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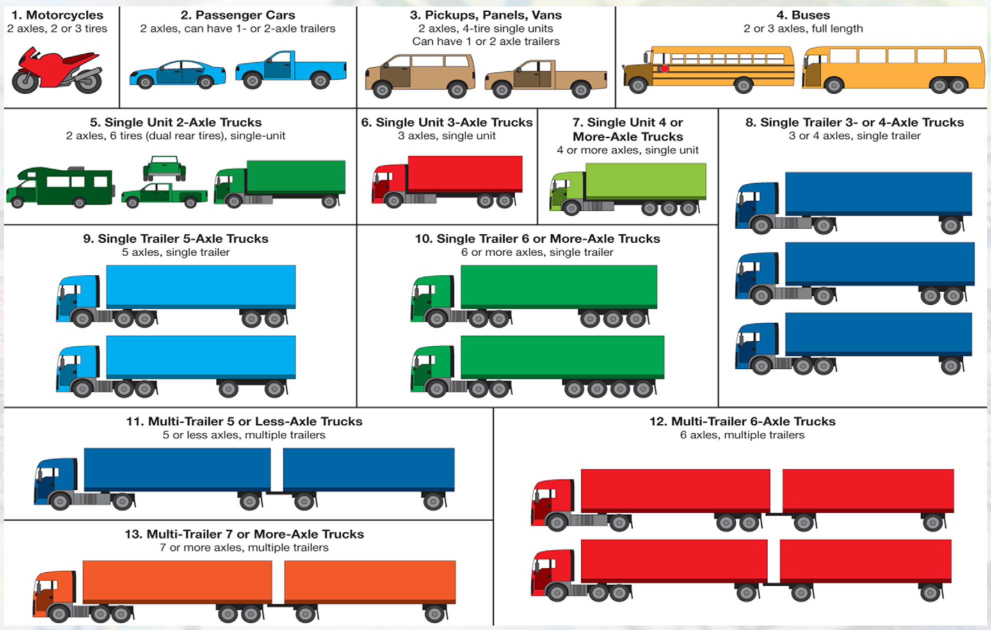

Changes in Highway Expenditures and Revenues in an Era of CAVs, Volume A: Road Agencies

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16. Abstract
The emerging transportation technologies – vehicle connectivity, electrification, and automation – are expected to impact highway expenditures, revenue, and user equity. With regard to the expenditures, the provision of new infrastructure and modification of existing infrastructure will incur significant capital spending. With regard to revenue, the changing patterns of travel that will accompany the new technologies and the increase in electric, connected and autonomous vehicle (ECAV) operations will impact key sources of highway revenue – vehicle registration and fuel tax revenues. These revenue and expenditure changes will expectedly happen disproportionately across the highway user groups (vehicle classes), and therefore will have different impacts on the highway agency's user-imposed expenditures and user-derived revenues, and thus, the revenue-expenditure equity across the user groups. The objective of the present study is develop a framework to elucidate how ECAV operations are expected to impact highway expenditures, highway revenues, and user equity across highway user groups. In assessing the highway expenditure changes, the study developed a model to predict highway infrastructure repair cost based on system usage. Data from national level and state level (Indiana) are used in a case study to demonstrate the framework. The results suggest that ECAVs will significantly alter the levels of highway system usage, travel volumes, and ultimately, deterioration rates of the infrastructure. Higher deterioration, coupled with new infrastructure needs to support the emerging technologies, will lead to increased highway expenditure. From the revenue perspective, the results suggest that ECAVs will cause a drastic reduction in fuel tax revenues from the overall vehicle fleet in the state, increased highway expenditures overall, and significant changes to user equity. To address the anticipated agency revenue shortfalls in the ECAV era, this study proposes revisions to the current fee structure to address revenue and equity concerns in that era. The goal is to address the highway system efficiency and equity in both near term and long term. In the near term, this study developed a novel variable tax scheme under which each vehicle class pays a different fuel tax rate. It is shown that this can promote user equity and system efficiency in the ECAV era. Regarding long-term financial palliatives, the study discussed mileage-based fee structures to supplement the highway revenue in the era of ECAVs.

17. Key Words
Highway user equity, Highway expenditures, Highway revenues, Autonomous vehicles, Electric vehicles, Connected vehicles.

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LIST OF ACRONYMS

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 Equivalent
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

CHAPTER 1. INTRODUCTION

1.1. Study Background

1.1.1 The Technologies

A fully autonomous vehicle (AV) characterizes and navigates the roadway environment (neighboring vehicles, the guideway, lane markings, traffic signals and signs, and obstacles) using sensors (radar, lidar, camera, and sonar). It also has artificial intelligence (AI) algorithms that not only fuse information from these sensors for path planning, but also and controls the steer and pedals, with little or no input from the human occupant. Typically, the AV is also equipped with connectivity capabilities and therefore combine the sensed information with information gained through connectivity from other entities including vehicles in its vicinity. Vehicle autonomy is classified in levels from 0 to 5 (SAE, 2021). Levels 1–5 are automated (Level 3 is partially autonomous, and Levels 4 and 5 are fully autonomous). The level of automation translates directly into infrastructure needs and consequently, expenditures for infrastructure retrofit, renewal, and new types of infrastructure.

