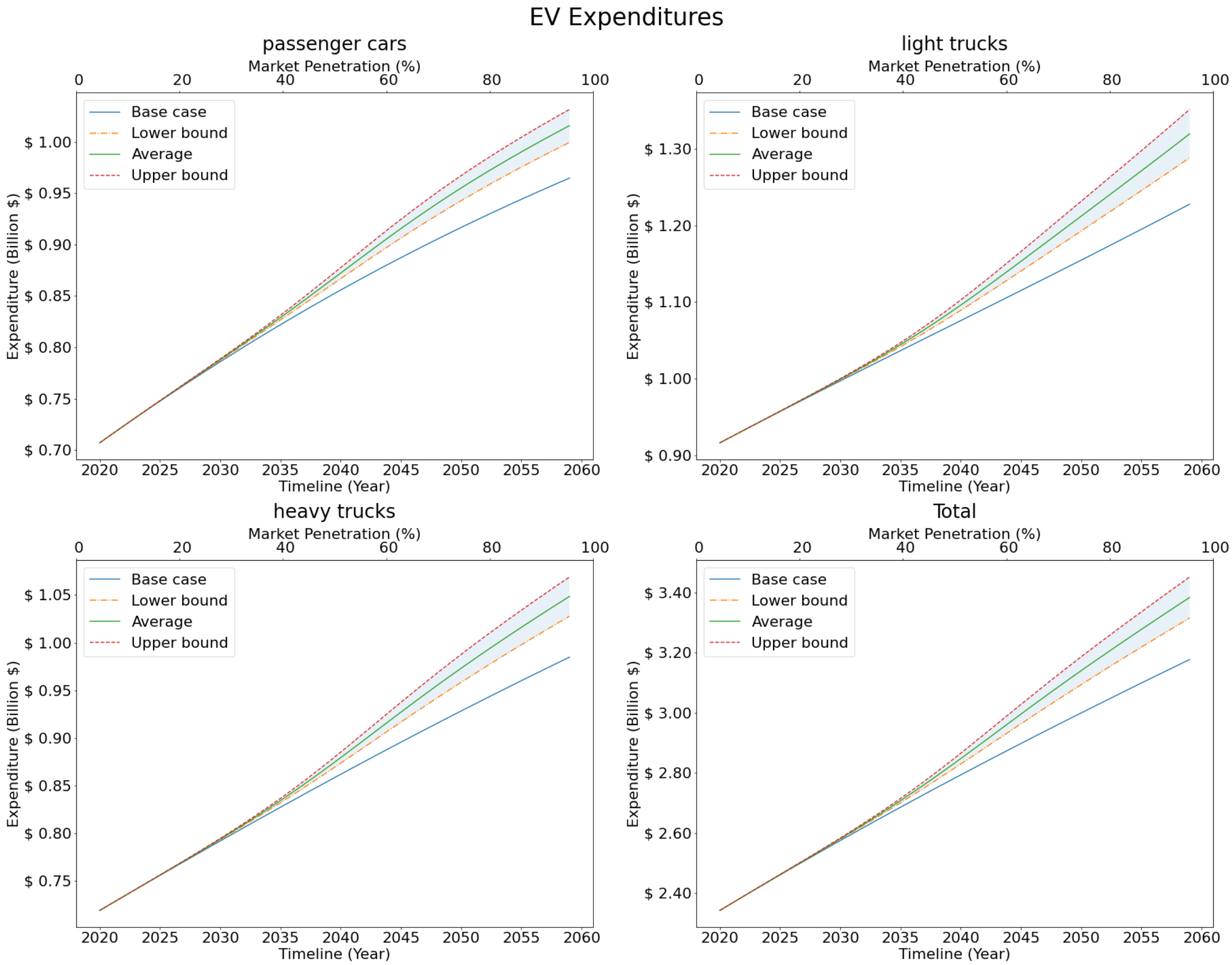


Figure 4.7: Annualized Total Highway Expenditures for the Electric Vehicles scenario

Table 4.5: Annualized Highway Expenditures Estimates in the era of EVs from low market penetration (2020s) through high market penetration / saturation (late 2050s)

	Annualized Total Cost			
Year	**Base Case**	**Lower Estimate**	**Average**	**Upper Estimate**
2020	$2,381,994,219	$2,381,994,219	$2,381,994,219	$2,381,994,219
2021	$2,407,171,270	$2,407,247,974	$2,407,286,325	$2,407,324,677
2022	$2,432,211,804	$2,432,399,886	$2,432,493,923	$2,432,587,959
2023	$2,457,111,769	$2,457,457,179	$2,457,629,873	$2,457,802,561
2024	$2,481,867,471	$2,482,430,428	$2,482,711,878	$2,482,993,308
2025	$2,506,475,576	$2,507,334,140	$2,507,763,353	$2,508,192,520
2026	$2,530,933,097	$2,532,187,357	$2,532,814,335	$2,533,441,211
2027	$2,555,237,392	$2,557,014,228	$2,557,902,331	$2,558,790,225
2028	$2,579,386,153	$2,581,844,461	$2,583,072,997	$2,584,301,122
2029	$2,603,377,400	$2,606,713,534	$2,608,380,437	$2,610,046,563
2030	$2,627,209,472	$2,631,662,497	$2,633,886,888	$2,636,109,864
2031	$2,650,881,019	$2,656,737,153	$2,659,661,476	$2,662,583,299
2032	$2,674,390,991	$2,681,986,430	$2,685,777,731	$2,689,564,749
2033	$2,697,738,630	$2,707,459,756	$2,712,309,621	$2,717,152,352
2034	$2,720,923,460	$2,733,203,384	$2,739,326,008	$2,745,437,075
2035	$2,743,945,277	$2,759,255,826	$2,766,883,772	$2,774,493,517
2036	$2,766,804,138	$2,785,642,803	$2,795,020,253	$2,804,369,844
2037	$2,789,500,352	$2,812,372,442	$2,823,746,101	$2,835,078,332
2038	$2,812,034,467	$2,839,431,645	$2,853,039,944	$2,866,588,410
2039	$2,834,407,262	$2,866,784,564	$2,882,846,253	$2,898,824,041
2040	$2,856,619,734	$2,894,373,815	$2,913,077,373	$2,931,666,679
2041	$2,878,673,087	$2,922,124,551	$2,943,619,805	$2,964,963,890
2042	$2,900,568,726	$2,949,950,809	$2,974,343,867	$2,998,542,413
2043	$2,922,308,239	$2,977,763,064	$3,005,115,071	$3,032,223,362
2044	$2,943,893,389	$3,005,475,646	$3,035,805,201	$3,065,836,925
2045	$2,965,326,107	$3,033,012,866	$3,066,301,377	$3,099,234,256
2046	$2,986,608,476	$3,060,313,122	$3,096,512,034	$3,132,295,204
2047	$3,007,742,722	$3,087,330,777	$3,126,369,570	$3,164,931,585
2048	$3,028,731,207	$3,114,036,078	$3,155,830,072	$3,197,086,617
2049	$3,049,576,412	$3,140,413,641	$3,184,870,929	$3,228,731,599
2050	$3,070,280,935	$3,166,460,094	$3,213,487,241	$3,259,861,047
2051	$3,090,847,476	$3,192,181,405	$3,241,687,805	$3,290,487,327
2052	$3,111,278,827	$3,217,590,298	$3,269,491,246	$3,320,635,521
2053	$3,131,577,866	$3,242,703,972	$3,296,922,638	$3,350,338,977
2054	$3,151,747,545	$3,267,542,249	$3,324,010,759	$3,379,635,702
2055	$3,171,790,884	$3,292,126,140	$3,350,785,997	$3,408,565,629
2056	$3,191,710,958	$3,316,476,821	$3,377,278,843	$3,437,168,666
2057	$3,211,510,893	$3,340,614,932	$3,403,518,878	$3,465,483,380
2058	$3,231,193,857	$3,364,560,131	$3,429,534,137	$3,493,546,188
2059	$3,250,763,050	$3,388,330,856	$3,455,350,764	$3,521,390,916

Figure 4.7 and Table 4.5 present the impacts of vehicle electrification on highway expenditures. These results indicate that the disparity in highway expenditures between the base case and the electric vehicle paradigm are lower when compared with vehicle automation. The expenditures are higher for electric vehicles compared to the base case but only by a small amount (about 10% on average). This result is expected because vehicle electrification does not result in significant changes to highway travel volumes and patterns and the increase in expenditures is mostly due to the anticipated cost of providing supporting infrastructure. Because a majority of this is expected to be borne by private entities, the agencies do not see a huge increase in expenditures for electric vehicles as they would for vehicle automation.

ii. Highway Revenues

As seen in the previous section for highway expenditures, the changes under the electric vehicles scenario are expected to be minimal. On the other hand, highway revenues are expected to be impacted significantly in this scenario. This is because electric vehicles do not use gasoline or diesel, the taxes from which form a significant portion of the user revenue base. The expected highway revenues under various market penetration levels of non-automated electric vehicles are presented in this section.

Table 4.6 and Figure 4.8 present the results of the impacts of non-automated electric vehicles on revenues. From Table 4.6, it can be observed that the total revenues generated under electric vehicles is significantly lower than that for the base case. At low market penetration levels, the revenues generated under the electric vehicles scenario are nearly commensurate with those under the base case. This is because at these levels, the presence of electric vehicles is not significant enough to have noticeable impact. As the market penetration levels increase, the revenues increase slightly, albeit at a slower pace than the base case. This is in response to the VMT increasing while the impacts of the electrification are still minimal. As the market penetration increases however, the impacts of electrification begin to offset the increase in VMT, and the amount of revenues generated begin to decline as the amount of fuel consumed, and therefore fuel revenues decline due to electrification. This trend is exacerbated at moderate and high levels of market penetration, where the fuel revenues are at most only 40% to 50%, and 10% to 20% of the base case revenues, respectively.

Table 4.6: Annualized Highway Revenue Estimates in the era of EVs from low market penetration (2020s) through high market penetration / saturation (late 2050s)

	Annualized Total Highway Revenues			
Year	**Base Case**	**Lower Estimate**	**Average**	**Upper Estimate**
2020	$2,309,096,506	$2,286,665,186	$2,286,665,186	$2,286,665,186
2021	$2,330,606,539	$2,302,968,934	$2,302,987,515	$2,303,002,624
2022	$2,352,116,573	$2,318,098,020	$2,318,143,790	$2,318,181,045
2023	$2,373,626,607	$2,331,803,373	$2,331,887,816	$2,331,956,625
2024	$2,395,136,641	$2,343,790,787	$2,343,929,035	$2,344,041,844
2025	$2,416,646,675	$2,353,716,451	$2,353,928,222	$2,354,101,309
2026	$2,438,156,709	$2,361,183,970	$2,361,494,644	$2,361,749,074
2027	$2,459,666,743	$2,365,744,022	$2,366,185,873	$2,366,548,597
2028	$2,481,176,777	$2,366,898,235	$2,367,511,756	$2,368,016,848
2029	$2,502,686,811	$2,364,109,207	$2,364,944,465	$2,365,634,441
2030	$2,524,196,845	$2,356,818,832	$2,357,936,719	$2,358,863,870
2031	$2,545,706,878	$2,344,476,973	$2,345,950,194	$2,347,177,799
2032	$2,567,216,912	$2,326,581,882	$2,328,495,437	$2,330,098,675
2033	$2,588,726,946	$2,302,732,173	$2,305,183,093	$2,307,249,451
2034	$2,610,236,980	$2,272,687,697	$2,275,783,785	$2,278,412,700
2035	$2,631,747,014	$2,236,433,240	$2,240,290,643	$2,243,592,169
2036	$2,653,257,048	$2,194,235,403	$2,198,975,002	$2,203,067,351
2037	$2,674,767,082	$2,146,680,418	$2,152,423,218	$2,157,429,172
2038	$2,696,277,116	$2,094,680,544	$2,101,542,494	$2,107,584,879
2039	$2,717,787,150	$2,039,440,347	$2,047,527,186	$2,054,723,815
2040	$2,739,297,184	$1,982,381,571	$1,991,784,387	$2,000,243,021
2041	$2,760,807,217	$1,925,034,839	$1,935,826,917	$1,945,640,877
2042	$2,782,317,251	$1,868,914,959	$1,881,150,273	$1,892,395,238
2043	$2,803,827,285	$1,815,400,895	$1,829,114,294	$1,841,846,625
2044	$2,825,337,319	$1,765,639,881	$1,780,848,720	$1,795,105,409
2045	$2,846,847,353	$1,720,488,334	$1,737,195,139	$1,752,995,183
2046	$2,868,357,387	$1,680,493,019	$1,698,688,675	$1,716,035,534
2047	$2,889,867,421	$1,645,907,521	$1,665,574,557	$1,684,459,225
2048	$2,911,377,455	$1,616,733,780	$1,637,849,402	$1,658,253,689
2049	$2,932,887,489	$1,592,776,885	$1,615,315,571	$1,637,215,220
2050	$2,954,397,523	$1,573,702,699	$1,597,638,255	$1,621,005,687
2051	$2,975,907,556	$1,559,090,848	$1,584,397,943	$1,609,204,488
2052	$2,997,417,590	$1,548,478,855	$1,575,134,078	$1,601,351,689
2053	$3,018,927,624	$1,541,395,925	$1,569,378,453	$1,596,980,916
2054	$3,040,437,658	$1,537,386,771	$1,566,678,720	$1,595,642,446
2055	$3,061,947,692	$1,536,026,858	$1,566,613,420	$1,596,917,889
2056	$3,083,457,726	$1,536,930,906	$1,568,800,312	$1,600,428,262
2057	$3,104,967,760	$1,539,756,408	$1,572,899,792	$1,605,837,224
2058	$3,126,477,794	$1,544,203,741	$1,578,614,936	$1,612,850,986
2059	$3,147,987,828	$1,550,014,087	$1,585,689,392	$1,621,216,131

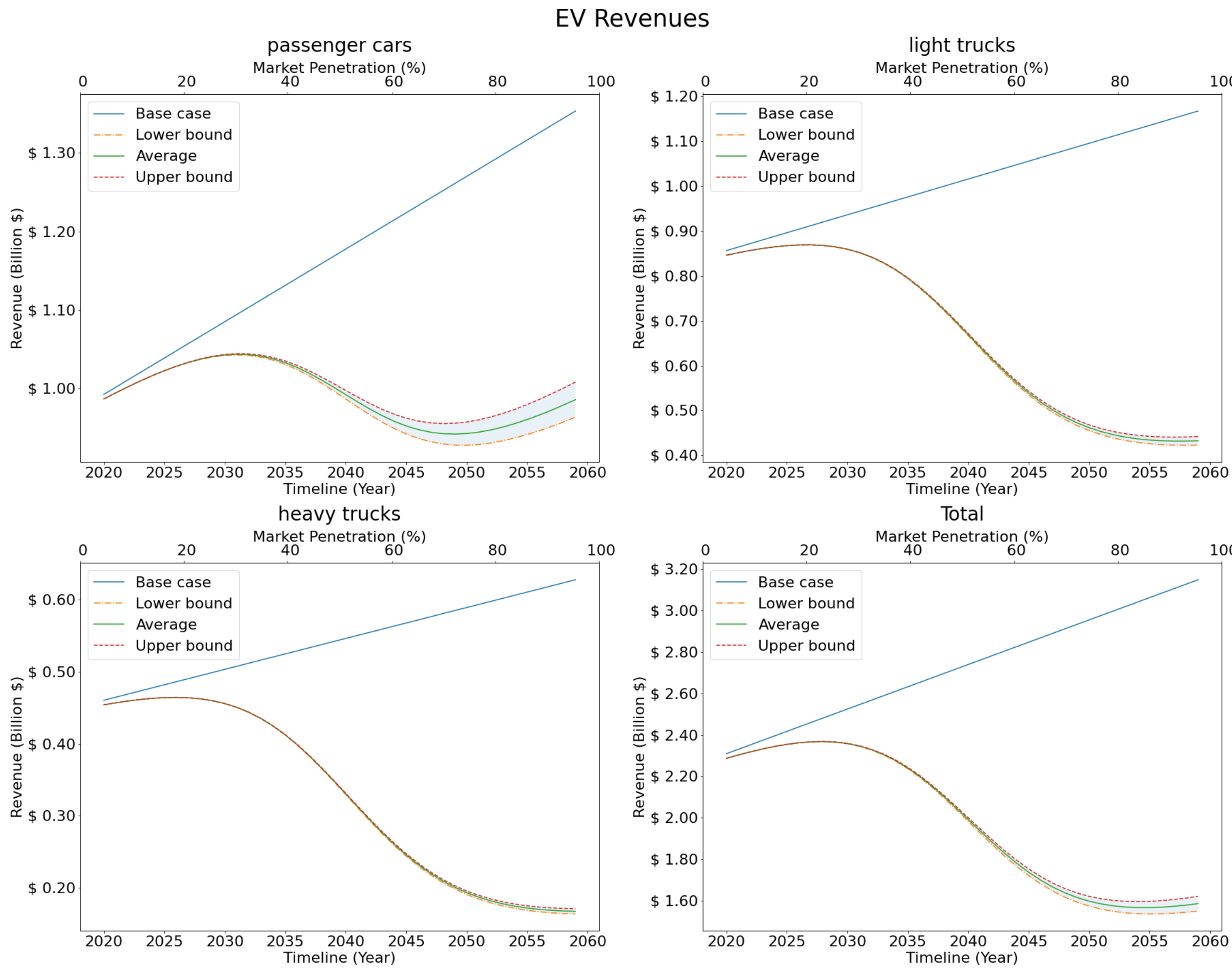


Figure 4.8: Annualized Total Highway Revenues for the Electric Vehicle scenario

iii. User Equity Analysis

Due to the significant decline in highway revenues under vehicle electrification, coupled with the slight increase in highway expenditures, the equity ratios under this scenario change significantly compared to the base case (Figure 4.9). The trend across the vehicles classes follows the trend observed in vehicle connectivity as well as automation, with passenger cars overpaying their share while light-and heavy-duty trucks underpay. This change in equity ratios reflects the changes in the relative contributions of the vehicle classes to the revenues: trucks make up a smaller portion of the fuel revenues compared with passenger cars (owing to their far smaller share of VMT). Therefore, a given change in the actual revenues will result in a much bigger percentage change for trucks compared to passenger cars. Therefore, the EVs non-consumption of fuel results in much higher loss of revenues for trucks than passenger cars, leaving the passenger cars to overpay their share of the responsibility.

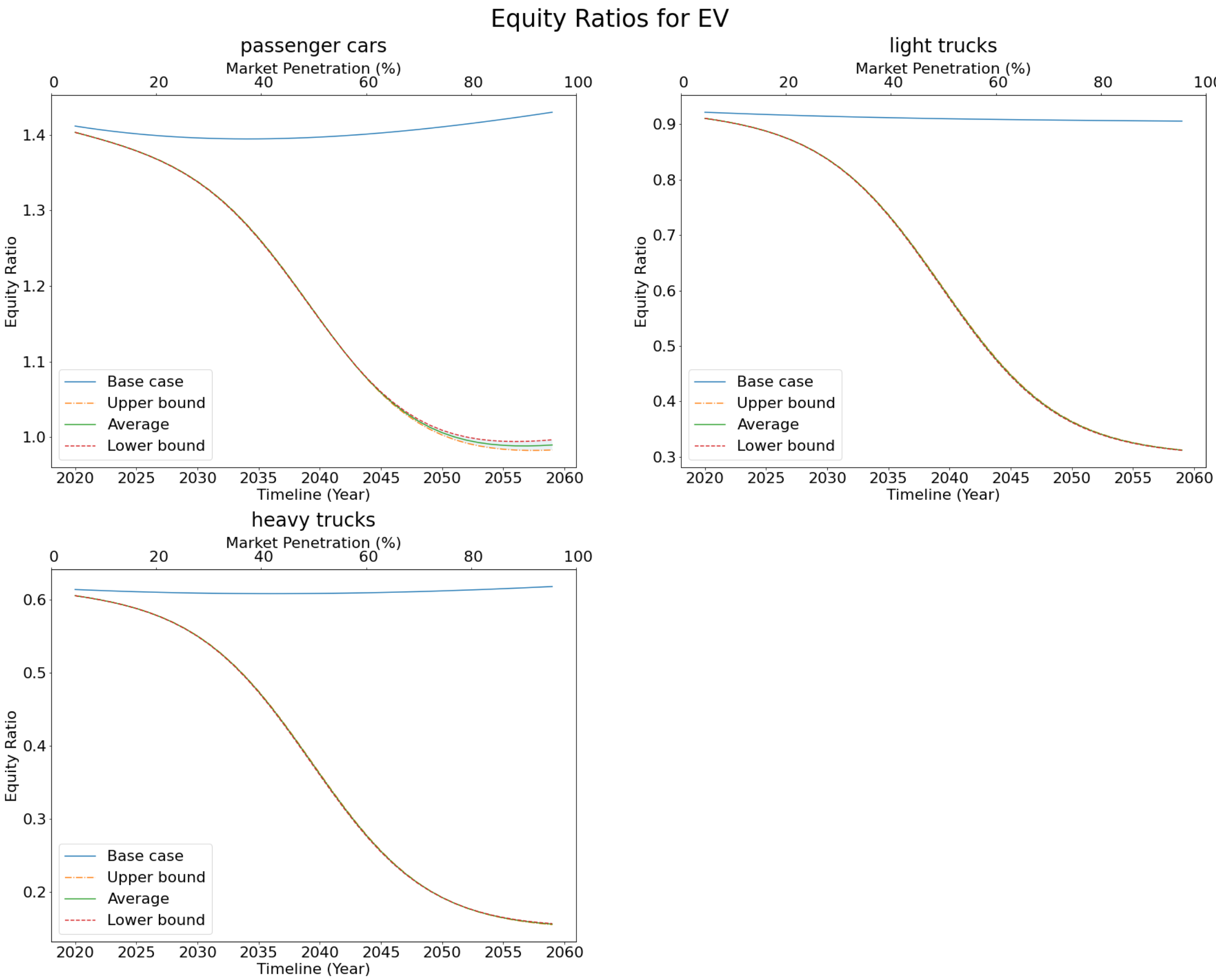


Figure 4.9: Equity Ratios for non-automated electric vehicles scenario

b) Automated Electric Vehicles (EAVs)

Vehicle autonomy is for the most part being developed in tandem with electric propulsion technology. Even though the two technologies are not interdependent, the timing of their developments is such that companies and vehicle manufacturers are investing in both simultaneously. It is therefore a realistic scenario to expect autonomous vehicles with electric propulsion.

To assess the impact of electric autonomous vehicles on highway expenditures and revenues, we shall rely on the assumptions established in section 3.4.3c). Vehicle automation is assumed to increase overall travel as outlined in sections 3.4.3b) and 3.5; and we shall assume increases of 10%, 15% and 20% increase in VMT as a result of automation for the low, moderate and high market penetrations respectively. These increases are expected due to the benefits of automation, as outlined in sections 3.4 and 3.5. In summary, these include an apparent increase in road capacity because AVs can drive with much shorter headways compared with human drivers, reduced congestion that results from smooth driving characteristics of AVs and potential for platooning on highways. These and other benefits have been shown to result in an induced demand that accounts for the assumed overall increase in travel and VMT.

Electric propulsion is expected to only marginally impact the travel patterns and the overall VMT, although it is expected to severely impact the revenues. Thus, overall, electric autonomous vehicles are expected to result in increased highway expenditures and decreased highway revenues. This section presents the result of this analysis for the various levels of market penetration.

i. Highway Expenditures

In the era of automated electric vehicles, highway travel patterns, and consequently highway expenditures are equivalent to those discussed for the scenario with non-electric automated vehicles. This assumes the amount of travel will mostly be driven by automation and not electrification. However, the effect of the combination of these two technologies will likely be synergistic. For simplicity in analysis however, this thesis assumes that the changes in highway travel patterns and the resulting increase in highway expenditures will be nearly identical for automated electric vehicles as for automated non-electric vehicles. Therefore, the results of this analysis are not reported in this section but rather in Section 4.3.2.a).

Highway Revenues

Highway revenues in the era of automated electric vehicles are expected to be much lower compared with the base case because electric vehicles do not use fuel and therefore will have no contribution to the fuel revenues. As far as revenues are concerned, the impact of automated electric vehicles will be nearly identical to that of non-automated electric vehicles. As was the case with highway expenditures, the results of this analysis are not reported here, and the reader is referred to section.4.3.3a).ii for the detailed results.

ii. User Equity Analysis

Automated electric vehicles represent the worst-case scenario for automation and electrification in the context of highway expenditures and revenues. On the one hand, the automation is expected to drive up the overall travel demand, and with it, expenditures on highway infrastructure development and upkeep. On the other hand, the electrification will significantly impact the revenues generated from fuel taxes as a larger portion of the vehicle fleet move away from fossil fuels. The combination of the two results in the worst of the impacts of the two scenarios combined. The equity ratios presented in Figure 4.10 affirms this result. The equity ratios for the automated EVs scenario are much less than the base case for all vehicle classes. Like the trend observed in the non-automated electric vehicles scenario, the equity ratios are close to those of the base at very low market penetration rates. As the market penetration increases however, the equity ratios sharply decline, reflecting the drop in revenues resulting from loss of fuel revenues due to electrification. The equity ratios also show that passenger cars are overpaying their share of the responsibility throughout the period of analysis, although the degree of overpay reduces with increasing market penetration. Light and heavy-duty trucks consistently underpay their share, and the degree to which they underpay worsens with increasing market penetration.

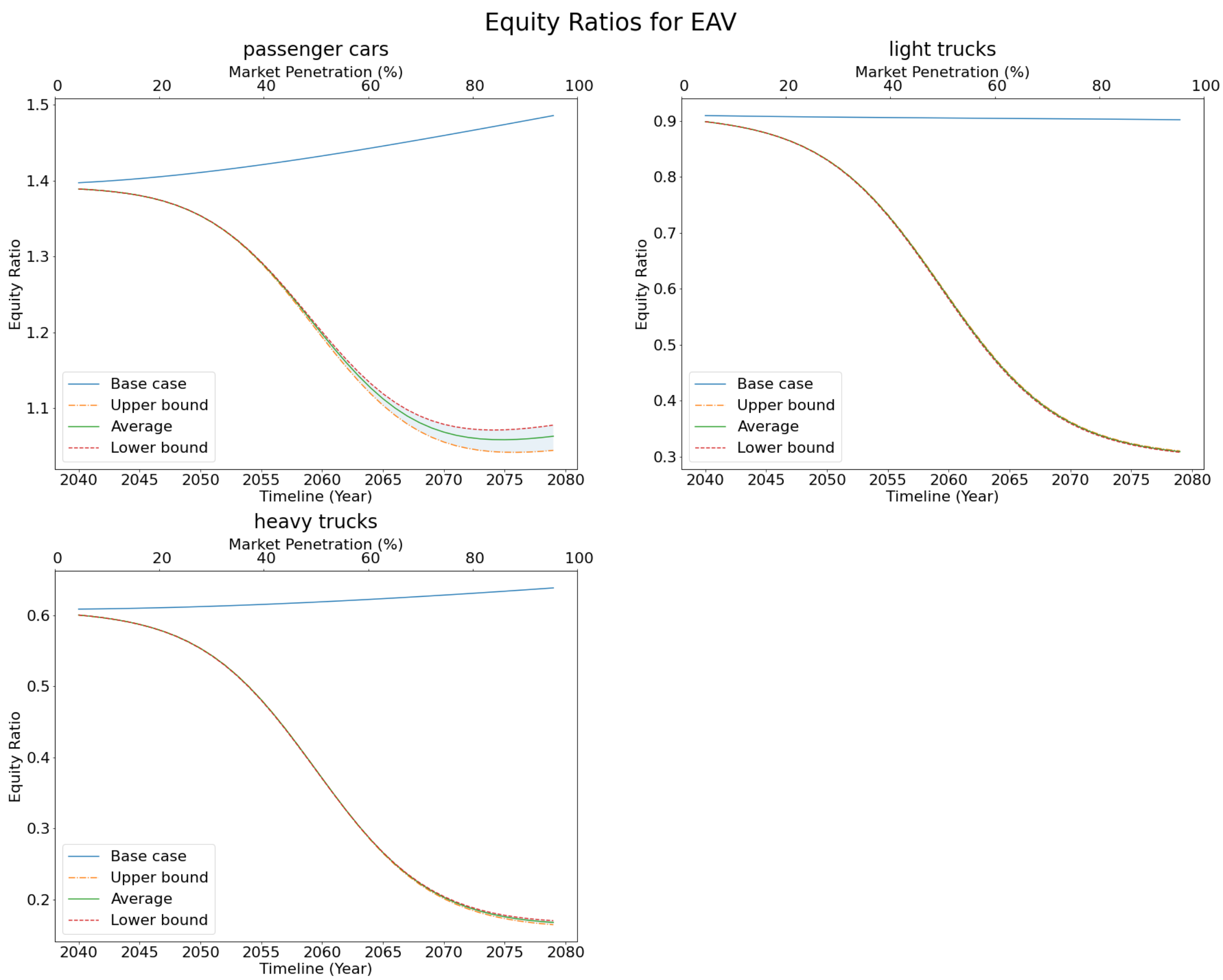


Figure 4.10: Equity Ratios for automated electric vehicles from low through high market penetration

4.3.4 Connected and Automated Vehicles (CAV)

In previous sections, this thesis documented how vehicle connectivity, automation, and electrification, individually or together, could yield varying impacts on highway expenditures, revenues, and equity. In each case, this thesis examines the anticipated changes in VMT, highway infrastructure deterioration and consequently, highway expenditures. Highway cost allocation studies estimate these expenditures and allocate them to the appropriate user groups (vehicle classes) based on their share of travel.

This section discusses the results for the scenario involving both connected and automated vehicles (CAVs). The CAV scenario combines the effects of connectivity and automation. The combined impact can be assumed to be equal to the sum of the individual parts or can indeed be greater than the sum of the individual parts by some marginal percentage. Many researchers have argued and confirmed that the presence of connectivity can greatly enhance the capabilities and functions of automation (Dong et al., 2020; Duell et al., 2016; Huegle et al., 2019; Kreidieh et al., 2018; Li, Chen, Du, et al., 2020; Stern et al., 2018). As a working assumption, it is logical to assume that the combined impact will be greater than the sum of the individual parts, although the exact extent is difficult to ascertain. The strength of the expected synergy is thought to be a function of the prevailing levels of connectivity and automation, or the gap between their prevailing levels of advancement (Ha, Chen, Du, et al., 2020). The subsequent estimated changes due to autonomous vehicles are based on assumed AV market penetration and associated VMT and ESAL changes (see Sections 2 and 3.5). At low AV market penetrations of 20% - 30%, total VMT is assumed to increase by 10%, at moderate market penetrations of 40% - 60%, total VMT is assumed to increase by 20% and finally at high market penetrations of 70% - 90%, VMT is assumed to increase by 30% (Fagnant & Kockelman, 2015b; Fagnant & Kockelman, 2015c). With this increase in total VMT, an increase in total load on highway infrastructure is also expected. At the same time, the improvements in traffic flow and resulting changes in vehicle fuel economy are expected to be reflected in changes in the highway revenues.

a) Highway Expenditures

It is anticipated that changes in highway expenditures under the era of CAVs will be driven by investments in connectivity infrastructure, supporting infrastructure for vehicle automation such as cloud computing, could storage and other network facilities, and smart highway installations such as traffic lights, message signs. (Fagnant & Kockelman, 2015a; Litman, 2017) Furthermore, the increase in travel demand that would arise as automation gains market adoption would also result in higher usage and therefore increased expenditures to provide and maintain highway infrastructure. Consequently, the overall impacts of this scenario on highway expenditures can be expected to exhibit synergies between the impacts of automation and connectivity individually. This section presents the results of this analysis under specified levels of market penetration.

For this scenario, the results presented in Table 4.7 and Figure 4.11 for highway expenditures show the significant disparity in the costs incurred under this scenario compared with the base case. The disparities are similar to those seen under the automation and the connectivity scenarios and are driven by the same influences as discussed in the respective sections. However, the results presented here indicate even higher disparities at all levels of market penetration. This is due to the synergistic effect of the combination of these two technologies.

Table 4.7: Annualized Highway Expenditure Estimates in the era of CAVs from low market penetration (2040s) through high market penetration / saturation (late 2070s)

	Annualized Total Expenditures			
Year	**Base Case**	**Lower Estimate**	**Average**	**Upper Estimate**
2040	$2,856,619,734	$2,856,619,734	$2,856,619,734	$2,856,619,734
2041	$2,878,673,087	$2,878,848,022	$2,879,022,946	$2,879,197,861
2042	$2,900,568,726	$2,900,996,350	$2,901,423,914	$2,901,851,418
2043	$2,922,308,239	$2,923,091,322	$2,923,874,204	$2,924,656,885
2044	$2,943,893,389	$2,945,166,308	$2,946,438,693	$2,947,710,545
2045	$2,965,326,107	$2,967,262,721	$2,969,198,099	$2,971,132,243
2046	$2,986,608,476	$2,989,431,349	$2,992,251,600	$2,995,069,235
2047	$3,007,742,722	$3,011,733,613	$3,015,719,278	$3,019,699,736
2048	$3,028,731,207	$3,034,242,568	$3,039,744,010	$3,045,235,580
2049	$3,049,576,412	$3,057,043,365	$3,064,492,223	$3,071,923,111
2050	$3,070,280,935	$3,080,232,813	$3,090,152,804	$3,100,041,226
2051	$3,090,847,476	$3,103,917,594	$3,116,933,265	$3,129,895,248
2052	$3,111,278,827	$3,128,210,689	$3,145,052,299	$3,161,805,397
2053	$3,131,577,866	$3,153,225,643	$3,174,728,076	$3,196,088,977
2054	$3,151,747,545	$3,179,068,564	$3,206,162,154	$3,233,036,319
2055	$3,171,790,884	$3,205,828,209	$3,239,519,878	$3,272,881,963
2056	$3,191,710,958	$3,233,565,098	$3,274,909,268	$3,315,774,350
2057	$3,211,510,893	$3,262,301,237	$3,312,361,679	$3,361,748,932
2058	$3,231,193,857	$3,292,012,463	$3,351,818,157	$3,410,710,399
2059	$3,250,763,050	$3,322,625,386	$3,393,125,186	$3,462,428,930
2060	$3,270,221,699	$3,354,020,252	$3,436,041,998	$3,516,552,915
2061	$3,289,573,048	$3,386,039,846	$3,480,259,219	$3,572,637,029
2062	$3,308,820,355	$3,418,503,182	$3,525,425,960	$3,630,180,986
2063	$3,327,966,882	$3,451,221,589	$3,571,180,579	$3,688,672,180
2064	$3,347,015,893	$3,484,014,391	$3,617,179,854	$3,747,625,209
2065	$3,365,970,641	$3,516,721,771	$3,663,122,258	$3,806,612,910
2066	$3,384,834,369	$3,549,213,306	$3,708,762,902	$3,865,286,104
2067	$3,403,610,302	$3,581,391,840	$3,753,919,811	$3,923,381,861
2068	$3,422,301,641	$3,613,193,254	$3,798,472,774	$3,980,722,012
2069	$3,440,911,561	$3,644,583,250	$3,842,356,909	$4,037,204,669
2070	$3,459,443,202	$3,675,552,401	$3,885,553,231	$4,092,791,679
2071	$3,477,899,670	$3,706,110,566	$3,928,078,196	$4,147,494,558
2072	$3,496,284,029	$3,736,281,469	$3,969,973,628	$4,201,360,783
2073	$3,514,599,300	$3,766,097,936	$4,011,297,890	$4,254,461,613
2074	$3,532,848,455	$3,795,597,993	$4,052,118,665	$4,306,881,998
2075	$3,551,034,416	$3,824,821,870	$4,092,507,403	$4,358,712,709
2076	$3,569,160,052	$3,853,809,836	$4,132,535,287	$4,410,044,534
2077	$3,587,228,173	$3,882,600,712	$4,172,270,473	$4,460,964,249
2078	$3,605,241,534	$3,911,230,942	$4,211,776,339	$4,511,552,017
2079	$3,623,202,826	$3,939,734,065	$4,251,110,502	$4,561,879,887