Connectivity can be defined as the capability to receive or transit information between the ego vehicle and others (vehicles, infrastructure, pedestrians, and so on) to facilitate efficient and safe operations. This facilitates the ego vehicle's awareness of happenings within a specified locus (typically, about a thousand feet); communication with neighboring vehicles and other entities; cognizance of the intentions of neighboring vehicles so that the ego vehicle can maneuver in ways to avoid a collision. Enabling technologies for connectivity include DSRC, global positioning systems, cellular, Near Field Communication, radio, Wi-Fi, and Bluetooth. From a wider systems perspective, there are continual advancements in connectivity technology and there is ongoing national debate regarding protocols for communications and the optimal setups for specific applications in the practice. Cyberinfrastructure investments are needed to enhance roadway vehicle connectivity.

Unlike gasoline vehicles that use internal combustion, electric vehicles (EVs) use an electric motor for propulsion. Electric propulsion was prominent a century ago but has waned over the past few decades due to limitations in the driving range, inadequacy of charging points or lines, and increased attractiveness of competing sources of energy. The new millennium has seen a resurgence of EVs, due to growing need to reduce reliance on foreign energy sources, the role of electrification in addressing climate change, and technological advancements in electric charging. The power sources of the electric motor include: electricity from an extra-vehicular source (in-pavement, guideway, and overhead chargers or pantographs) and the battery (which requires periodic swapping or recharging). EV charging stations receive AC power from the electric grid. However, their batteries are charged using DC power. As such, the EV charging station is fitted with AC-to-DC converter or the EV is made to possess an onboard AC-to-DC converter. As such, the electric propulsion of vehicles can require significant investments in charging related infrastructure.

1.1.2 Synergies among these Emerging Technologies

Researchers have argued that AV-CV-EV synergies will exist through their concurrent deployment (not necessarily the same, but rather, overlap in their deployment initiation times) (Labi and Sinha, 2022), making it unlikely that these technologies will be deployed independently of each other. For example, Anderson et al. (2014) and Ha et al. (2020b) identified the sibling relationship between vehicle connectivity and autonomy. Hobert et al. (2015) and Stern et al. (2018) stated that vehicle connectivity can promote the advancement of AVs. They assert that due to the limited range of traditional sensors, V2V and V2I connectivity can provide the AV with a more reliable wider awareness of its driving environment which enables it to make more informed strategic decisions (e.g., planning routes) and operational decisions (e.g., changing lanes). With regard to EV and AV symbiosis, the electric propulsion of AVs is an obvious scenario because computers are powered by electricity and therefore, it seems more prudent for a computer-driven vehicle to be powered by the same energy type. Automation improves the business case of EVs (Offer, 2015). Also, electric powered AVs enhance the productivity of travel time and have contributed to the development of new business models in transportation mobility. Researchers including Adler et al. (2019) have stated that vehicle automation, electrification, shared ownership and connectivity, will collectively transform the transportation market and terrain. Freedman et al. (2018) were more specific, stating that electric AVs (particularly, those that are shared-use) will be most cost-effective where the trips are short, within city limits where vehicle occupancy is relatively high, and where vehicles are not likely to be stranded due to poor access to electric charging stations. It has been argued that the effect of the sum of the technologies is likely to be superior to the sum of their individual effects (the word "effect" here could mean a cost or a benefit). The strength of such synergy (and hence, its effects) will depend on the prevailing levels of advancement of the innovations in question, and their relative maturity thereof (Ha et al., 2020a). In other words, the benefits of these synergies may be manifest more clearly when the two technologies have reached higher levels of maturity.

Due to these synergies, it seems reasonable to study the impacts of these technologies not only individually, but also combined. As such, this study addresses not only the prospective impacts of AVs, CVs and EV on highway expenditures, revenue, and equity, but also the impacts of the various permutations of the three technologies. When all these three technologies are present in a vehicle, it is referred to as ECAV. ECAVs are likely to cause a change 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 are expected to 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 currently 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. These anticipated dynamics and feedback of the impacts of emerging vehicle technologies are summarized in Figure 1.1 below.

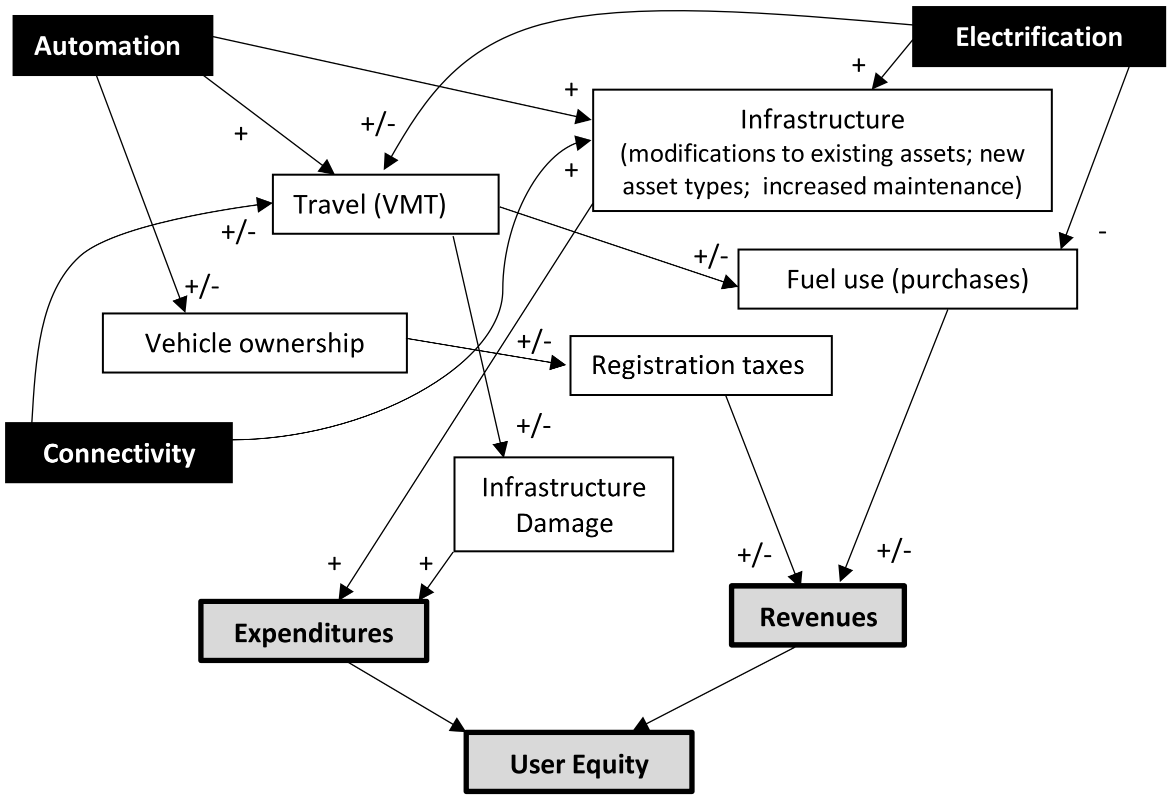

Figure 1.1 System dynamics overview and anticipated impact feedback

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 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 long as the tax rate is fixed per gallon while fuel efficiencies continue to improve, this trend is expected to continue (Kile, 2021; Kirk & Mallet, 2020). The gap is expected to grow even wider (Figure 1.2) as alternative fuels become more available and used for propulsion. Therefore, the introduction of electric CAVs will only exacerbate this trend.

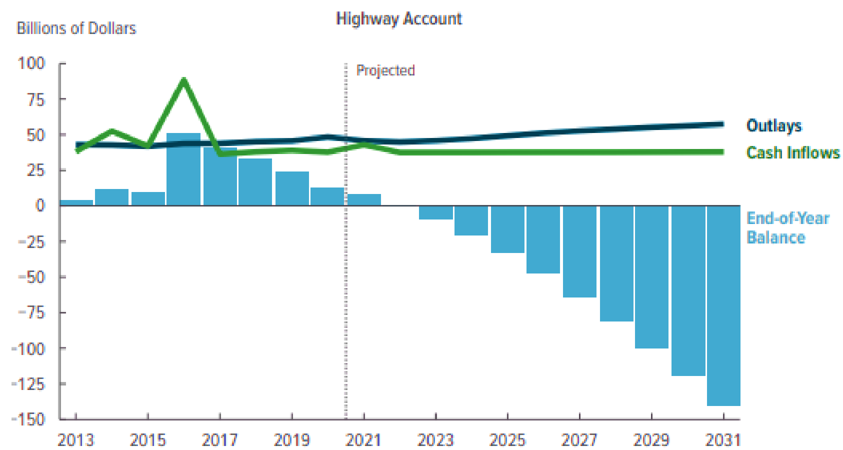

Figure 1.2 Annual revenues, outlays and balance of the Highway Trust Fund in CBO's 2021 baseline projections (Kile, 2021)

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. It is expected that each of these technologies will influence, to varying extents, the expenditures on highway infrastructure maintenance, replacement, and new assets. Also, these technologies will affect fuel consumption and hence, highway revenues from the fuel tax. As such, a study is 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 construction of new asset types. Highway revenues consist of user and non-user sources at federal, state, and local levels. 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. Non-user sources include federal grants and disbursements.