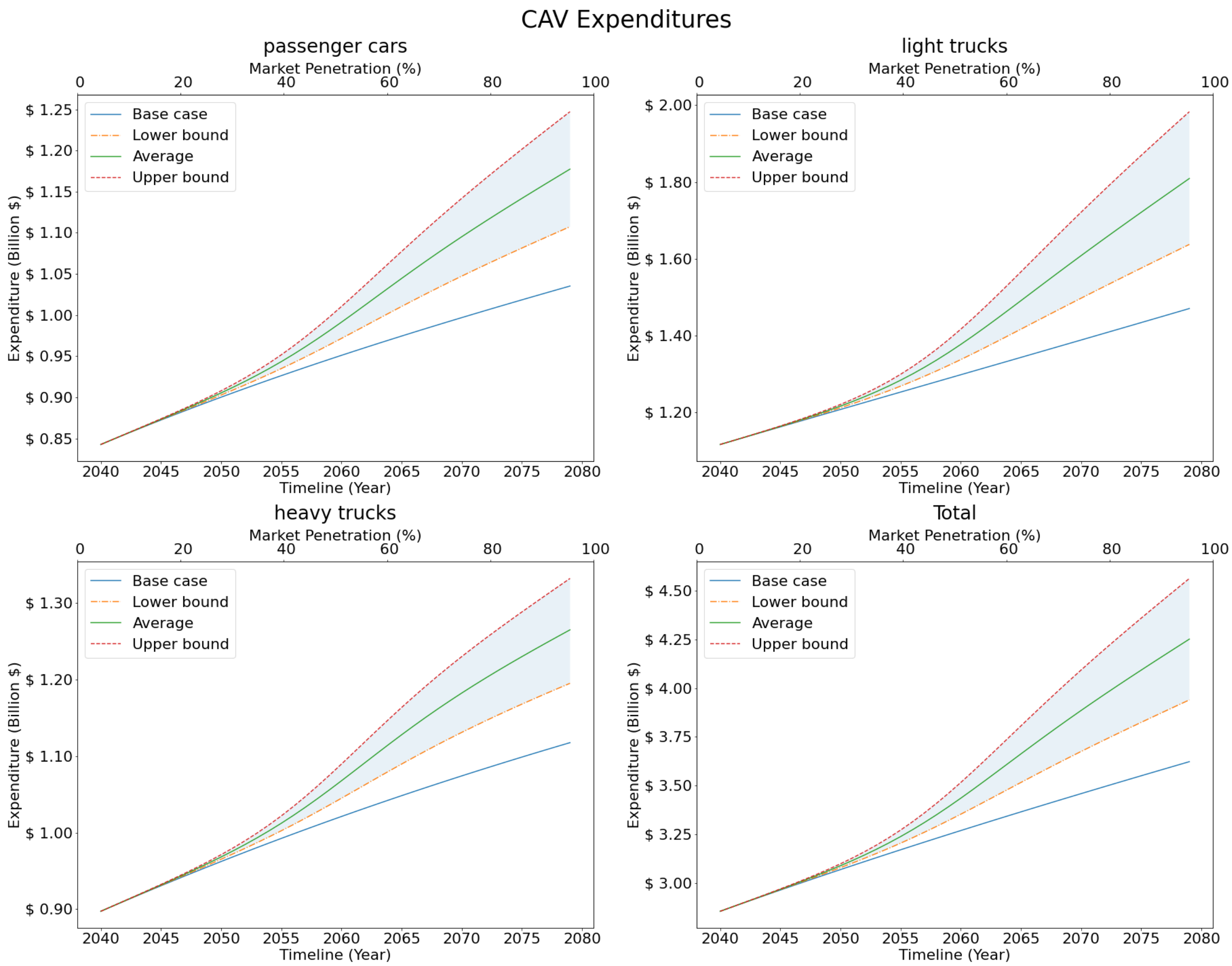


Figure 4.11: Annualized Total Highway Expenditures for the CAV scenario from the low market penetration through high market penetration

b) Highway Revenues

The results for the scenario involving both connected and automated vehicles suggest a revenue increase compared with the base case. As shown in Table 4.8 and Figure 4.8, the revenues for the CAV scenario exceeds that of the base case. This can be attributed to the significant increase in VMT that is anticipated in the CAV era. Even though mass market adoption of CAVs also results in significant improvements in fuel economy, this is offset by the increased VMT, and consequently, the consumption of fuel. This results in higher fuel taxes being collected. Furthermore, the increase in travel demand results in more vehicles being bought and registered, which contributes to the non-fuel revenues arising from registration fees.

Table 4.8: Annualized Highway Revenue Estimates in the era of CAVs from low market penetration (2040s) through high market penetration / saturation (late 2070s)

	Annualized Total Revenues			
Year	**Base Case**	**Lower Estimate**	**Average**	**Upper Estimate**
2040	$2,739,297,184	$2,739,297,184	$2,739,297,184	$2,739,297,184
2041	$2,760,807,217	$2,760,894,380	$2,761,023,579	$2,761,152,776
2042	$2,782,317,251	$2,782,531,859	$2,782,849,953	$2,783,168,030
2043	$2,803,827,285	$2,804,223,121	$2,804,809,796	$2,805,396,414
2044	$2,825,337,319	$2,825,985,390	$2,826,945,830	$2,827,906,117
2045	$2,846,847,353	$2,847,840,404	$2,849,311,941	$2,850,783,121
2046	$2,868,357,387	$2,869,815,251	$2,871,975,243	$2,874,134,472
2047	$2,889,867,421	$2,891,943,207	$2,895,018,122	$2,898,091,503
2048	$2,911,377,455	$2,914,264,471	$2,918,539,997	$2,922,812,581
2049	$2,932,887,489	$2,936,826,638	$2,942,658,419	$2,948,484,775
2050	$2,954,397,523	$2,959,684,715	$2,967,508,996	$2,975,323,601
2051	$2,975,907,556	$2,982,900,414	$2,993,243,479	$3,003,569,796
2052	$2,997,417,590	$3,006,540,437	$3,020,025,325	$3,033,482,033
2053	$3,018,927,624	$3,030,673,506	$3,048,022,121	$3,065,324,589
2054	$3,040,437,658	$3,055,366,013	$3,077,394,584	$3,099,349,591
2055	$3,061,947,692	$3,080,676,377	$3,108,282,455	$3,135,774,384
2056	$3,083,457,726	$3,106,648,589	$3,140,788,487	$3,174,756,029
2057	$3,104,967,760	$3,133,305,749	$3,174,962,671	$3,216,366,439
2058	$3,126,477,794	$3,160,644,772	$3,210,789,587	$3,260,572,779
2059	$3,147,987,828	$3,188,633,460	$3,248,181,886	$3,307,227,913
2060	$3,169,497,862	$3,217,210,902	$3,286,982,141	$3,356,074,303
2061	$3,191,007,895	$3,246,291,509	$3,326,973,673	$3,406,762,140
2062	$3,212,517,929	$3,275,772,187	$3,367,898,920	$3,458,879,217
2063	$3,234,027,963	$3,305,541,420	$3,409,482,164	$3,511,987,310
2064	$3,255,537,997	$3,335,488,665	$3,451,452,606	$3,565,658,660
2065	$3,277,048,031	$3,365,512,528	$3,493,564,079	$3,619,506,743
2066	$3,298,558,065	$3,395,526,674	$3,535,608,949	$3,673,207,590
2067	$3,320,068,099	$3,425,463,057	$3,577,425,342	$3,726,510,483
2068	$3,341,578,133	$3,455,272,647	$3,618,898,279	$3,779,239,074
2069	$3,363,088,167	$3,484,924,212	$3,659,956,176	$3,831,285,330
2070	$3,384,598,201	$3,514,401,859	$3,700,564,471	$3,882,599,135
2071	$3,406,108,234	$3,543,701,999	$3,740,718,013	$3,933,176,074
2072	$3,427,618,268	$3,572,830,255	$3,780,433,418	$3,983,045,330
2073	$3,449,128,302	$3,601,798,637	$3,819,742,199	$4,032,258,860
2074	$3,470,638,336	$3,630,623,169	$3,858,685,033	$4,080,882,443
2075	$3,492,148,370	$3,659,322,016	$3,897,307,280	$4,128,988,708
2076	$3,513,658,404	$3,687,914,081	$3,935,655,674	$4,176,652,029
2077	$3,535,168,438	$3,716,418,023	$3,973,776,017	$4,223,944,981
2078	$3,556,678,472	$3,744,851,609	$4,011,711,679	$4,270,936,066
2079	$3,578,188,506	$3,773,231,320	$4,049,502,719	$4,317,688,388

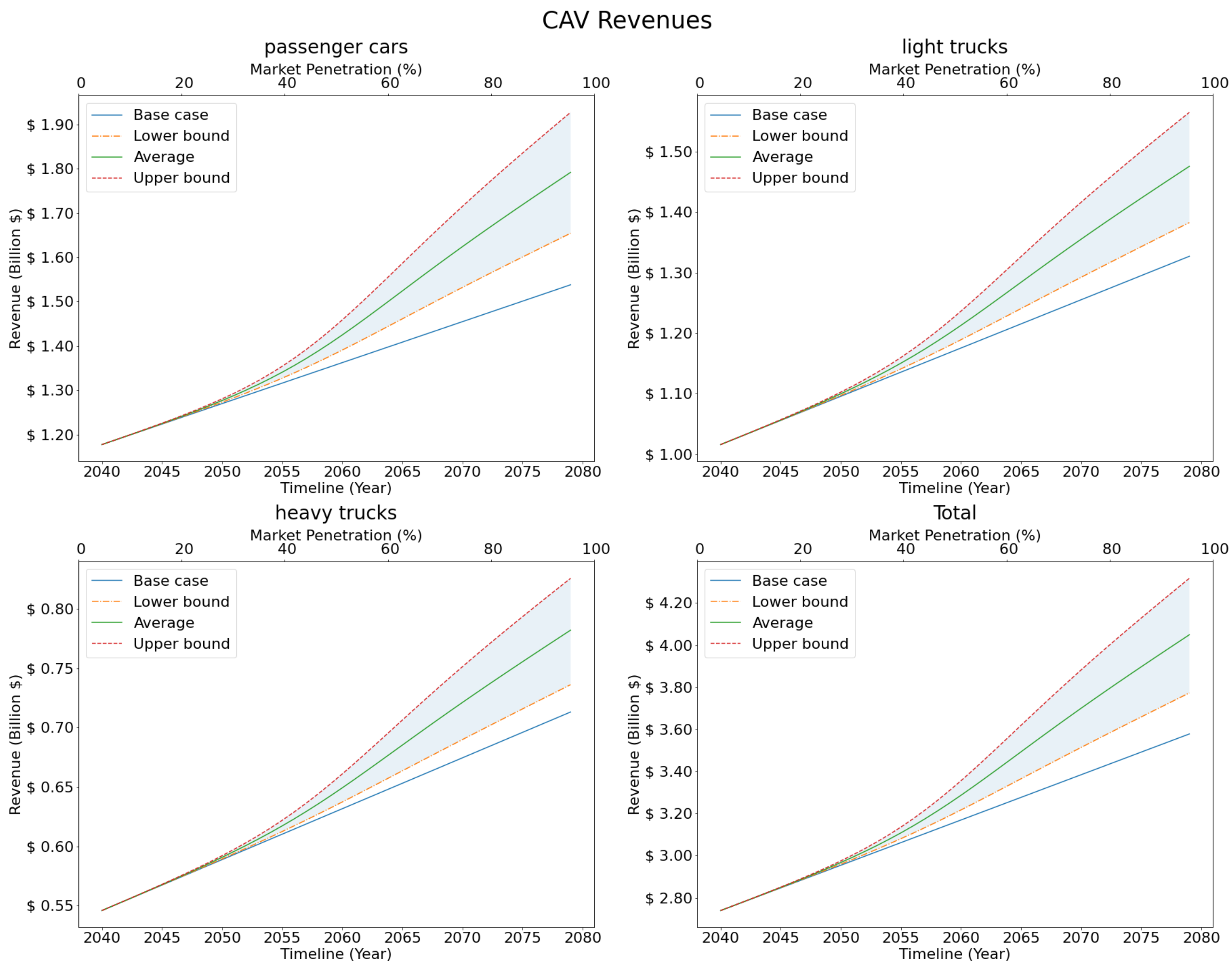


Figure 4.12: Annualized Total Highway revenues for CAV scenario from low market penetration through high market penetration

c) User Equity Analysis

Figure 4.13 presents the equity ratios for the CAV scenario for all vehicle classes at the various levels of market penetration. For passenger cars, the equity ratios in the CAV scenario are higher than the base, indicating that the share of overpay for passenger cars is higher under CAV compared with the base case. This increase in equity can be attributed to the increased VMT under CAV, along with the synergistic effects of automation and connectivity, leading to an amplification of the effects of both. The trend is reversed for light and heavy-duty trucks, where the equity ratios are less under CAV compared with the base case. This can be attributed to the lower growth in VMT of the two vehicle classes. Light and heavy-duty trucks both have VMTs that are several times lower than passenger cars, and therefore, their overall growth is much smaller compared with passenger at the same rate. This results in the equity ratios declining with increased market penetration because the revenues decline due to increased fuel efficiency. Because the VMT does not grow fast enough that the non-fuel revenues can counteract the decrease in fuel revenues, the expenditures grow faster than the revenues, resulting in declining equity ratios.

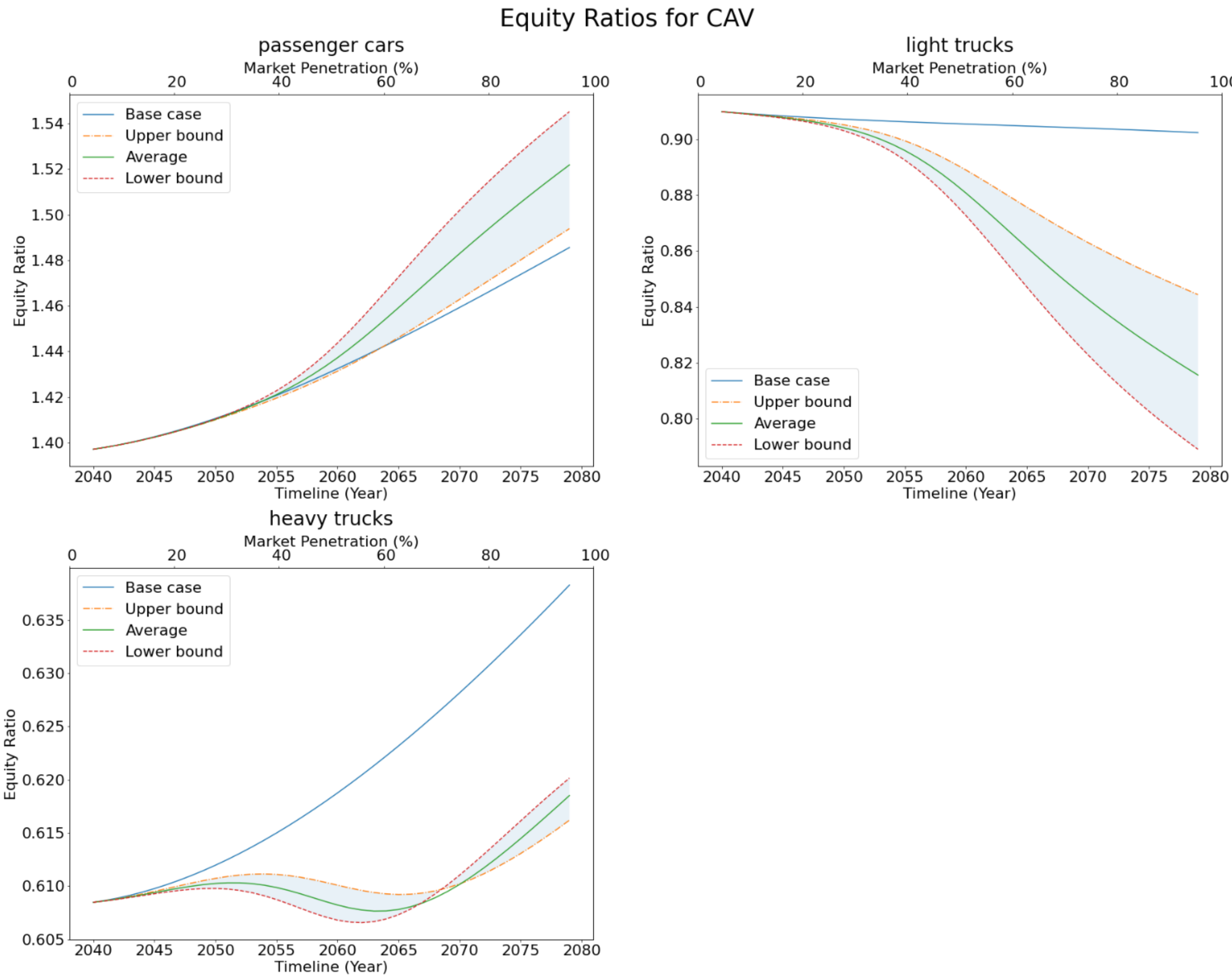


Figure 4.13: Equity Ratios for CAV scenario

4.3.5 Electric, Connected, and Automated Vehicles (ECAVs)

Electric, connected, and automated vehicles (ECAVs) represent the integration of all the three vehicle technologies explored separately or pairwise in earlier sections of this thesis. It is expected that after the technologies mature and the manufacturing processes advance enough to allow for high volume production, vehicle manufacturers will bundle these technologies together in their vehicles. The impacts explored in earlier sections that pertain to the individual technologies, also apply here. However, it is reasonable to assume that the impacts are not going to be simply a sum total of the individual impacts but will rather have synergistic effects. For example, we have seen that both automation and connectivity can result in increased travel demand. Because connected vehicles can communicate with each other and with infrastructure, traffic across intersections may flow smoother as vehicles are able to negotiate their trajectories on approaches to intersections, eliminating the need for stop-and-go traffic (Kreidieh et al., 2018; Stern et al., 2018), that is typical at intersection approaches. Furthermore, automated vehicles can drive smoother and achieve much closer headways with each other (Dong et al., 2020; Li, Chen, Du, et al., 2020), resulting in increased roadway capacity. The reduced travel times and apparent increase in roadway capacity may likely fuel induced demand that will ultimately result in increased travel. Both connected and automated vehicles will have these effects to a limited extent. However, the combination of both these technologies will likely yield greater effects that each individual technology. By extension, vehicle electrification will also exacerbate some of these impacts, while also significantly impacting the revenues. The analysis of ECAVs therefore applies the effects of all the individual technologies and amplifies them slightly to simulate a synergistic effect. The results of this analysis are presented herein:

a) Highway Expenditures

The impacts of electric propulsion, automation, and connectivity (ECAV) on highway expenditures are similar to those reported for the CAV scenario 4.3.4.a). This is because while electrification drives up the costs for the provision of electric infrastructure, for highways, this is increase is only marginal. Most of the increase in highway expenditures are driven by automation and connectivity. The two technologies combined result in increased travel and consequently, increased highway infrastructure stewardship costs. Furthermore, the supporting infrastructure required to support these technologies leads to an increase in highway expenditure. Therefore, although higher for ECAVs, the highway expenditures are much closer to those of CAVs. The highway expenditures under ECAV are reported in Table 4.9 and Figure 4.14 at the low, moderate, and high market penetration.