1.3.2. Objectives

The main objectives of this report are to estimate, in the prospective 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, certain portions of this report also consider three categories of highway users: passenger cars, light duty trucks and heavy-duty trucks.

1.3.3. Study Scope and Framework

The study analyzes the impacts of highway expenditures, revenues, and user equity in the era of three 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 (Volovski et al., 2015). For example, costs associated with highway safety elements, such as guardrails, signage, and right-of-way are load independent and thus must be evenly distributed to all highway users based on their VMT contributions. These are referred to as common costs because they apply to all vehicle classes and depend only on their respective VMTs. 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 (Sinha et al., 1984). Similarly, bridge widths, vertical and horizontal clearances need to be larger to accommodate larger vehicles. The costs associated with these considerations therefore exceed those of small passenger cars. These costs are attributed to each vehicle class based on their respective weights (and sizes) and are appropriately referred to as attributable costs. Therefore, to for allocate the attributable costs to the vehicle classes, Equivalent Single Axial Loads (ESALs), AASHTO load equivalency factors, and Passenger Car Equivalents (PCEs) are used, and to allocate common costs, VMT is used (Sinha et al., 1988; Agbelie et al., 2017).

The study developed highway cost models used to estimate highway expenditures using highway statistics data for all 50 states published by the FHWA. The study assessed highway expenditures and revenues for only the state of Indiana, for purposes of illustration. The data are adapted from Volovski et al., (2015), and 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 report. The analysis for expenditure and revenue assessments were repeated for each of the several levels of ECAV implementation. This is because 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. 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). Figure 1.3 provides the study scope and framework.

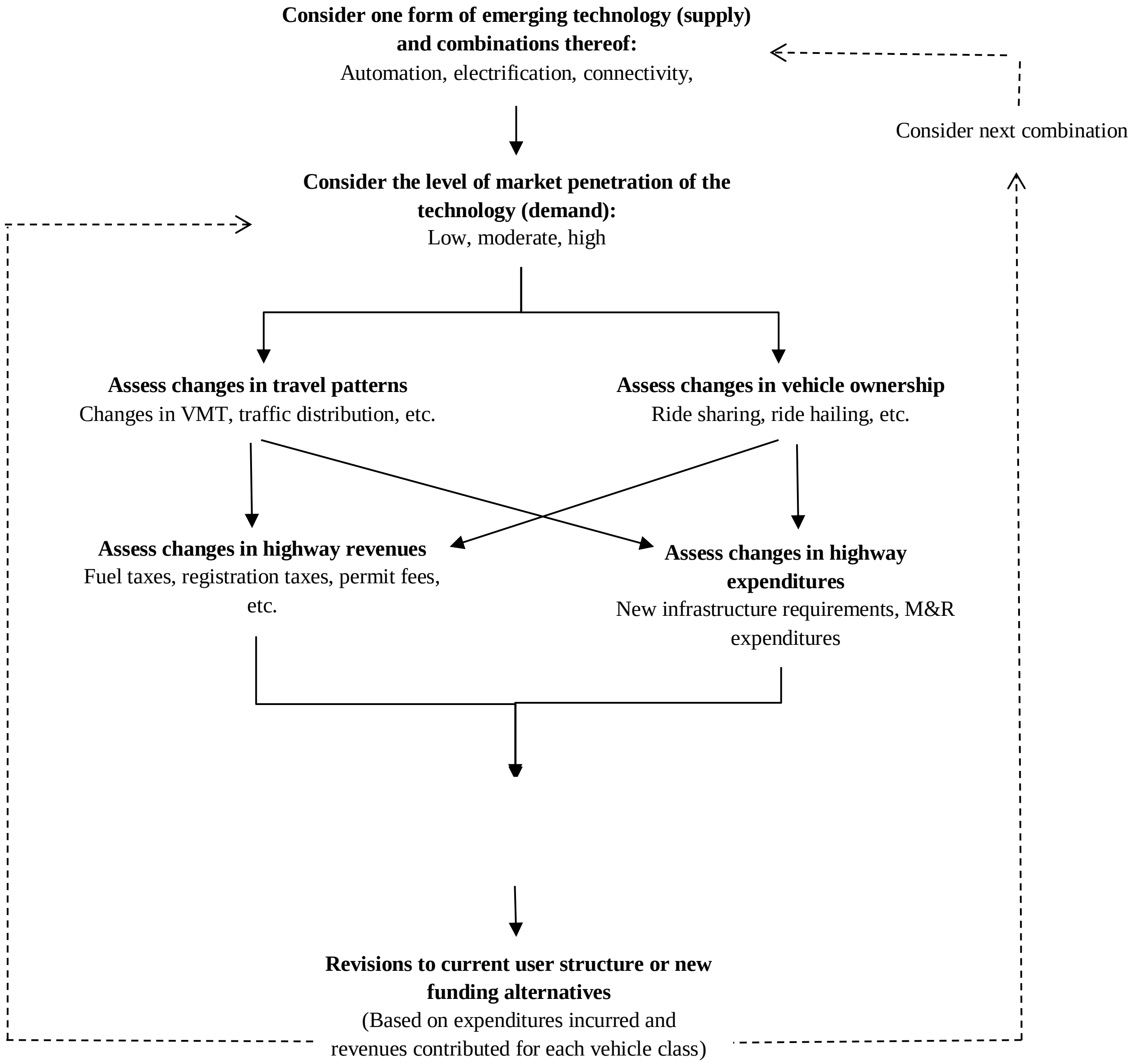

Figure 1.3: Study scope and framework

1.3.4. Assumptions

The analyses of highway revenues and expenditures in this study are based on a number of assumptions. These include projections of demand and supply of each of the vehicle technologies, the level of synergistic interactions among them, and the rate of growth of VMT and system usage. These assumptions are discussed in specific detail in each of the relevant sections and are summarized here.

1.3.4.(a) VMT and System Usage

It is assumed that ECAV adoption will impact VMT and travel patterns, and ultimately, the expected changes in highway expenditures and revenues. As these technologies increase in market penetration, they will likely result in changes in travel patterns that may result in increased travel overall. 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 report). This report assumes that as the VMT changes the overall composition of the traffic stream does not change significantly over the analysis period. In other words, the percentage of vehicles in each highway vehicle class in the stream remains fairly the same. The vehicle class percentages used in this study represent the average of traffic stream data from 1994 through 2019, based on FHWA highway statistics data (FHWA, 2020).

1.3.4.(b) Highway Expenditures and Revenues

Highway expenditure and revenue projections presented in this report are estimated using regression models (detailed in Section 3.2). These estimates are based on the 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. The reason is that most highway system expenditures are for construction works and major repairs. Thus, increased system usage causes more frequent repairs due to increased wear and tear, and results in the need for construction of new facilities. Furthermore, mainstream, and auxiliary expenditures related to highway systems such as congestion 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 made in the system usage analysis also applies to revenue estimation. Non-fuel revenues include vehicle registration fees, heavy vehicle permit fees, motor carries surcharge fees, etc. (see Sections 2.4 and 3.7 of this report). The analyses presented in this report assume that non-fuel revenues scale linearly with system usage. For example, it is assumed that revenues from vehicle registration fees will 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 expenditure and revenue estimates are presented in 2012 dollars and are not adjusted for inflation.

1.3.4.(c) Demand Projection and Market Penetration Rates for ECAVs

This study assumes that the market penetration rates grow following a sigmoid curve: slow adoption at the inception due to limited market exposure, followed by a critical takeoff point where the market penetration rate accelerates sharply and then slows down as the market reaches saturation (see section 3.4 for details). In the analyses presented in this report, 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 surge in late 2020s-to-early 2030s, follow a sigmoid adoption curve, reach peak sales a few decades later, and approach market saturation in the mid-2050s to early 2060s. This is generally consistent with other estimates and projections found in the literature. Demand projections and rates of market penetration are discussed in detail in Section 3.4 of this report.

1.4. Organization of this Report

The remainder of this report is organized as follows: Chapter 2 presents a review of literature. This covers an overview of highway cost allocation studies and the relatively scanty literature on the relationships between EVs and CAVs on one hand, and their prospective impacts on highway expenditures, revenues, and equity on the other hand. Chapter 3 presents the study methodology, including the assumptions used and a description of the data used in the study. Chapters 4 and 5 present the results of this analysis and discussion, respectively. Chapter 6 discusses the fiscal impacts of EVs and current trends in EV charging mechanisms and fees, and Chapter 7 presents the concluding remarks (study summary, conclusions, limitations, and future research directions). Chapter 8 presents a synopsis of USDOT performance indicators, and Chapter 9 lists the study outcomes and outputs, including publications, conference papers and presentations, anticipated impacts of the study, and challenges and lessons learned. Finally, the report references are presented and the authors' published work related to this research project, are listed.