Table 4.9: Annualized Highway Expenditure Estimates in the era of ECAVs from low market penetration (2040s) through high market penetration / saturation (late 2070s)

	Annualized Total Expenditures adjusted for ECAV			
Year	**Base Case**	**Lower Estimate**	**Average**	**Upper Estimate**
2040	$2,856,619,734	$2,856,619,734	$2,856,619,734	$2,856,619,734
2041	$2,878,673,087	$2,878,943,437	$2,879,102,454	$2,879,277,364
2042	$2,900,568,726	$2,901,229,574	$2,901,618,241	$2,902,045,718
2043	$2,922,308,239	$2,923,518,374	$2,924,229,993	$2,925,012,582
2044	$2,943,893,389	$2,945,860,403	$2,947,016,874	$2,948,288,483
2045	$2,965,326,107	$2,968,318,535	$2,970,077,408	$2,972,010,992
2046	$2,986,608,476	$2,990,969,992	$2,993,532,667	$2,996,349,115
2047	$3,007,742,722	$3,013,908,259	$3,017,529,222	$3,021,507,319
2048	$3,028,731,207	$3,037,244,581	$3,042,241,399	$3,047,728,497
2049	$3,049,576,412	$3,061,108,614	$3,067,872,119	$3,075,294,881
2050	$3,070,280,935	$3,085,647,650	$3,094,651,435	$3,104,525,613
2051	$3,090,847,476	$3,111,023,752	$3,122,831,685	$3,135,769,519
2052	$3,111,278,827	$3,137,408,100	$3,152,678,211	$3,169,391,659
2053	$3,131,577,866	$3,164,972,019	$3,184,454,890	$3,205,752,737
2054	$3,151,747,545	$3,193,874,572	$3,218,404,399	$3,245,181,504
2055	$3,171,790,884	$3,224,247,312	$3,254,724,345	$3,287,941,990
2056	$3,191,710,958	$3,256,177,719	$3,293,541,829	$3,334,199,420
2057	$3,211,510,893	$3,289,693,801	$3,334,890,469	$3,383,990,480
2058	$3,231,193,857	$3,324,752,956	$3,378,694,647	$3,437,204,272
2059	$3,250,763,050	$3,361,238,031	$3,424,765,288	$3,493,579,255
2060	$3,270,221,699	$3,398,962,450	$3,472,809,566	$3,552,718,491
2061	$3,289,573,048	$3,437,684,391	$3,522,453,957	$3,614,121,517
2062	$3,308,820,355	$3,477,127,911	$3,573,276,932	$3,677,227,421
2063	$3,327,966,882	$3,517,007,298	$3,624,845,550	$3,741,461,626
2064	$3,347,015,893	$3,557,050,466	$3,676,749,758	$3,806,278,979
2065	$3,365,970,641	$3,597,017,817	$3,728,629,503	$3,871,197,570
2066	$3,384,834,369	$3,636,714,534	$3,780,192,001	$3,935,820,483
2067	$3,403,610,302	$3,675,995,890	$3,831,218,869	$3,999,845,261
2068	$3,422,301,641	$3,714,766,532	$3,881,564,666	$4,063,062,876
2069	$3,440,911,561	$3,752,975,436	$3,931,149,305	$4,125,349,019
2070	$3,459,443,202	$3,790,608,400	$3,979,946,994	$4,186,650,765
2071	$3,477,899,670	$3,827,679,664	$4,027,973,958	$4,246,971,353
2072	$3,496,284,029	$3,864,223,840	$4,075,276,588	$4,306,355,125
2073	$3,514,599,300	$3,900,288,829	$4,121,921,012	$4,364,873,984
2074	$3,532,848,455	$3,935,930,047	$4,167,984,533	$4,422,616,055
2075	$3,551,034,416	$3,971,205,985	$4,213,549,012	$4,479,676,744
2076	$3,569,160,052	$4,006,174,998	$4,258,696,033	$4,536,152,091
2077	$3,587,228,173	$4,040,893,112	$4,303,503,576	$4,592,134,103
2078	$3,605,241,534	$4,075,412,639	$4,348,043,894	$4,647,707,723
2079	$3,623,202,826	$4,109,781,403	$4,392,382,311	$4,702,949,055

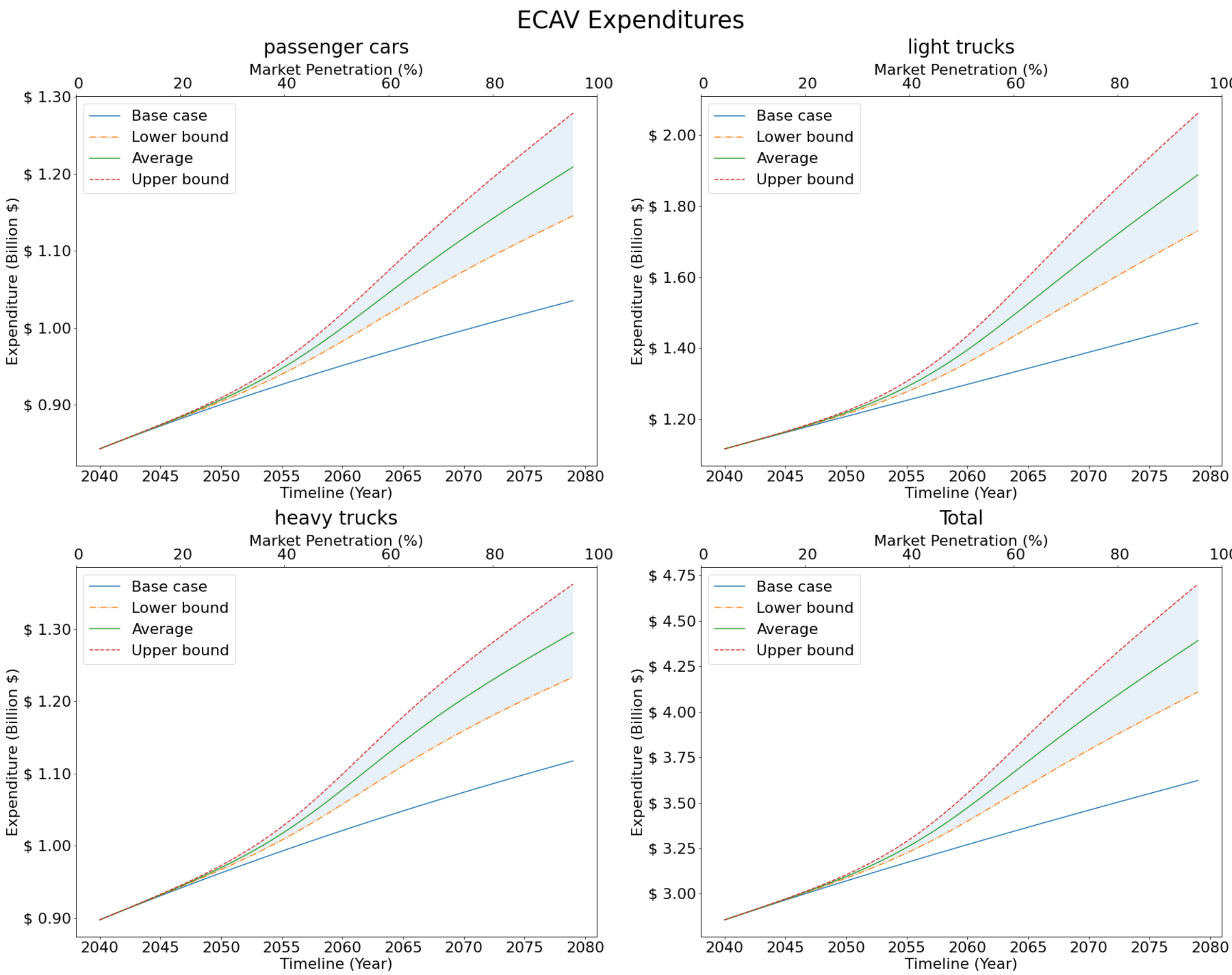


Figure 4.14: Annualized Total Highway Expenditures under ECAV scenario from low through high market penetration

b) Highway Revenues

Highway expenditures for the ECAV scenario are much closer to those for the CAV scenario. However, the revenues for the ECAV scenario are much closer to those under the electric vehicle scenario. This is largely because the disparity in revenues between the ECAV paradigm and the base case are driven primarily by the loss of fuel revenues resulting from vehicle electrification. At low market penetration rates, the disparity in revenues between the base case the ECAV paradigm is minimal. However, this disparity grows as the market penetration increases from low to the moderate or high levels. The non-fuel revenues, however, are higher for under ECAVs than the base case for all levels of market penetration. This is because the increase in travel demand resulting from the mass market adoption of the vehicle technologies necessitates new vehicle purchases that contribute to the revenues from registration fees and other taxes. Overall, the decline in revenues under the ECAV scenario are driven primarily by the loss of fuel revenues due to electrification. At low market penetrations (10% - 30%), the fuel revenues are 70% to 90% of the base case fuel revenues. At high market penetration rates however, these declines to around 10% to 20% of the base case fuel revenues. Therefore, as the market penetration rates increase, the total revenues become more reliant on non-fuel revenues. This can be seen by the slight increase in revenues from passenger cars as the market penetration rate increases. The increase is a result of non-fuel revenues increasing in response to increased VMT resulting from wide adoption of ECAVs.

Table 4.10: Annualized Highway Revenues Estimates in the era of ECAVs from low market penetration (2040s) through high market penetration / saturation (late 2070s)

	Annualized Total Highway Revenues for ECAV			
Year	**Base Case**	**Lower Estimate**	**Average**	**Upper Estimate**
2040	$2,739,297,184	$2,712,686,753	$2,712,686,753	$2,712,686,753
2041	$2,760,807,217	$2,728,236,202	$2,728,369,467	$2,728,518,113
2042	$2,782,317,251	$2,742,489,706	$2,742,817,057	$2,743,182,169
2043	$2,803,827,285	$2,755,183,380	$2,755,785,441	$2,756,456,906
2044	$2,825,337,319	$2,766,007,900	$2,766,990,184	$2,768,085,605
2045	$2,846,847,353	$2,774,604,580	$2,776,103,401	$2,777,774,670
2046	$2,868,357,387	$2,780,563,081	$2,782,752,209	$2,785,192,870
2047	$2,889,867,421	$2,783,421,906	$2,786,519,702	$2,789,972,838
2048	$2,911,377,455	$2,782,673,211	$2,786,949,759	$2,791,715,837
2049	$2,932,887,489	$2,777,773,769	$2,783,557,244	$2,790,001,044
2050	$2,954,397,523	$2,768,164,130	$2,775,845,278	$2,784,400,668
2051	$2,975,907,556	$2,753,297,887	$2,763,331,193	$2,774,502,131
2052	$2,997,417,590	$2,732,682,309	$2,745,582,212	$2,759,938,167
2053	$3,018,927,624	$2,705,930,160	$2,722,260,753	$2,740,424,825
2054	$3,040,437,658	$2,672,820,146	$2,693,177,332	$2,715,805,987
2055	$3,061,947,692	$2,633,360,318	$2,658,346,452	$2,686,101,009
2056	$3,083,457,726	$2,587,845,259	$2,618,037,937	$2,651,549,763
2057	$3,104,967,760	$2,536,895,278	$2,572,813,713	$2,612,647,097
2058	$3,126,477,794	$2,481,465,374	$2,523,539,258	$2,570,157,462
2059	$3,147,987,828	$2,422,814,721	$2,471,360,886	$2,525,101,257
2060	$3,169,497,862	$2,362,434,181	$2,417,645,320	$2,478,708,064
2061	$3,191,007,895	$2,301,938,527	$2,363,885,872	$2,432,338,310
2062	$3,212,517,929	$2,242,938,973	$2,311,587,748	$2,387,382,519
2063	$3,234,027,963	$2,186,916,879	$2,262,150,780	$2,345,153,577
2064	$3,255,537,997	$2,135,119,156	$2,216,768,716	$2,306,789,811
2065	$3,277,048,031	$2,088,489,950	$2,176,359,877	$2,273,184,020
2066	$3,298,558,065	$2,047,644,128	$2,141,536,032	$2,244,946,938
2067	$3,320,068,099	$2,012,879,060	$2,112,607,857	$2,222,405,550
2068	$3,341,578,133	$1,984,214,972	$2,089,618,873	$2,205,629,966
2069	$3,363,088,167	$1,961,451,642	$2,072,396,732	$2,194,478,850
2070	$3,384,598,201	$1,944,230,066	$2,060,610,941	$2,188,652,960
2071	$3,406,108,234	$1,932,090,516	$2,053,828,435	$2,187,748,151
2072	$3,427,618,268	$1,924,521,832	$2,051,561,586	$2,191,302,111
2073	$3,449,128,302	$1,920,999,801	$2,053,306,146	$2,198,831,928
2074	$3,470,638,336	$1,921,014,671	$2,058,568,849	$2,209,861,856
2075	$3,492,148,370	$1,924,089,116	$2,066,885,733	$2,223,942,081
2076	$3,513,658,404	$1,929,788,526	$2,077,832,909	$2,240,660,020
2077	$3,535,168,438	$1,937,725,575	$2,091,031,594	$2,259,645,887
2078	$3,556,678,472	$1,947,560,782	$2,106,149,109	$2,280,574,158
2079	$3,578,188,506	$1,959,000,493	$2,122,897,222	$2,303,162,308

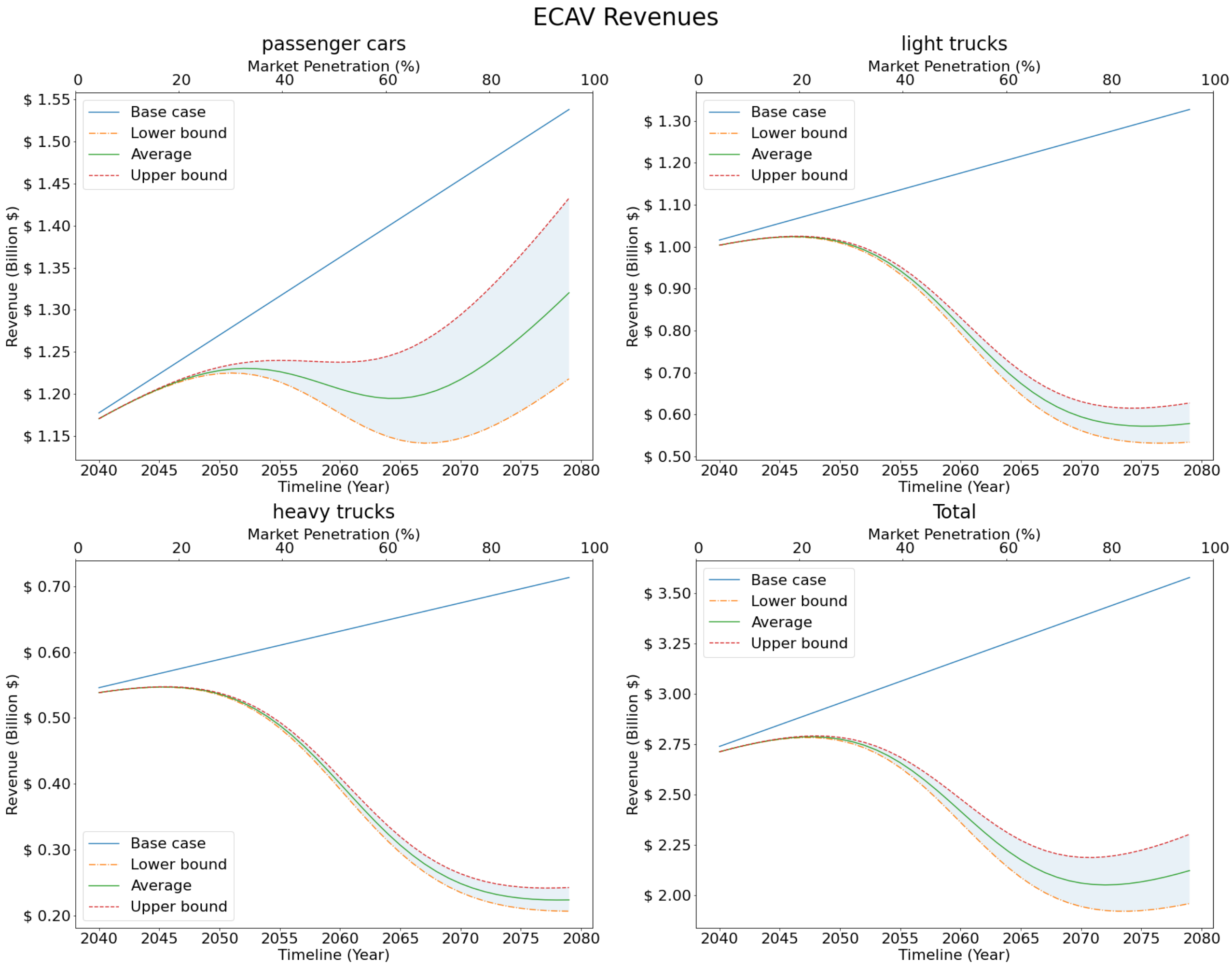


Figure 4.15: Annualized Total Highway Revenues for the ECAV scenario from low through high market penetration

c) User Equity Analysis

Under ECAV, the equity ratios depict a similar tend to that seen under the previous scenarios reported. The results for the ECAV scenario suggest that if this scenario becomes a reality, passenger cars will be overpaying their share of the cost responsibility while light and heavy-duty trucks will be underpaying their share. Heavy-duty trucks contribute half as much in the proportion of their revenues as the proportion of costs they incur, resulting in an equity ratio of about 0.5 at low market penetration rates (Figure 4.16). This ratio gets worse as the market penetration increases because the revenues decrease overall. Overall, the system is both inequitable and inefficient. If this scenario becomes a reality, then the highway agency will need to revise the user fee structure to rectify such inefficiency and inequity.

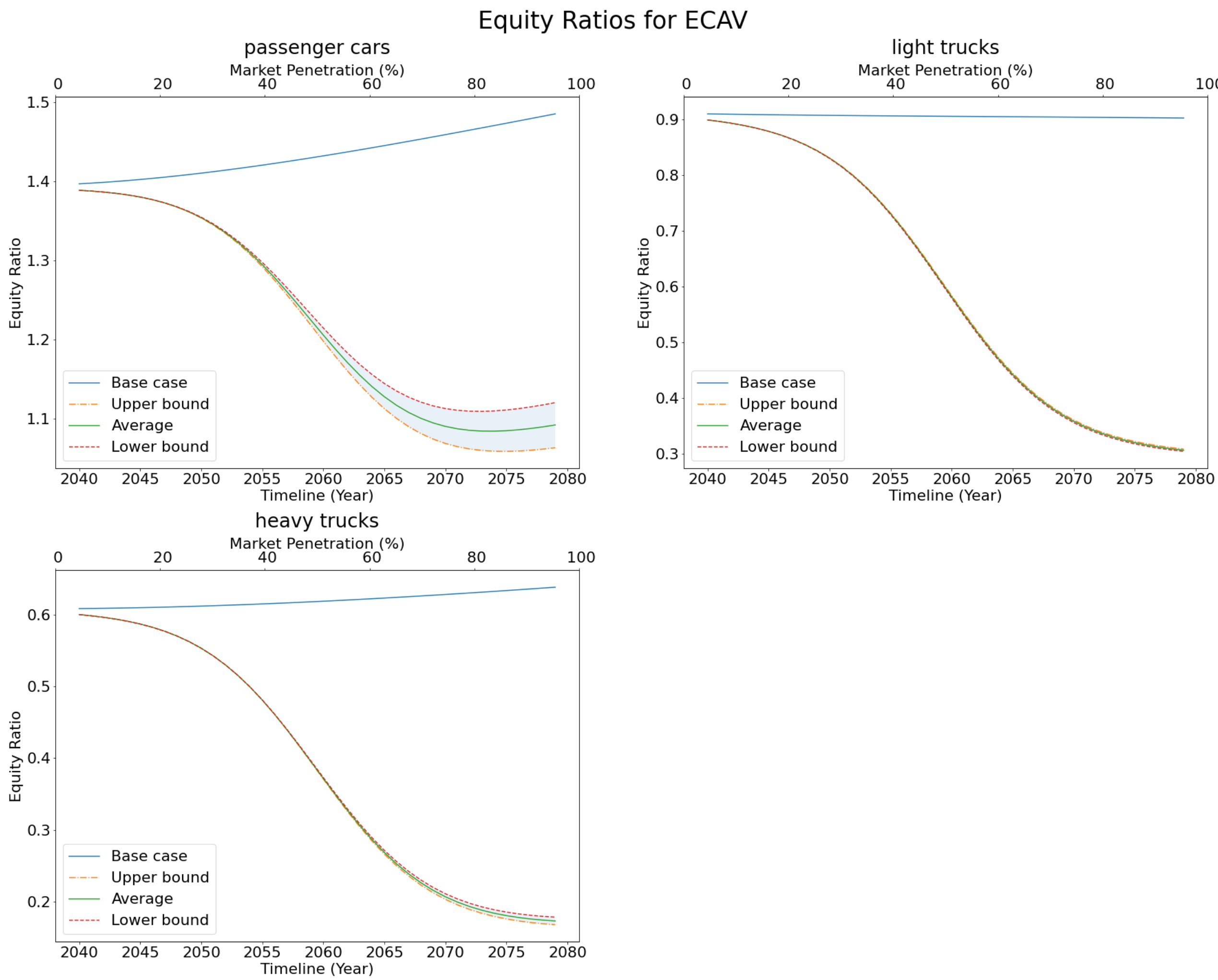


Figure 4.16: Equity Ratios for ECAV scenario

4.4 Chapter Summary

This chapter presented the results of the analysis of the impacts of emerging vehicle technologies on highway revenues, expenditures, and equity. The results indicate that vehicle connectivity has marginal impacts on highway expenditures, revenues, and equity. At the low market penetration, the expenditures are only slightly higher for connected vehicles than the base case (Figure 4.1). This difference can mostly be attributed to the increase in expenditures for provision of connectivity equipment, as well as the slight improvement in fuel economy for the connected vehicles. At moderate market share of CVs, the disparity is even wider as these effects are exacerbated. At high market penetration levels when most vehicles are equipped with connectivity, the need for investments in (and maintenance of) connectivity infrastructure is greater. The revenues are only slightly lower for connected vehicles compared with the base case. This difference is attributable to slight improvements in fuel economy of connected vehicles.

Vehicle automation has a is expected to have a more severe impact on highway expenditures compared with connectivity. This disparity grows with the increasing level of market penetration. This can be attributed in part to the increased overall travel that is to be expected with vehicle automation as detailed in Section 3.4.2. This increase in system usage results in faster deterioration of the infrastructure which will then require more frequent maintenance. Furthermore, the increase in overall travel demand necessitates investments in new infrastructure to support the growth. Additionally, investments in connectivity and other smart infrastructure to support the automation functionality adds to the increased expenditure. The revenues are significantly lower for automated vehicles across all levels of market penetration. Similar to the case for expenditures, the revenues disparity is significant and grows with increasing levels of market penetration. This is mostly because of the improved fuel efficiency of AVs.

Electric vehicles are expected to have impacts on expenditure that are similar to connected vehicles. Highway revenues, however, are expected to be impacted significantly in this scenario. This is because electric vehicles do not use gasoline or diesel, the taxes from which form a significant portion of the user revenue base. Combinations of these vehicle technologies are expected to have impacts on highway expenditures and revenues that are similar to the individual scenarios, with added synergistic effects.

5. DISCUSSION

5.1 Introduction

The last few decades have seen a consistent decline in the amount of revenue generated from highway user groups for the purpose of financing highway developments and maintenance. This consistent decline can be attributed to two primary reasons; the fuel tax rates have not been adjusted to account for inflation and the decline in the purchasing power of the dollar. This has led to funding shortfalls that year after year, the gaps have generally been filled by transfers from the treasury's general fund ("The Highway Trust Fund Explained," 2020; Schank & Rudnick-Thorpe, 2011). The second major reason for the decline in highway revenues is the increase in motor vehicle fuel efficiency. Due to increased need for environmental sustainability and tightening regulations, vehicle fuel economy has consistently been improving over the last few decades, and the use of alternative fuels is also increasing (Mead, 2021; USDOT, 2019). This has led to a consistent decline in the revenues collected from fuel taxes (Agbelie et al., 2012; Kile, 2021; Kirk & Mallet, 2020). Although this trend is not immediately obvious due to the corresponding increase in vehicles and vehicle miles of travel, revenues adjusted for VMT gives a clear picture of the severity of the problem in the near and long term.

The growing funding gap lends urgency to the need for improving the current structure of the highway financing mechanism and developing new and sustainable strategies that satisfactorily attain the finance-related goals of revenue adequacy and efficiency of the highway system and equity among the highway users. Researchers have previously explored alternative user charging schemes and their feasibility in terms of implementation cost and technological needs (Oh & Sinha, 2008). Some notable examples include inflation-indexed taxation structures, ad valorem taxes (Agbelie et al., 2010), and distance-based taxes (Agbelie et al., 2012; Agbelie et al., 2016; Oh & Sinha, 2008). In order to be sufficient, a revenue scheme must meet certain criteria, namely: (i) revenue adequacy (sufficiency, stability and accountability), (ii) system efficiency, (iii) equity between user groups, (iv) cost of implementation, and (v) public acceptability.

The emergence of electric, connected, and automated transportation threatens to disrupt the highway financing system because these technologies are expected to affect key factors that influence revenues and expenditures associated with highway financing. This thesis discusses the eminent shortfalls in highway funding and other challenges as the transportation industry prepares transitions towards the new emerging technologies. This thesis discusses and proposes revisions to the current user fee structure in a way that is expected to promote sustainability, efficiency, and equity in the highway financing system. To address the likely shortfalls in revenue due to the emerging technologies, the thesis proposes funding mechanisms that include a revision of the fuel tax code, introduction of a distance-based tax, and a reorganization of the vehicle class taxonomy. These are detailed and discussed in the subsequent sections of this chapter.

5.2 **Improving the Highway Financing Mechanism**

5.2.1 User Fee Structure Revision

Two of the main reasons for conducting a highway cost allocation study are: (i) to assess system usage, expenditures, and generated revenues in a bid to improve system efficiency through revision of existing user fee structures and/or introduction of new funding alternatives, and (ii) to assess, and improve the user equity of the system. The current highway financing system faces an eminent shortfall of revenues. Therefore, there is a clear and urgent need to revise the current user fee structure to address and reverse the growing revenue deficit. Furthermore, the forthcoming mass market adoption of emerging vehicle technologies poses new challenges for highway financing and user equity. Some of these technologies, such as connectivity and automation are poised to alter travel behaviors and impact overall travel characteristics and vehicle ownership patterns. Not only does this impact the amount of revenues generated from registration taxes, licensing fees, etc., it also creates new travel patterns such as ride sharing that could have huge implications for the current revenue streams. Additionally, these new patterns could have numerous implications for equity and access within the populous. Other technologies, such as electrification threaten to eliminate huge portions of the tax revenue base, the fuel tax. This thesis therefore proposes a revision to the current user fee structure that will help address the issues raised.

The proposed revision to the user fee structure puts user equity at the center of the discussion, ensuring that any new fees assessed to users not only guarantees system efficiency but also user equity. Throughout the results presented in Chapter 4 of this thesis, it was evident that some vehicle classes, i.e., passenger cars were consistently overpaying their share of the cost responsibility, as reflected in the calculated equity ratios. At the same time, other classes, such as the light and heavy-duty trucks were found to be consistently underpaying their share of the costs incurred, as illustrated by their equity ratios being consistently less than one. The main reason for this disparity is the difference their relative share of vehicle miles of travel. As a class, passenger cars' total VMT is several times that of light and heavy trucks. Also, because the current user fee structure chargers a flat tax per gallon of fuel used, vehicle classes that have more miles of travel pay more in taxes than their counterparts with fewer miles of travel. This would have been an equitable system had the damage incurred followed the same model. However, as has been shown in numerous studies, trucks and other heavy vehicles cause more in damage to highway infrastructure than their lightweight counterparts. Therefore, for every mile of travel on the system, a heavy truck causes more damage to the infrastructure than a passenger car yet pays the same fee in tax rate. Although heavy vehicles are assessed heavy vehicle fees and additional taxes, this has not been enough to make up for the disparity in revenues contributed, nor has it been enough to offset to deficit.

To address this issue, this thesis proposes a user fee structure, the *variable tax scheme*, to address the short-term deficits in revenues but also provide a transition to a long-term sustainable financing structure in the era of ECAVs. In the short term, this thesis proposes a revised fuel tax structure in which each vehicle class is assessed a different fuel tax rate, according to its size and weight requirements. The exact rates to be paid by each vehicle class are determined through optimization as illustrated below. In the long term, a distance-based user fee is introduced as the industry moves away from fuels and embraces electric vehicles. Studies have shown that distance-based taxes provide a sustainable long term financing alternative to the current fuel tax-based system (Agbelie et al., 2010; Agbelie et al., 2012; Oh & Sinha, 2008; Sorensen & Taylor, 2005). Other alternatives offered to the flat fuel tax include ad valorem fuel taxes, inflation indexed taxes, etc.

Recall from chapter 2 that for a given highway user class i with fleet fuel efficiency e_i running on fuel type k, fuel revenues generated can be estimated using equation (5.1), where $p_{i,k}$ represents the proportion vehicles in the class running on fuel type k. And given the total cost responsibility for the vehicle class C_i, percentage cost responsibility CRP_i, percentage revenue attribution RCP_i, and non-fuel revenue y_i, the equity ratio can be computed using equation (5.2).

$$R_{i,k} = \left(\frac{VMT_i}{e_{i,k}}\right) \times T_k \times p_{i,k} \tag{5.1}$$

$$ER_i = \frac{RCP_i}{CRP_i} \tag{5.2}$$

By combining equations (5.1) and (5.2), we get that the equity ratio can be expressed as

$$ER_i = \frac{RCP_i}{CRP_i} = \frac{\frac{\sum_k\left(\frac{VMT_i}{e_{i,k}} \times T_k \times p_{i,k}\right) + y_i}{\sum_i \sum_k\left(\frac{VMT_i}{e_{i,k}} \times T_k \times p_{i,k}\right) + y_i}}{\frac{C_i}{\sum_i C_i}} \tag{5.3}$$

And if we include a distance-based tax, x_i, and equate (5.3) to the desired value of 1.00, we get:

$$ER_i = \frac{\frac{\left(\sum_k\left(\frac{VMT_i}{e_{i,k}}\right) \times T_{i,k} \times p_{i,k}\right) + y_i + x_i}{\sum_i\left(\sum_k\left(\frac{VMT_i}{e_{i,k}}\right) \times T_{i,k} \times p_{i,k}\right) + y_i + x_i}}{\frac{C_i}{\sum_i C_i}} = 1.00 \tag{5.4}$$

Equation (5.4) can be optimized subject to constraints given below:

$$T_{i,k} \le \mu \tag{5.5}$$

$$x_i \le \lambda \tag{5.6}$$

$$T_{i,k}, x_i \ge 0 \tag{5.7}$$

$$\sum_i\left(\sum_k\left(\frac{VMT_i}{e_{i,k}}\right) \times T_{i,k} \times p_{i,k}\right) + y_i + x_i \ge \sum_i C_i \tag{5.8}$$

Where μ is the maximum allowed fuel tax rate and λ is the maximum allowed VMT tax rate for the given ECAV operation and market penetration rate. Constraints (5.5) and (5.6) limit the allowable tax rate, in a bid to promote public acceptance of the structure. Constraint (5.7) restricts the taxes to positive values only because taxes cannot be negative. Finally, constraint (5.8) ensures that the generated revenues from all sources are at least equal to or greater than the total costs or expenditures, ensuring system efficiency. In solving the problem, the algorithm adjusts the tax rates $T_{i,k}$ for each vehicle class and fuel type, and the VMT tax x_i so that the objective function and all constraints are satisfied. With these constraints in place, this proposed revenue scheme satisfies all the criteria established earlier for an efficient and equitable system, namely: (i) revenue adequacy (sufficiency, stability, and accountability), (ii) system efficiency, (iii) equity between user groups, (iv) cost of implementation, and (v) public acceptability. The cost of implementation may require further research to precisely ascertain. However, a simple implementation could rely technological solutions such as imbedded sensors (RFID tags, NFC, or other forms of identification) to identify vehicles by class at gas stations and apply the relevant taxes accordingly.

5.2.2 Efficiency Comparison among Users

In addition to revising the user fee structure to improve equity as discussed in the preceding section, there must be also a reliable way to assess the relative performance of each user group regarding its responsibilities. Across the highway system, one must be able to compare the performance and resource use of each user group relative to others. This is necessary because while the equity gives an indication of relative performance in terms of cots and contributions, the equity ratio cannot reliably be used to compare performances across two systems (or even across multiple years). Furthermore, regulatory agencies can benefit from reliable performance comparisons of systems within their jurisdiction. For example, the federal government can benefit from an assessment of each state's infrastructure output for a given amount of federal investment.

Within the context of highway user groups, this thesis proposes a method to reliably compare the performance of each user group relative to others. For a given highway user group (vehicle class), consider the cost incurred per mile of travel on the highway system, and the revenue generated (contributed). For an efficient and equitable system, the cost incurred per mile of travel must equal the revenue generated (contributed) for each highway user group (vehicle class). This is shown as the efficiency line in Figure 5.1. Vehicle classes that underpay their share of the cost responsibility (i.e incur more cost per mile than they contribute in revenue) appear below the efficiency line. Similarly, vehicle classes overpaying their responsibility appear above the efficiency line. Figure 5.1 illustrates this approach using data for the moderate ECAV market penetration scenario (Section 4.3.5). The base case and moderate ECAV data shown in the figure as explained the relevant sections of this thesis and the moderate ECAV (optimized) data represents the moderate ECAV data with the revised user fee structure introduced in Section 5.2.1 of this thesis (more illustrations of the application of the proposed user fee structure are presented in Section 5.3).

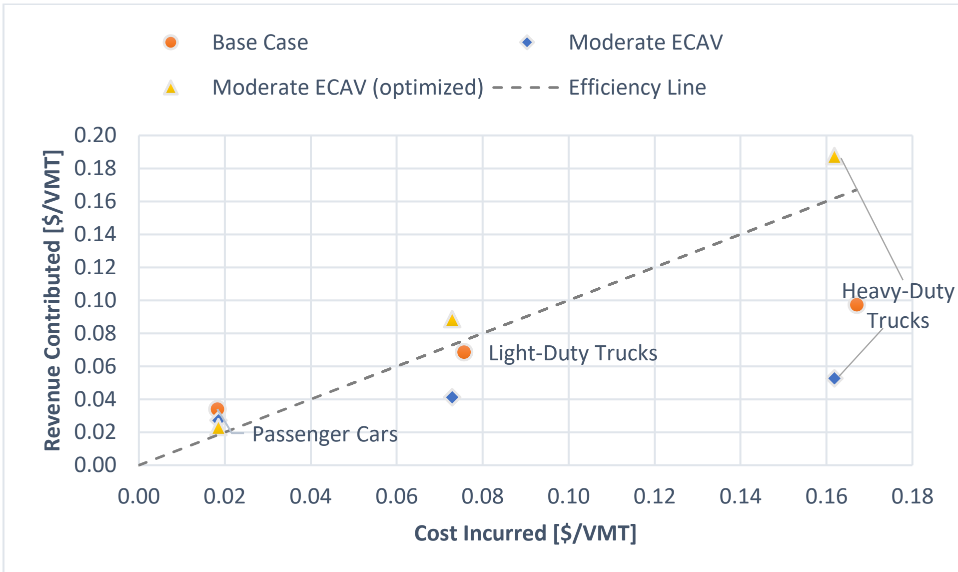


Figure 5.1: Revenue-Expenditure Efficiency comparison across the vehicle classes

Although this comparison is presented here for the three highway user groups used in this thesis, it can be extended to the 13 FHWA vehicle classes, or any arbitrary number of classes. Furthermore, it is not restricted to comparisons of vehicle classes as shown in this context. Under defined performance measures, the same method can be applied to compare states' performance of highway infrastructure per amount of investment. In such situations, however, care must be taken to control for variables such as variations in climatic conditions and inventory size.