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CHAPTER 2. LITERATURE REVIEW

2.1. Introduction

An assessment of the impacts of EV and CAV (ECAV) adoption on highway expenditures and revenues must be preceded by examining the procedures that have been used to attribute these expenditures and revenues. This includes a review of literature on ECAV impact analysis, with respect to the cost and revenues associated with highways. The information also includes demand projections associated with various rates of ECAV market penetration. This chapter also reviews literature on highway cost allocation methods. Sources of 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

The emerging vehicle technologies of automation, connectivity and electrification are poised to yield numerous impacts including, safety, mobility, reliability, comfort, convenience and security, among others (Du et al., 2020; FHWA, 2017; Li et al., 2020A; Saeed et al., 2020). These technologies offer promises of making transportation more equitable and accessible to diverse sections of the population. It is anticipated that with increased vehicle automation, individuals that currently are unable to drive (for example, 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), 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. (2020) 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. This suggests that the impacts of these technologies may exhibit greater variability than expected and therefore, must be analyzed within the broader context that accounts for such uncertainties caused by competing alternatives and individual preferences.

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 power alternatives, with several legacy and newer vehicle manufacturers committing to produce electric vehicles (Deloitte, 2020; McKinsey & Company, 2021). Beyond the obvious environmental benefits of low emissions, 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 relative to gasoline vehicles from the perspective of 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).

The benefits of vehicle automation and electric propulsion will be significant after the technology gains enough market penetration. For this to happen, however, the supporting infrastructure must be in place (Engel et al., 2018; Markel, 2010; Wood et al., 2017). With regard to 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 report. Due to the anticipated (and in some cases, insipient) impact of these technologies on infrastructure expenditures and revenue, the traditional amounts that are used in highway cost allocation, will be disrupted, and such allocation needs to be revised. This is discussed in the next section.

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 the costs of other assets including intelligent transportation systems and safety-related infrastructure. 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 where necessary. Figure 2.1 presents a simplified framework for the highway cost allocation process. This section of the report 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.

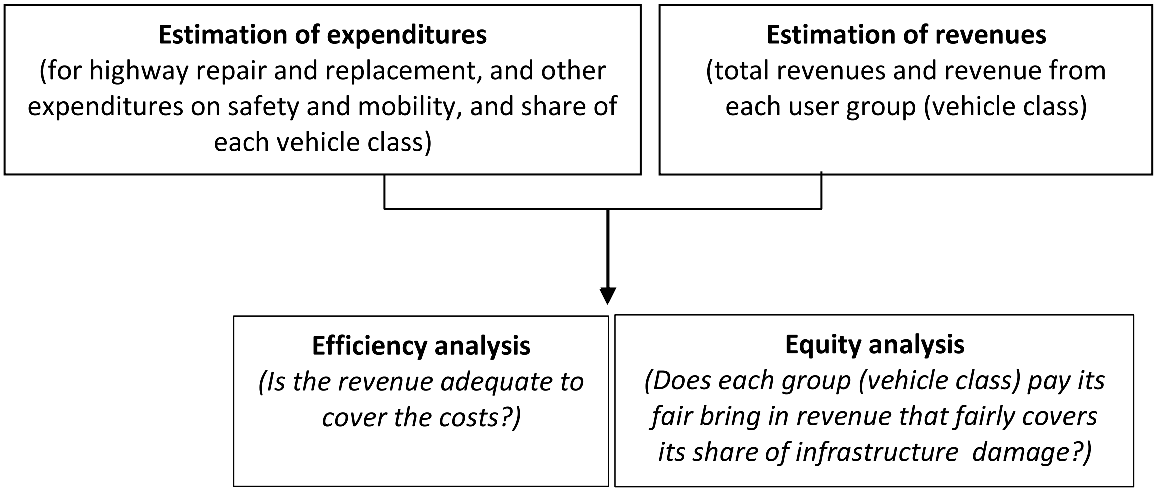


Figure 2.1: Highway cost allocation (HCA) process

Table 2.1: Notable recent studies on highway cost allocation or revenue efficiency.

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. 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 common methods for highway cost allocation.