5.3 Impacts and User Fee Schemes Under Different ECAV Paradigms

Under the ECAV scenarios, significant changes are expected to the travel patterns, vehicle ownership patterns, and total VMT. Consequently, highway expenditures and revenues, which are tied in large part to these patterns are expected to be impacted. With these changes, equity among vehicle classes will likely be impacted. These impacts were reported in Chapter 4 of this thesis. This section discusses these impacts in detail and applies the variable tax scheme to address the adverse effects of these impacts to achieve system efficiency and equity. Using the variable tax scheme, this section recommends optimal tax rates and/or fees that must be levied on each vehicle class at a given ECAV scenario to maintain system efficiency and equity.

5.3.1 Connected Vehicles

Connected vehicles, as outlined in Section 3.4.1 require connectivity infrastructure for their operations. Infrastructure such as cellular connectivity, cloud infrastructure, etc. are necessities for connected vehicles to operate as intended. This is because the vehicles will need to communicate with other vehicles through vehicle to vehicle (V2V) communication protocols, with infrastructure (V2I) and the cloud computing network. While development, deployment and maintenance of this infrastructure will require funding, much of the cost is expected to be borne by the private sector. The cost of connectivity equipment and features on a vehicle for example is expected to be borne by the individual purchasing the vehicle, and cellular networks and cloud infrastructure will likely be owned and operated privately. Transportation agencies and public entities may however incur costs for provision of some of the services that support connected vehicles. Such services may include intelligent transportation devices such as smart traffic signals and their control modules. Such costs are considered as part of the common costs as they are independent of the vehicle size and weight.

Vehicle connectivity, per se, is not expected to significantly change travel patterns and overall VMT. Some marginal changes in VMT may be expected because of the benefits that are associated with vehicle connectivity. The connectivity capability means that vehicles will be able to communicate with other vehicles and coordinate well, eliminating the need for stop-and-go traffic and erratic driving, potentially increasing road, and intersection capacities. This is likely to result in induced demand and increase in VMT. However, because the vehicles under this scenario are still not fully autonomous, these benefits will only be realized in part and thus the changes to VMT will be marginal. Consequently, the resulting changes in highway expenditures are also expected to be marginal, as reported in Section 4.3.1. At low market penetration levels of CVs, the disparity in expenditures between the base case and the CV scenario is about 0.3%, and at the moderate and high market penetration levels, this disparity grows to approximately 3% and 6%, respectively (see Table 4.1). In each case, the disparity is less than 10% of the total expenditure. Similarly, the revenues are expected to change only marginally, due to the improved fuel efficiency that will accompany vehicle connectivity. The revenues for the CV scenario are closer to the base case compared to the expenditures. The disparities are approximately 0.1%, 0.3%, and 1% at the low, moderate, and high market penetration rates (see Table 4.2). Consequently, the equity ratios under the connected vehicles paradigm are similar to that of the base case, as can be seen in Figure 4.3, averaging less than one percentage change in each case between the base case and the CV scenario.

Connected vehicles still operate with the same fundamental functionality as conventional vehicles with regards to highway revenues. Therefore, an application of the variable tax scheme simply adjusts the fuel taxes to achieve better equity and system efficiency. A sample user fee scheme is presented in Table 5.1. Note that other tax rates are possible under different constraints of the minimum and maximum allowable tax rates. In this example, the minimum allowable tax rate used is $0.01 (1 cent) and the maximum was $0.50 (50 cents).

Table 5.1: Proposed User fees under the variable tax scheme for different market penetration levels of CV

Vehicle Class	**Fuel Tax Rate ($ / Gallon)**				**Equity ratio**
	Fed Diesel	State Diesel	Fed Gas	State Gas	
Low CV Market Penetration					
Passenger Cars	0.01	0.01	0.01	0.01	1.02
Light Duty Trucks	0.17	0.50	0.23	0.15	1.00
Heavy Duty Trucks	0.50	0.50	0.50	0.50	0.98
Moderate CV Market Penetration					
Passenger Cars	0.01	0.01	0.01	0.01	1.04
Light Duty Trucks	0.42	0.26	0.21	0.20	1.00
Heavy Duty Trucks	0.50	0.50	0.50	0.50	0.97
High CV Market Penetration					
Passenger Cars	0.01	0.01	0.01	0.01	1.05
Light Duty Trucks	0.42	0.26	0.21	0.20	1.01
Heavy Duty Trucks	0.50	0.50	0.50	0.50	0.96

5.3.2 Automated Vehicles (AVs)

Vehicle automation is set to disrupt travel and transportation, the impact almost identical to that brought about by the invention of the automobile itself. With the need for a driver eliminated, traffic accidents are expected to reduce significantly, as well over 90% of traffic crashes can be attributed to human error (NHTSA, 2008). In addition to improved safety, autonomous vehicles are also expected to reduce the unproductive time spent during a commute. The vehicles will drive themselves autonomously and drivers will become passengers and thus free to engage in other activities, leading to a more productive use of their time. Furthermore, travel delays will be reduced because autonomous vehicles will likely be able to coordinate their trajectories much better in relation to other vehicles on the road, resulting in fewer conflicts and thus smoother flow of traffic (Du et al., 2020; Li, Chen, Dong, et al., 2020).

Autonomous vehicles are expected to impact travel behaviors and overall travel volumes. As discussed in detail in Sections 3.4.2 and 3.5, autonomous vehicles may have one of two competing effects on travel patterns and behaviors. On the one hand, the autonomy of the vehicles may increase the accessibility of ride-sharing alternatives, reducing the need or motivation for travelers or commuters to own vehicles due to the ease of summoning a vehicle to take them to their destination when needed. This increase in ride sharing and on demand mobility may likely result in an overall decrease vehicle ownership and the overall VMT is likely to decrease as the market penetration increases. However, this scenario applies only to commuter traffic that consists of passenger cars and light duty vehicles, and not to heavy vehicles and freight trips. Thus, its impact is likely to be limited. On the other hand, autonomous vehicles, with their superior ability to keep to lanes without significant deviations, smoother driving capabilities, etc. are expected to yield an increase in road capacity. As suggested and/or demonstrated in in the literature and discussed in Section 3.5 of this thesis, an increase in road capacity is typically followed by an induced demand in traffic, leading to an increase in overall travel. Thus, all things considered, vehicle automation can be generally expected to result in an increase in overall VMT.

In discussing the anticipated changes in travel patterns and VMT due to automation, this research assumed overall VMT increases of 10% at low market penetration, 15% at moderate levels, and 20% at high levels of AV market penetration. With these changes, highway expenditures are expected to increase accordingly, as reported in Section 4.3.2 of this thesis. Similarly, highway revenues are expected to be slightly impacted by vehicle automation. The impact on revenues is not expected to be very significant as under this scenario, autonomous vehicles are expected to be propelled by internal combustion engines. The more likely case, however, is that AVs will have electric propulsion, the impacts of which are reported in Section 4.3.3b). When AVs are not electric, the resulting equity ratios are presented in Figure 4.4 under the different levels of market penetration. Applying the variable tax scheme to the AV paradigm yields results presented in Table 5.2. Similar to the connected vehicles case, the proposed tax rates achieve the desired equity and efficiency in the highway system. Other optimal tax rates can also be implemented subject to different constraints of the minimum and maximum allowable tax rates to facilitate public acceptance.

Table 5.2: Proposed User fees under the variable tax scheme for different market penetration levels of AV

Vehicle Class	**Fuel Tax Rate ($ / Gallon)**				**Equity ratio**
	Fed Diesel	State Diesel	Fed Gas	State Gas	
Low AV Market Penetration					
Passenger Cars	0.01	0.01	0.01	0.01	1.00
Light Duty Trucks	0.25	0.30	0.23	0.14	1.00
Heavy Duty Trucks	0.30	0.30	0.30	0.30	1.00
Moderate AV Market Penetration					
Passenger Cars	0.01	0.01	0.01	0.01	1.00
Light Duty Trucks	0.40	0.12	0.23	0.40	1.00
Heavy Duty Trucks	0.40	0.24	0.30	0.30	1.00
High AV Market Penetration					
Passenger Cars	0.01	0.01	0.01	0.01	1.00
Light Duty Trucks	0.47	0.12	0.23	0.39	1.00
Heavy Duty Trucks	0.50	0.45	0.31	0.31	1.00

5.3.3 Electric Vehicles

a) Non-Automated Electric Vehicles

The impacts of electric vehicles are discussed assuming specific percentages of human-driven and automated vehicles. The first case considered is that of human-driven electric vehicles. This is a particularly relevant scenario in this study because the technology underlying this scenario is already mainstream and gaining market share. Although the impacts have not become significant enough to affect highway expenditures and revenues, the scenarios being forecasted are expected to have significant impacts once the market penetrations become significant. The electric vehicles under this scenario are still human driven, therefore, it is expected that electrification alone will not significantly alter travel patterns or result in significant changes in VMT. However, because electric cars do not use fossil fuels, they are expected to make no contributions to the fuel tax and therefore result in significant decreases in highway revenues.

At low market penetrations, approximately three in ten cars on the road are expected to be electric, meaning that the revenue potential will become only 70% of what it would have been had the cars not been electric. Similarly, moderate market penetration reduces the revenue potential to 40% and a high market share of 90% electric vehicles implies only 10% of the cars on the road will be buying fuel and thus paying fuel taxes, further reducing the fuel revenue potential to just 10% of the base case. This decrease in revenue is necessarily due to cars not buying fuels, therefore, a variable tax on fuels alone is not enough to solve the problem.

In line with the framework of the variable tax scheme, a component of user fee structure is a distance-based tax. For electric vehicles, this can be a VMT tax levied on each vehicle class. The optimal rate for each class can be determined using optimization tools, considering the relative VMT of the class, the relative percentage of the vehicle fleet that is electric (market penetration level) and the fuel taxes paid by non-electric vehicles in the class. The small percentage of cars that are still not electric continue paying the same fuel tax rates as before, or accordingly as deemed appropriate at that time, while EVs pay a VMT tax (or electric charging fee) imposed to make up the deficit in revenue. These deficits will vary based on the market penetration of the EVs. Therefore, each level of market penetration will have a different taxation scheme to maintain parity in revenues and expenditures as well as achieve optimal equity. The VMT tax be implemented to be paid as a once off fee at the beginning or end of the year or paid monthly based on miles traveled.

Alternatively, the fee can be implemented as an energy tax (billed in $ / kWh) at the charging station similar to how gasoline taxes are collected. Table 5.3 illustrates some proposed VMT tax rates under different levels of EV market penetration.

Table 5.3: Proposed User fees under the variable tax scheme for different market penetration levels of non-automated EVs

Vehicle Class	**Fuel Tax Rate ($ / Gallon)**				**VMT Tax ($ / mile)**	**Equity ratio**
	Fed Diesel	State Diesel	Fed Gas	State Gas		
			Low EV Market Penetration			
Passenger Cars	0.01	0.01	0.01	0.01	0.0001	1.08
Light Duty Trucks	0.50	0.39	0.27	0.14	0.0001	1.00
Heavy Duty Trucks	0.50	0.50	0.50	0.50	0.1000	0.95
			Moderate EV Market Penetration			
Passenger Cars	0.01	0.01	0.01	0.01	0.0001	1.08
Light Duty Trucks	0.50	0.50	0.50	0.50	0.0350	1.00
Heavy Duty Trucks	0.50	0.50	0.50	0.50	0.1500	0.94
			High EV Market Penetration			
Passenger Cars	0.01	0.01	0.01	0.01	0.0001	1.01
Light Duty Trucks	0.01	0.01	0.40	0.40	0.0827	1.00
Heavy Duty Trucks	0.50	0.50	0.50	0.50	0.2000	1.00

b) Automated Electric Vehicles (EAVs)

In previous sections, we have shown how vehicle automation is expected to have significant impacts on travel patterns and overall VMT. This study assumed VMT increases of 10%, 15% and 20% at low, moderate, and high market penetrations, respectively. The results suggest that vehicle electrification negatively impacts the total highway revenues by reducing the share of fuel revenues obtained. At low market penetrations, we can expect up to 30% of all vehicles in the fleet to be electric, meaning that at the worst case, only 70% of available vehicles contribute to the revenue, while 100% of the vehicle fleet incurs a portion of the cost. Similarly, at moderate and high market penetrations, only 40% and 10% respectively are expected to contribute to the fuel revenues. The combination of two presents the increase in expenditures due to automation and the reduction in revenue due to electrification.

The exact impact of the combination is hard to ascertain as it is unclear how the two technologies would interact to achieve synergy. One possible outcome is that the combination would have the increased expenditure expected of autonomation and the decreased revenue associated with vehicle electrification. However, it is also possible for the interaction of the two to produce an outcome that is significantly more severe than each scenario on its own. It is possible that the increase in expenditures under the combined scenario exceed that of automation alone considered in earlier chapters, and that the decrease in revenues fall below that of electrification considered previously. The true outcome is likely to fall between the two extremes. Yet still, this is difficult to ascertain given that no data exists yet about the actual trends and possible interactions. Thus, for simplicity, this research treats the combined scenario as a simple sum of the impacts of each individual scenario, without any synergies. In future research, after the trends emerge and more data is available about the interactions, it is recommended that research should examine the issue more closely with relevant modeling tools.

As reported in the results in Section 4.3.3b), the expenditures are significantly higher for the various levels EAV market share compared with the revenues. Therefore, additional measures will have to be implemented to achieve equity. Since the reduction in fuel revenues is due to vehicle electrification, adjustments to fuel taxes alone will have very little impact on the efficiency and equity ratios. Therefore, the best approach is to introduce an EV VMT tax (as done in Section 5.3.3a) or an EV fee ($/kw-hr). Table 5.4 presents a proposed VMT tax scheme, along with the variable fuel taxes for non-electric vehicles for optimal efficiency and equity at various levels of market penetration.

Table 5.4: Proposed User fees under the variable tax scheme for different market penetration levels of automated EVs

Vehicle Class	**Fuel Tax Rate ($ / Gallon)**				**VMT Tax ($ / mile)**	**Equity ratio**
	Fed Diesel	State Diesel	Fed Gas	State Gas		
Low EV Market Penetration						
Passenger Cars	0.01	0.01	0.04	0.04	0.0001	1.07
Light Duty Trucks	0.50	0.01	0.01	0.01	0.1202	1.00
Heavy Duty Trucks	0.50	0.50	0.50	0.50	0.1500	0.95
Moderate EV Market Penetration						
Passenger Cars	0.01	0.01	0.01	0.01	0.0001	1.06
Light Duty Trucks	0.01	0.01	0.01	0.01	0.1081	1.00
Heavy Duty Trucks	0.50	0.50	0.50	0.50	0.1500	0.96
High EV Market Penetration						
Passenger Cars	0.01	0.01	0.01	0.01	0.0001	1.00
Light Duty Trucks	0.01	0.01	0.01	0.01	0.0774	1.00
Heavy Duty Trucks	0.50	0.50	0.50	0.50	0.1841	1.00

5.3.4 Electric, Connected, and Automated Vehicles (ECAV)

In the previous sections, we have discussed the impacts of the three different vehicle technologies on highway expenditures and revenues. These technologies have different impacts on highway expenditures and revenues. Vehicle connectivity, for example, has minimal impact on both highway revenues and expenditures because it does not significantly alter the travel patterns or volumes, nor does it significantly change vehicles fuel usage. Automation and electrification on the other hand each significantly impact the balance of expenditures and revenues. While automation marginally improves vehicles fuel efficiency, thus marginally affecting fuel revenues, its impact on expenditures is much more pronounced. This is because at significant market penetration, automation results in increased travel and results in increased loading on the highway infrastructure, leading to accelerated deterioration.

Pavements and other structural elements of highways are designed to withstand loadings from a given amount of traffic volumes within the design limits. Designs for structural elements incorporate axle loading and distribution as per design standards as outlined in manuals and specifications such as the AAHSTO bridge design guide. Even with traffic volumes and weights remaining within the specified limits, over time, these structural members degrade and require replacement after a given time (its service life). This is because with every load of traffic supported, live loads are induced within the structural members, which in turn induce moments and stresses within the members. This pattern of repeated stresses in the members, even though within design limits tends to deteriorate the members over their service life. This process, however, is accelerated slightly when the loads increase due to increased volumes or changes in axle loadings. Thus, any changes to the volumes or axle distribution will directly affect the deterioration rates, and in turn the maintenance timelines which directly translate to changes in highway expenditures. Electrification has a more pronounced impact on highway revenues than it does on highway expenditures. At significant levels of market penetration, the share of vehicles that consume fossil fuels and thus pay fuel taxes decreases substantially, along with it, the revenues. Each of these individual technologies has thus been shown to impact the expenditures and revenues, and consequently, the user equity in highway financing.

It is expected that the automobile of the future will contain not only one or two of these technologies, but all three. Increasingly, the market trends point to a future where cars will be electric, connected and most importantly, autonomous. Combining these technologies is expected to amplify the combined impacts of these technologies on highway expenditures, revenues, and equity. As reported in Section 4.3.4, having connectivity and automation is expected to enhance the benefits of both. At low market penetration, the impacts are likely to remain similar to the impacts of automation alone. This is because at this level of market penetration, only approximately 30% of vehicles will be equipped with the technologies. Expected benefits such as platooning, intersection coordination, etc. may not be fully realized in mixed traffic. As the market penetration increases, the benefits become more pronounced as the synergy between automation and connectivity becomes significant. Vehicles coordinate at intersections and result in smoother traffic flows and at highway cruising speeds, platoons can form more easily. In addition, because these vehicles are also connected to the cloud and internet, they can obtain real-time traffic updates and update their routes and speeds accordingly. The result will be an apparent increase lane and intersection capacity, fewer delays, and smoother traffic flows overall. This will result in an induced demand that will result in VMT increments.

Electrification of vehicles, as discussed earlier, reduces the share of vehicles in the fleet that pay fuel taxes. This leads to a significant decrease in the revenues collected, as fuel revenues are a major portion of highway user revenues (see Table 4.6 and Figure 4.8). At low market penetration levels, the earning potential from fuel taxes is reduced to 70% of the vehicles in the fleet, and at moderate and high market penetration levels, that potential becomes 40% and 10% respectively. Therefore, the equity ratios for many of the user groups are far from the optimal value of 1.00 (Figure 4.16). Applying the variable tax scheme to the ECAV scenario can yield an efficient and equitable financing structure as presented in Table 5.5.

Table 5.5: Proposed User fees under the variable tax scheme for different market penetration levels of ECAVs

Vehicle Class	**Fuel Tax Rate ($ / Gallon)**				**VMT Tax ($ / mile)**	**Equity ratio**
	Fed Diesel	State Diesel	Fed Gas	State Gas		
			Low ECAV Market Penetration			
Passenger Cars	0.01	0.01	0.01	0.01	0.0001	1.05
Light Duty Trucks	0.50	0.01	0.01	0.01	0.1342	1.00
Heavy Duty Trucks	0.50	0.50	0.50	0.50	0.2000	0.97
			Moderate ECAV Market Penetration			
Passenger Cars	0.01	0.01	0.01	0.01	0.0001	1.06
Light Duty Trucks	0.01	0.01	0.01	0.01	0.1081	1.00
Heavy Duty Trucks	0.50	0.50	0.50	0.50	0.1500	0.96
			High ECAV Market Penetration			
Passenger Cars	0.01	0.01	0.01	0.01	0.0011	1.00
Light Duty Trucks	0.01	0.01	0.01	0.01	0.0974	1.00
Heavy Duty Trucks	0.50	0.50	0.50	0.50	0.1841	1.00

5.4 User Equity Analysis

5.4.1 Assessing System Inequity

Highway user equity was introduced in Section 2.5 of this thesis. Equity is one of the two main motivations for conducting a highway cost allocation study. The other is efficiency of the system in recovering the infrastructure costs. System efficiency examines how closely the system revenue matches the expenditure. A system is considered efficient if the revenues generated match or exceed the total expenditure, otherwise the system operates at a deficit (Agbelie et al., 2010; ODOT, 1980; Volovski et al., 2015). Highway cost allocation studies are conducted in part to identify these potential deficits and examine various proposals for mitigating or eliminating these deficits. These may include projections of revenue trends under given conditions (Agbelie et al., 2010), revisions to current taxation schemes (Agbelie et al., 2012; Agbelie et al., 2016), and proposals of novel funding alternatives (ECONorthwest, 2014; Oh & Sinha, 2008). Highway cost allocation studies assess user equity of a highway system as a precursor to adjusting user fee structures to ensure equitable distribution of costs incurred and revenues contributed by each user (FHWA, 1997; Litman, 2002; Sinha et al., 1984; Volovski et al., 2015).

The current method of reporting user equity does not offer a simple way to assess system performance based on the equity ratio. The current method presents equity ratios for each individual user group, but not overall figure for the system. This makes it challenging to compare system wide performance between two systems or the same system across different times. For example, after adjusting the user fee structure, analyses may show changes in equity ratios across the user groups. Group one's equity ratio may change from 1.3 to 1.1, and group three's may change from 0.6 to 0.8. However, it is difficult to quantify the improvement in the system equity following this change.

This thesis proposes a method to assess and report system equity. The method is illustrated using data on equity ratios for the 13 FHWA vehicle classes from Volovski et al (2015) (because data used in the analyses in this thesis is augmented to three vehicle classes). The data is presented in Figure 5.2. For a system with perfect equity, each user group has an equity ratio equal to 1.00. When plotted on a graph, these would fall on a line (shown as the Unity Equity line in Figure 5.2). A value of the equity other than 1.00 for a user group signifies inequity in the system (overpayment or underpayment of the cost responsibility). When plotted on a graph, the inequity in the system can be represented as an area between the equity ratio line and the unity equity line (shaded area in Figure 5.2). By computing this area, one can estimate the level of inequity in the system. A large area means a high deviation from the unity equity line and therefore high system inequity. A lower area means low system inequity. Ideally, this area is zero for a perfectly equitable system as the equity ratio line will coincide with the unity equity line, resulting in zero area.

By quoting the value of the shaded area in Figure 5.2, one can compare user equity across multiple systems or across different times. Improvements in equity ratios across the system can be presented as percentage changes in this area.

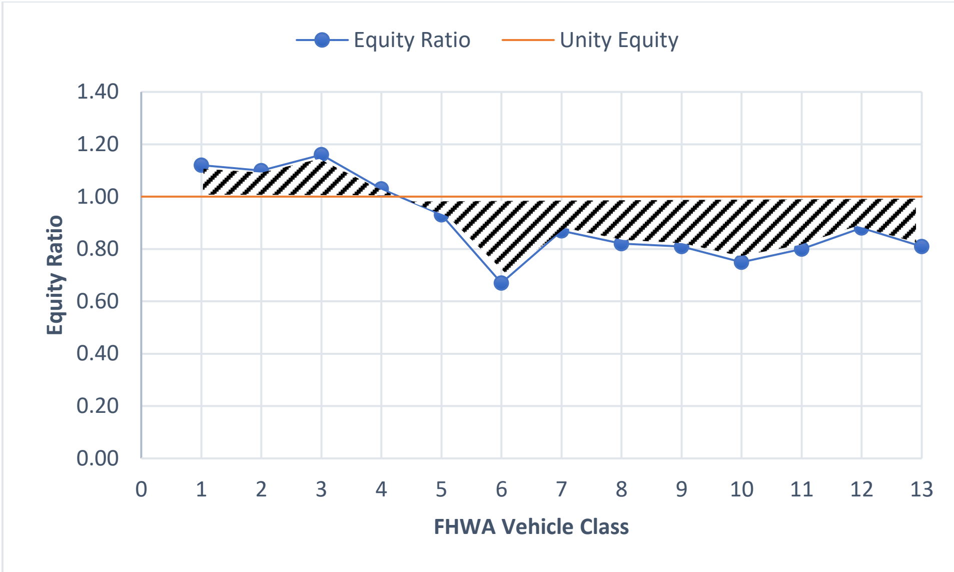


Figure 5.2: Equity Ratios for 13 FHWA vehicle classes (based on equity rations from Volovski et al., 2015)

5.4.2 Reimagining the Equity Ratio

The concept of user equity analysis is an important aspect of any highway cost allocation study and is explored in greater detail in Section 2.5 of this thesis. In summary, user equity analysis compares the revenues contributed to the costs incurred by each user. In highway cost allocation studies, this is quantified using the concept of the equity ratio. The equity ratio signifies the percentage of revenue a system user contributes compared with their share of cost responsibility (see section 2.5) (FHWA, 1997; Sinha et al., 1984; Volovski et al., 2015). This concept is widely used across the highway transportation landscape to indicate the level of equity in the system. However, it has one major limitation. In its current form, the equity ratio does not give any indication of system efficiency. It compares only proportions, and therefore, any information about scale of magnitude is completely lost. This makes it harder to examine system efficiency without reference to additional measures and information.

This thesis proposes a reimagined interpretation of the equity ratio, which will indicate both system efficiency and equity, from here on referred to as the *Modified Equity Ratio* (MER). Rather than accounting only for the proportions of revenues and costs that each user contributes and incurs, respectively, the new modified equity ratio considers the actual contribution and cost incurred. For example, assuming the total system cost is $1 million, and the system revenue is $0.1

million, suppose a user incurs \$200,000 in costs but contributes \$20,000 in revenues. Under the traditional equity ratio, this user's equity ratio can be calculated as follows:

$$ER_{user} = \frac{RCP_{user}}{CRP_{user}} = \frac{\frac{\$20{,}000}{\$100{,}000}}{\frac{\$200{,}000}{\$1{,}000{,}000}} = \frac{20\%}{20\%} = 1.00 \tag{5.9}$$

From Equation (5.9), the user equity ratio is calculated to be 1.00. This signifies a perfectly equitable system from the perspective of this user. As can be inferred however, this system is inefficient and runs a significant deficit. But this information is not conveyed simply by looking at the equity ratio. The modified equity ratio is defined according to equation (5.10):

$$MER_i = \frac{RC_i}{CR_i} \tag{5.10}$$

Where MER_i = Modified Equity Ratio for highway user class i

RC_i = Revenue Contribution in dollars from highway user class i

CR_i = Cost Responsibility in dollars incurred by highway user class i

Using Equation (5.10), the modified equity ratio for this user class can be calculated as follows:

$$MER_{user} = \frac{RC_{user}}{CR_{user}} = \frac{\$20{,}000}{\$200{,}000} = 0.10 \tag{5.11}$$

The modified equity ratio calculated in Equation (5.11) indicates that the highway user is underpaying their share of the cost responsibility. The result also shows the magnitude of the deficit. This information was not conveyed by the traditional equity ratio. Consider a second example where the total system cost is \$20 million, and the total revenues generated for the year is \$100 million. Suppose a user in this system occasioned \$10 million in costs but generated \$20 million in revenue for the system. Using the traditional equity ratio, the user's equity can be calculated as

$$ER_{user} = \frac{RCP_{user}}{CRP_{user}} = \frac{\frac{\$20m}{\$100m}}{\frac{\$10m}{\$20m}} = \frac{20\%}{50\%} = 0.40 \tag{5.12}$$

And using the modified equity ratio, the user's equity can be calculated as

$$MER_{user} = \frac{RC_{user}}{CR_{user}} = \frac{\$20m}{\$10m} = 2.00 \tag{5.13}$$

The traditional equity ratio shows a value significantly less than unity (0.40), indicating that the user is underpaying their share of the cost responsibility. However, looking at the revenues contributed by this user, one can infer that this is not the case. In fact, the user is contributing twice as much in revenues as their share of the cost responsibility. This is communicated by the modified equity ratio which calculates a user equity ratio of 2.00.

Unlike the traditional equity ratio, the modified equity ratio will show the operational efficiency of the system as well as the equity within the system. A MER of 1.00 indicates a system that is efficient and equitable and is ideal. MER less than unity indicate a system operating at a deficit and shows underpayment for the given user class. Similarly, MER greater than unity indicates an efficient, yet inequitable system. The system is operating at a surplus but the user in question is overpaying their share of responsibility. The MER can be quoted for an individual user group or for the system overall, and has the same interpretation in either case, only in each case applied to an individual user group or the system as whole. As a comparative illustration, consider the results reported in Section 4.3.1 for the low market penetration of connected vehicles and those reported in Section 4.3.3a) for the low market penetration of non-automated electric vehicles. The results are summarized in Table 5.6 below:

Table 5.6: Comparison of Equity Ratio and Operational Ratio for high, way revenues and expenditures for connected vehicles and non-automated electric vehicles at low market penetration

Vehicle Class	**Expenditures**	**Revenues**	**Equity Ratio**	**Modified Equity Ratio**
		Non-Automated EV at low market penetration		
Passenger Cars	$948,234,525	$1,512,674,865	1.83	1.60
Light Duty Trucks	$1,666,118,969	$1,156,113,644	0.88	0.69
Heavy Duty Trucks	$1,373,581,909	$598,043,867	0.58	0.44
System Total	$3,987,935,404	$3,266,832,376	1.00	0.82
		Connected Vehicles at low market penetration		
Passenger Cars	$966,370,398	$1,693,497,136	1.82	1.75
Light Duty Trucks	$1,697,296,931	$1,444,417,602	0.89	0.85
Heavy Duty Trucks	$1,401,319,830	$773,521,652	0.57	0.55
System Total	$4,064,987,159	$3,911,436,390	1.00	0.96

Based on the traditional Equity Ratio, one can infer that passenger vehicles are overpaying their share of the responsibility while light and heavy-duty trucks are underpaying in both scenarios. However, it is difficult to tell how big the deficit is and therefore the extent to which each vehicle class is under or overpaying. When considered as a system, the traditional equity ratio is always 1.00 for the system because 100% of the revenues are paid by the users, as are the costs incurred. System wide, the proportion of costs incurred is exactly equal to proportion of revenues generated. Using the modified equity ratio however, it is easy to see that in the case of non-automated EVs, passenger cars are paying 160% of their share of the responsibility, while light and heavy-duty trucks are only paying 70% and 44% of their shares, respectively. Furthermore, we can infer that the system is operating with a 20% deficit. Additionally, looking across the two scenarios, the traditional equity ratios are similar, which may lead one to conclude that the two systems are operating under similar conditions. However, the connected vehicles scenario is operating almost at parity, with only a 4% deficit while the non-automated EV scenario is operating with a 20% deficit. This information is apparent from the modified equity ratio but cannot be inferred from the traditional equity ratio alone. This therefore demonstrates the superiority of the modified equity ratio as a metric for assessing system equity and efficiency.

5.5 Vehicle Classification for Highway Expenditure and Revenue Reporting

As has been shown in this thesis, wide adoption of ECAVs will result in increased VMT across the board. For lower vehicle classes and passenger cars, the effect on infrastructure will be equivalent to repeated loading cycles, increasing the number of times the infrastructure is loaded. For heavier vehicles, the effects are exacerbated by the additional weight imposed on the pavements and bridges. Not only is the frequency of the load increasing, but that load may often be close to the legal limits. Repeated loading can exacerbate the deterioration of infrastructure and lead to failure (Antaki & Gilada, 2015; Behravesh et al., 2016; Lin & Yoda, 2017). This will lead to a significantly reduced service life for both pavements and bridges. In turn, this will lead to increased expenditures on maintenance and rehabilitation, in addition to new constructions.

While any increase in VMT will likely have the same effect on infrastructure, ECAVs are uniquely situated to exacerbate these impacts. For human driven vehicles, minute deviations from the lane center resulting from small movements of the hands while driving ensure that each set of wheels is covering a slightly different part of the pavement for each car as it drives along. Automated vehicles, on the other hand, are designed for fast reaction times, making billions of computations a second and adjusting the steering inputs accordingly. As a result, they are likely to maintain a straighter driving trajectory relative to human drivers. While this may be better for passenger comfort, it will have worse effects on the infrastructure. Because each vehicle can maintain a fixed distance from the edge of the lane, the result may be many vehicles driving over the same strip of pavement, concentrating their load on the same section of pavement as they drive along. The strips of pavement that are in contact with the tires will therefore be susceptible to rutting, fatigue cracking, aggregate polishing, etc. An argument can be made for programming AVs to deliberately deviate slightly from a given edge by a certain distance to prevent the aforementioned effects. However, this will directly contradict the anticipated benefit of AVs increasing road capacity due to their ability to keep tight tolerances and therefore requiring narrower lanes than human-driven vehicles. In the face of this contradiction, it is more likely that the former phenomena will prevail, and AVs will be programed to hold the straight line when possible, leading to the damaging effects described earlier.

Given their anticipated disproportionate cost responsibility, and their inability to generate additional revenue relative to conventional vehicles, it is difficult to justify the classification of ECAVs in the same classes as conventional vehicles. Furthermore, many of these vehicles may likely be electric, meaning their revenue contributions will be less than that of their conventional counterparts. This imbalance in disproportionate cost responsibility and lower revenue contribution warrants ECAVs being classified in different classes than conventional vehicles. For the purposes of highway expenditures and revenues assessment and reporting, ECAVs may be classified as a subcategory within each class. For example, using the FHWA vehicle classification as a basis, vehicles equipped with emerging vehicle technologies can be denoted with a letter following the class number to signify the type of technology present. For example, an automated passenger car can be denoted as class 2-A (the A signifying automation) and an electric bus can be denoted as class 4-E. Adopting such a classification would simplify highway expenditure and revenues reporting in the era of emerging vehicle technologies. Furthermore, such as scheme would make easier to assess, levy, and adjust appropriate fees for specific technologies according to their assessed impacts.

5.6 Broader Impacts of Vehicle Automation, Connectivity and Electric Propulsion

This thesis has explored the impacts and consequences of emerging vehicle technologies (automation, electrification, and connectivity) on highway expenditures, revenues, and equity. However, the impacts of the adoption of these technologies extends beyond highway financing. The impacts, some positive and others adverse, will ripple through many structures in society, from mobility and travel patterns to safety and land use patterns. Several researchers have examined the impacts of emerging vehicle technologies on the broader society in various contexts including infrastructure needs (Engel et al., 2018; Saeed et al., 2021; Sinha et al., 2017), car ownership and ride sharing (Fagnant & Kockelman, 2018; Plumer, 2013), highway and pedestrian safety (Marshall, 2018; Sivinski, 2011), and the built environment (Labi et al., 2015). Labi et al (2015) schematically illustrated the potential impacts of vehicle automation on the environment. The schematic has been adapted and reproduced below to include other technologies such as electrification and connectivity.