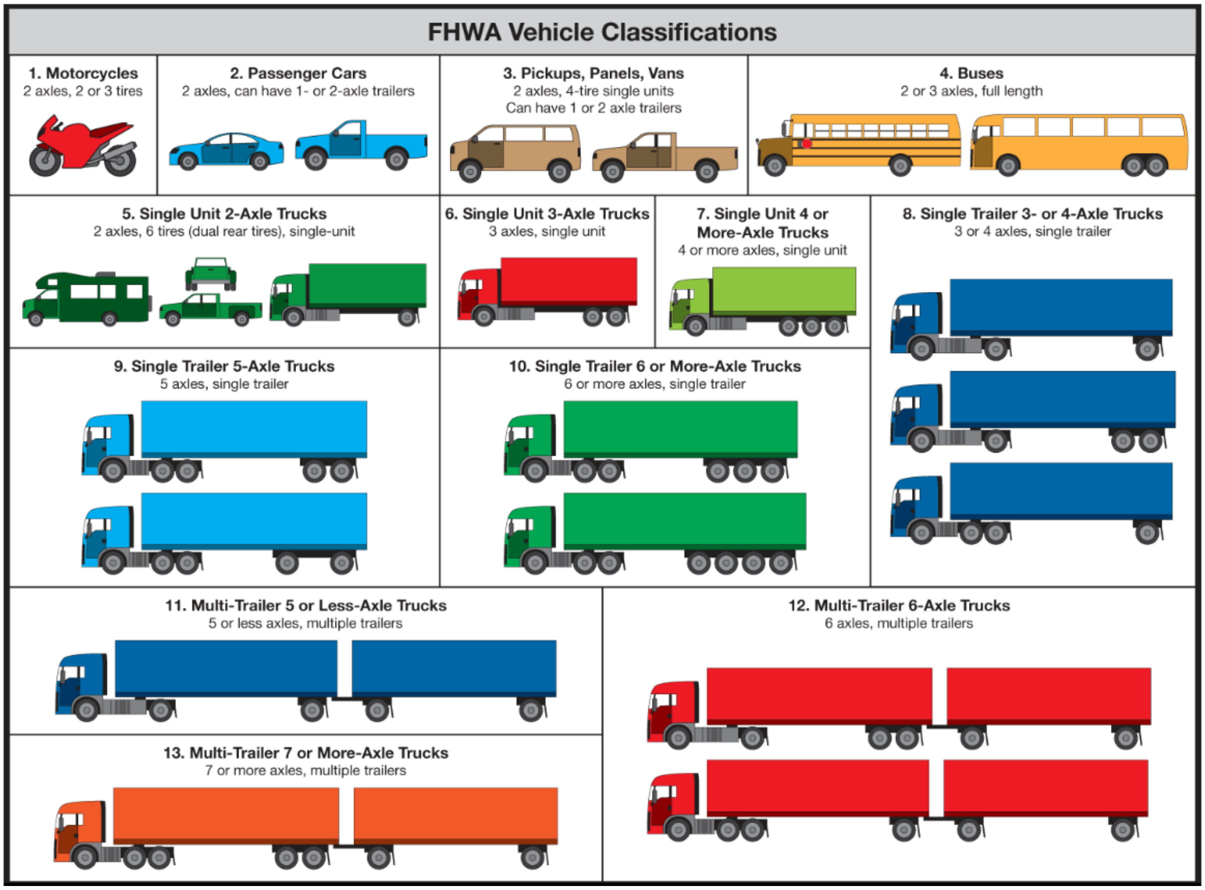


Figure 2.2: FHWA user groups (vehicle classes) (Randall, 2012).

In this discussion, it is necessary to review vital 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, in 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. As such, the costs are defined in two parts: *common costs* and *attributable costs* (Sinha et. al, 1984). Common costs refer to those shared by all vehicles regardless of their size or weight. These costs are due to factors such as weather, climate, and other factors. As such, these are attributed to the user groups based on their VMT contributions. Common-cost expenditure types 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 of passenger car equivalent (PCE) miles to allocate common costs instead of 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). Expenditure 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 in subsequent research that the equations relating traffic load and pavement thickness, are not linear. Therefore, changing the order in which vehicles are incrementally added, generally produces 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 associated with the Traditional Incremental Approach, Fwa & Sinha, (1985b) proposed an alternative approach, termed 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 road-thickness relationship. This allows correction of the returns-to-scale bias associated with the traditional incremental approach. Consequently, this method is considered advantageous over the traditional incremental approach. Such non-linearity is demonstrated in Figure 2.3 (Fwa & Sinha, 1985b). 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).