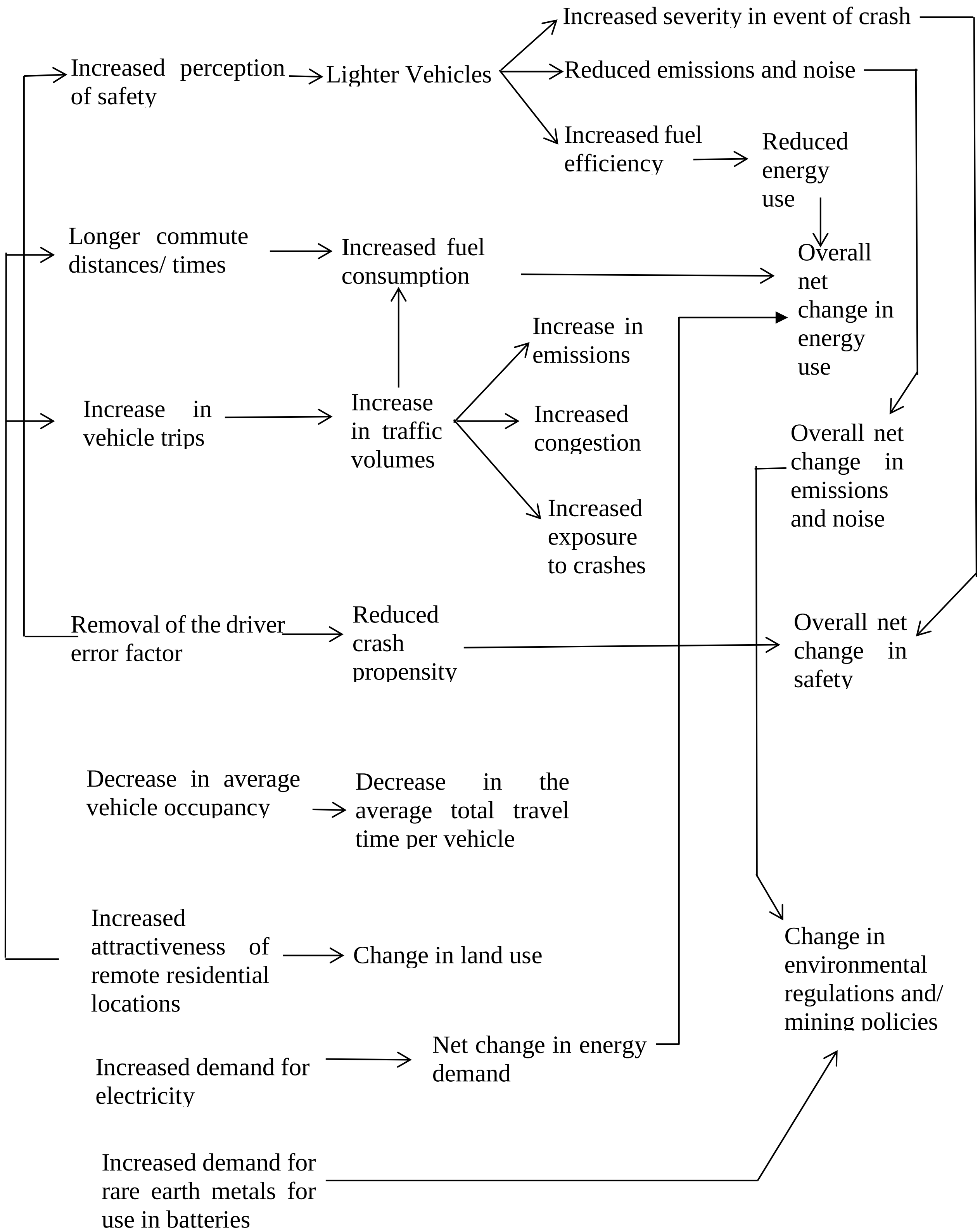


Figure 5.3: Broader impacts of vehicle automation, connectivity, and electrification [adapted from (Labi et al., 2015)]

Because most road traffic accidents can be attributed to human error (NHTSA, 2008), eliminating the driver error component through automation is expected to yield increased safety benefits. If this benefit is realized, vehicle manufacturers may no longer feel the need to design vehicles with robust crash withstanding features since crashes will be few and far between. Furthermore, having lighter vehicles can lead to better fuel efficiency and reduced emissions. While these are positive attributes for both the environment and consumers, it may lead to more severe injuries in the event of a crash. Automating the driving function also impacts the number of trips individuals may make. This is in part because individuals that cannot currently drive (children, the elderly and disabled individuals) will be able to take trips in AVs. Furthermore, automation may encourage individuals to live farther away from city centers if they can use their commute times to engage in productive activities while the AV drives them to their destination. This may in turn spur a change in land use patterns, and consequently increase the total travel volumes, and along with-it emissions and fuel consumption. Increased travel volumes may also result in increased congestion, emissions, and noise.

Wide adoption of electric vehicles is expected to increase the electricity demand. Barring an increase in the amount of electricity generated from renewable sources, this could lead to increased emissions from coal or natural gas used to generate the electricity. Furthermore, batteries used in electric vehicles require intensive mining of rare earth metals. Therefore, wide adoption of electric vehicles could result in increased mining operations, further degrading the environment. However, this could be reduced or counteracted by developing batteries that use less or none of the materials that require intensive mining practices. Furthermore, electric vehicles run quieter than internal combustion engines and have been shown to have lower life cycle costs. Therefore, wide adoption of electric vehicles may result in reduced noise pollution and lower vehicle operating costs.

Overall, adoption of emerging vehicle technologies is expected to have broader impacts that will ripple through various systems of the built environment. This thesis explored these impacts as it pertains to highway financing. However, the discussion on the broader impacts is more nuanced and requires further research to ascertain (or quantify). Each of the technologies (and their combinations thereof) can have specific impacts that may affect other systems, rippling through the built environment.

5.7 **Chapter Summary**

This chapter discussed in detail the implications and potential solutions to the impact of emerging vehicle technologies presented in Chapter 4 of this thesis. The chapter presented a proposed revision to the user fee structure that would address the funding shortfalls and inequity arising from adoption of emerging vehicle technologies. The proposed user fee structure introduces a variable tax scheme where each vehicle class pays a different tax rate according to their size and weight requirements. Further, a distance-based tax is proposed, applicable to electric vehicles. The combination of the variable tax scheme and distance-based tax addresses that current shortfall in revenues and the system inequity, and for the long term addresses the decline in fuel tax resulting from vehicle electrification. This chapter further illustrated the application of the variable tax scheme to different scenarios of emerging vehicle technologies at various levels of market penetration.

Chapter 5 of this thesis also discussed highway user equity. The chapter discussed an approach for assessing system inequity using graphical representation of user equity ratios. In this approach, user equity ratios are plotted as a line-graph (the equity line) and a separate line is drawn to represent the ideal equity ratio at 1.00. Then the area between the two line-graphs is used a measure of system inequity. The larger the area, the higher the inequity in the system (Figure 5.2). Further, this chapter also presented a reinterpretation of the equity ratio, the modified equity ratio. The modified equity ratio is computed by comparing the actual dollar amounts of revenues contributed and costs incurred (as opposed to proportions). This modification allows the equity ratio to convey not only information about the equity of the system but also its efficiency.

Finally, this chapter proposed a revised vehicle class taxonomy for the purpose of highway cost allocation, revenue attribution, and user equity analysis. This revision was warranted given the anticipated disproportionate cost responsibility and inability to generate additional revenue of ECAVs relative to conventional vehicles. Under the proposed taxonomy, ECAVs may be classified as a subcategory within each class. For example, using the FHWA vehicle classification as a basis, vehicles equipped with emerging vehicle technologies can be denoted with a letter following the class number to signify the type of technology present. For example, an automated passenger car can be denoted as class 2-A (the A signifying automation) and an electric bus can be denoted as class 4-E. Adopting such a classification would simplify highway expenditure and revenues reporting in the era of emerging vehicle technologies. Furthermore, such as scheme would make easier to assess, levy, and adjust appropriate fees for specific technologies according to their assessed impacts.

6. CONCLUDING REMARKS

6.1 Synopsis of the Research

This thesis addressed the impacts and consequences of emerging vehicle technologies on three key concepts in highway cost allocation: highway expenditures, revenues, and user equity. The study began with an extensive review of literature on highway cost allocation, the problems facing highway financing, and previous attempts to address them. Thereby, the thesis highlighted the gaps in the literature, particularly, the consideration of emerging vehicle technologies in highway cost allocation. The study highlights the need for infrastructure investments that are expected to accommodate the emerging vehicle technologies. With increasing EV and CAV operations, the revenues typically earned from vehicle registrations and fuel tax are expected to change due to changing demand for vehicle ownership and amount of travel, respectively.

The study proposed new models for estimating the cost of highway infrastructure construction and upkeep given estimated system usage. Using these models and highway statistics data, this research estimated (i) the expected changes in highway expenditures arising from wide adoption of ECAVs, (ii) the net change in highway revenues that can be expected to arise from ECAV operations, and (iii) the changes in user equity across the highway user groups (vehicle classes). The research identified the various dimensions of the impact of ECAVs on highway infrastructure expenditures and revenues as the new technologies are implemented over time and as the EV and CAV market penetration rates grow. Finally, this thesis recommended revisions to the current user fee structure that would improve system efficiency and reduce inequity for the near term and the long term.

6.2 Summary of the Problem Statement and Major Findings

The prospective emergence and adoption of vehicle connectivity, automation, and electric propulsion is likely to exacerbate the current and eminent crisis facing highway financing. To accommodate these emerging technologies, significant capital investments in new infrastructure, as well as modification of existing infrastructure are expected. Secondly, with increasing EV and CAV operations, the revenues typically earned from vehicle registrations and fuel tax are expected to change due to changing demand for vehicle ownership and amount of travel, respectively.

Furthermore, the literature review showed that previous attempts to address the problems with highway financing did not account for the impacts of emerging vehicle technologies. Therefore, it is necessary that a study is carried out to investigate the changes in the cost responsibility and revenue contribution of highway users regarding the upkeep of the highway infrastructure. The costs considered in this study consisted of expenditures on construction, preservation, maintenance, and operation of the infrastructure at both state and local levels. The asset types included pavements, bridges, and safety and mobility assets. Regarding revenues, the user and non-user sources at federal and state levels were included. The user sources included fuel tax, motor carrier surcharge tax, motor carrier fuel use tax, vehicle registration fees, driver license fees, taxes on truck and trailer sales, tires, and heavy vehicle use, and wheel taxes. Throughout, the impacts of electrification, connectivity and automation on highway expenditures and revenues were analyzed and documented.

The results of the research reveal that CAVs are expected to significantly change the travel patterns, leading to increased system usage which in turn results in increased wear and tear on highway infrastructure. This, with the need for new infrastructure to support and accommodate the new technologies is expected to result in increased highway expenditure. At the same time, CAVs are expected to have significantly improved fuel economy as compared to their human-driven counterparts, leading to a decrease in fuel consumption per vehicle, resulting in reduced fuel revenues. Furthermore, the prominence of EVs is expected to exacerbate this problem. This thesis analyzed the impacts of emerging vehicle technologies at varying levels of technological maturity and market penetration. In total, this thesis considered 18 scenarios of technological supply and market penetration. The technological supply was categorized at 5 levels resulting from various combinations of automation, electrification, and connectivity. The demand was categorized at 3 levels of market penetration namely low, moderate, and high. At each level of market penetration for each technological supply, the results showed increased expenditures in the emerging vehicle setting compared with the base case. The differences ranged from a few percentage points, translating to a few hundred million dollars to as high 20%. A similar trend was seen for the revenues, and consequently the user equity.

6.3 Contributions of this Research

To address the aforementioned shortfalls in highway revenues stemming from the adoption of new vehicle technologies, this thesis proposed a revision to the current user fee structure. This revision contains two major parts designed to address the system efficiency and equity in the near and long term. For the near term, this thesis recommended a variable tax scheme under which each vehicle class pays a different fuel tax rate. This ensures that both equity and system efficiency are improved during the transition to ECAV. In the long term, this thesis recommended supplementing the fuel tax with a distance based VMT tax, applicable to electric vehicles. Furthermore, this thesis also proposed a variation to the computation and interpretation of the equity ratio. The modified equity ratio accounts not only for the proportion of revenues paid and proportion of costs incurred, but also the relative magnitude of the surplus (or shortfall) experienced. Therefore, with this metric, one can infer both the equity and efficiency of a highway financing system.

Further, this thesis proposed a method of comparing the performance of highway user groups that allows to comparison across different systems or timelines. The proposed method assesses the costs incurred and the revenues contributed by each highway user group per mile of travel on the highway system. Finally, based on the result of the analysis of the impacts of ECAVs on highway expenditures and revenues, this thesis recommended an updated vehicle classification for the purposes of highway cost allocation and revenue attribution. Based on their disproportionate cost responsibility, and their lower ability to generate revenue when compared with conventional vehicles, this research recommended that ECAVs be classified as a subcategory within each class for the purpose of highway expenditures and revenues. Using the FHWA vehicle classification as a basis, each vehicle equipped with the emerging vehicle technologies can be considered a subcategory within each class, with letters denoting the technology present.

6.4 Study Limitations and Direction for Future Research

This research focused on the impacts of emerging vehicle technologies on highway expenditures, revenues, and user equity. The thesis conducted, and proposed solution approaches to address these impacts. It was recognized, however, that while these proposals may be optimal from a highway financing perspective, they may compete, and indeed be in direct conflict with other sectors of the economy. This is because economies of states are complex and have multiple interdependent elements. Commerce plays an important role in each state's economic output. A significant portion of the commerce is the trucking industry (Ahmed et al., 2012; Bilal et al., 2010). The approaches proposed in this thesis places a heavy burden on trucks to contribute equitably for the costs they incur on the state's transportation infrastructure. However, this is in direct conflict with the interest of the trucking industry who have every incentive to keep their costs low (Volovski et al., 2015). Enforcing these proposals therefore may have ramifications for the state's economy. Future research must therefore explore the impacts of implementing these proposals on the state's economic output, examining any resulting changes in commercial trucking, the weights of trucks on the roads, and their axle configurations. Furthermore, future studies may need to compare each state's infrastructure performance relative to the investments (Everett et al., 2014; Everett et al., 2013). This is to identify states that are efficient with their resources and identify what can be learned from them. Similarly, those that are inefficient may evaluate their processes and adopt better management strategies and infrastructure stewardship.

Finally, this thesis introduced infrastructure cost functions for estimating the cost of infrastructure based on estimated system usage. However, due to limited data availability, the models are coarse and can only estimate aggregate costs. More refined models are therefore needed to accurately estimate costs at a more granular level. With more data, models can be developed to estimate the costs by infrastructure type (bridge, pavement, etc.) (Ahmed et al., 2017; Volovski et al., 2017), investment type (new construction, maintenance, and rehabilitation, etc.) (Saeed et al., 2017; Woldemariam et al., 2016), and type of work (earthwork, design and engineering, construction, etc.) (Lavrenz et al., 2020), among others.

APPENDIX A. COST FUNCTION MODELLING

This appendix presents printouts of the python code used to model the cost functions used in the analyses presented in this thesis.

SVM Models

In [1]:
```
#import the relevant modules
import pandas as pd
import numpy as np
from sklearn.model_selection import train_test_split
import sklearn.metrics as metrics
from sklearn.svm import SVR
import matplotlib.pyplot as plt
from matplotlib.ticker import FuncFormatter
import csv
```

In [2]:
```
#read the datafile into a pandas table
file_path = ".\Highway Data1.xlsx"
data = pd.read_excel(file_path, header =[0,1], index_col = [0,1])
```

Attributable Costs

In [3]:
```
#prepare the model training data
training_labels = np.log(data['Capital Expenditures'])
training_data = np.log(data['Vehicle Ton-miles'])
```

Passenger cars

In [4]:
```
#extract data from table pertaining to passenger cars
X = np.array(training_data['Passenger Cars']).reshape(-1,1)
Y = np.array(training_labels['Passenger Cars'])
```

In [5]:
```
#split data into training and validation sets
X_train, X_test, y_train, y_test = train_test_split(X, Y, test_size = 0.2)
```

In [7]:
```
#fit the and validate the SVR model
passenger_cars_attr = SVR(kernel = 'rbf').fit(X_train, y_train)
modelscore = passenger_cars_attr.score(X_test, y_test)
print("The model R squared = %.2f"%modelscore)
```

```
The model R squared = 0.81
```

Light Trucks

In [8]:
```
#extract data from table pertaining to light trucks
X = np.array(training_data['Light Trucks']).reshape(-1,1)
Y = np.array(training_labels['Light Trucks'])
```

Light Trucks

In [8]:
```
#extract data from table pertaining to light trucks
X = np.array(training_data['Light Trucks']).reshape(-1,1)
Y = np.array(training_labels['Light Trucks'])
```

In [9]:
```
#split data into training and validation sets
X_train, X_test, y_train, y_test = train_test_split(X, Y, test_size = 0.2)
```

In [10]:
```
#fit the and validate the SVR model
light_trucks_attr = SVR(kernel = 'rbf').fit(X_train, y_train)
modelscore = light_trucks_attr.score(X_test, y_test)
print("The model R sqared = %.2f"%modelscore)
```

```
The model R sqared = 0.78
```

Heavy Trucks

In [11]:
```
#extract data from table pertaining to heavy trucks
X = np.array(training_data['Heavy Trucks']).reshape(-1,1)
Y = np.array(training_labels['Heavy Trucks'])
```

In [13]:
```
#split data into training and validation sets
X_train, X_test, y_train, y_test = train_test_split(X, Y, test_size = 0.2)
```

In [14]:
```
#fit the and validate the SVR model
heavy_trucks_attr = SVR(kernel = 'rbf').fit(X_train, y_train)
modelscore = heavy_trucks_attr.score(X_test, y_test)
print("The model R squred = %.2f"%modelscore)
```

```
The model R squred = 0.86
```

Common Costs

In [15]:
```
#prepare the model training data
training_labels = np.log(data['Common Costs'])
training_data = np.log(data['VMT'])
```

Passenger Cars

In [16]:
```
#extract data from table pertaining to passenger cars and split into training and testing sets
X = np.array(training_data['Passenger Cars']).reshape(-1,1)
Y = np.array(training_labels['Passenger Cars'])
X_train, X_test, y_train, y_test = train_test_split(X, Y, test_size = 0.2)
```

In [17]:
```
#fit and validate the SVR model
passenger_cars_common = SVR(kernel = 'rbf').fit(X_train, y_train)
modelscore = passenger_cars_common.score(X_test, y_test)
print("The model R squared = %.3f"%modelscore)
```

```
The model R squared = 0.758
```

Light Trucks

In [19]:
```
#extract data from table pertaining to light trucks and split into training and testing sets
X = np.array(training_data['Light Trucks']).reshape(-1,1)
Y = np.array(training_labels['Light Trucks'])
X_train, X_test, y_train, y_test = train_test_split(X, Y, test_size = 0.2)
```

In [20]:
```
# fit and validate the SVR model
light_trucks_common = SVR(kernel = 'rbf').fit(X_train, y_train)
modelscore = light_trucks_common.score(X_test, y_test)
print("The model R squared = %.3f"%modelscore)
```

```
The model R squared = 0.617
```

Heavy Trucks

In [21]:
```
#extract data from table pertaining to heavy trucks and split into training and testing sets
X = np.array(training_data['Heavy Trucks']).reshape(-1,1)
Y = np.array(training_labels['Heavy Trucks'])
X_train, X_test, y_train, y_test = train_test_split(X, Y, test_size = 0.2)
```

In [22]:
```
#fit and validate the SVR model
heavy_trucks_common = SVR(kernel = 'rbf').fit(X_train, y_train)
modelscore = heavy_trucks_common.score(X_test, y_test)
print("The model R squared = %.3f"%modelscore)
```

```
The model R squared = 0.775
```

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