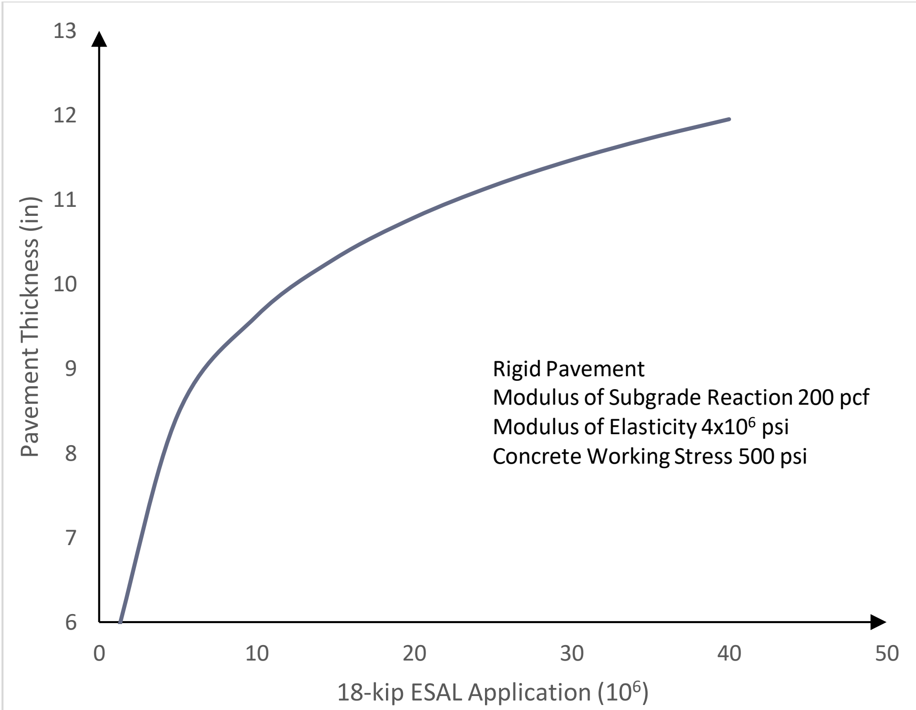


Figure 2.3: Relationship between load application (ESAL) and pavement thickness [adapted from (Fwa & Sinha, 1985b)]

c. <u>Performance Based Approach for Allocating the Costs of Maintenance and Rehabilitation</u>

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 in 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 allocated based on ESALs while those related to non-load factors are allocated based on VMT (Agbelie et al., 2016; Fwa & Sinha, 1985a).

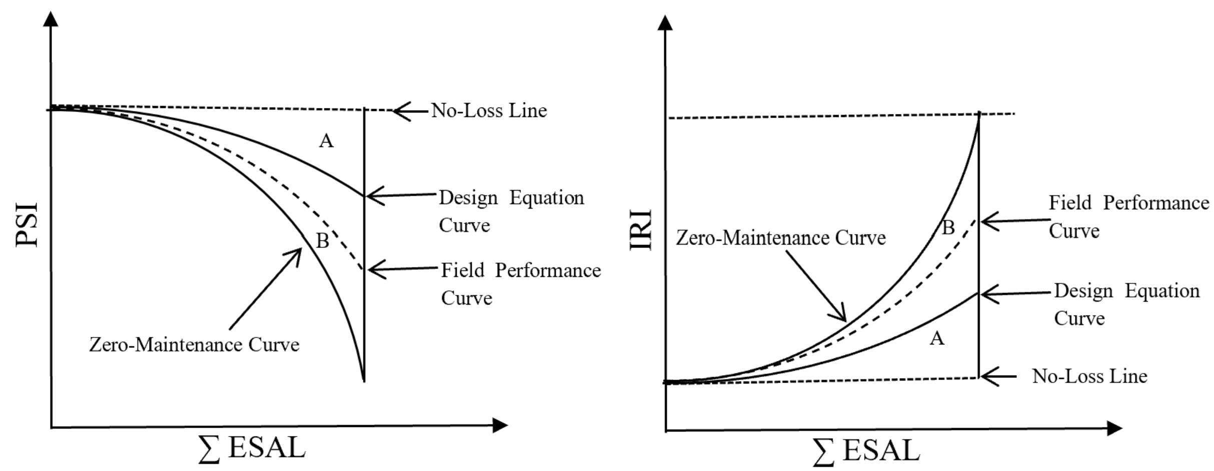


Figure 2.4: The zero-maintenance performance curve (Fwa & Sinha, 1985a)

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 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

However, in HCAS, 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 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. <u>The Federal Method of Bridge Cost Allocation</u>

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. <u>Allocation of Bridge Replacement and Rehabilitation Costs</u>

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. <u>Methods for Allocating the Costs of Highway Safety, Mobility and Other Assets</u>

Highway safety is an essential part of the planning process. Several accidents and crashes can be attributed to factors such as weather, human error, etc. However 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). Roadway assets and design elements that have been shown to reduce crash frequency and/or severity include: guard rails, rumble strips, crash barriers, stops signs, traffic signals, and medians that separate the travel lanes. 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, 2007; TRB, 2010).

Also, highway crashes may cause state-owned property to become damaged and thus need repair or replacement. Safety expenditures include not only the cost of repairs and replacements of safety assets, but also the expenditures on road and bridge projects that have a secondary benefit of highway safety and mobility enhancement. Examples include geometric realignments to ensure that existing horizontal and vertical curves ensure 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 report, 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, such expenditures are "consumed" by all vehicle classes on the highway, irrespective of the vehicle size or weight. In other words, the safety and mobility treatments are typically independent on vehicle weight or size; and therefore, cost allocation studies treat them as common costs (Agbelie et al., 2016; Gupta & Chen, 2012; Sinha et al., 1984; Sinha et al., 1989; Volovski et al., 2015). As common costs, these safety and mobility expenditures are allocated in the present study based on the contribution of each vehicle class 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 termed 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; FHWA, 2019) as illustrated in Figure 2.5.

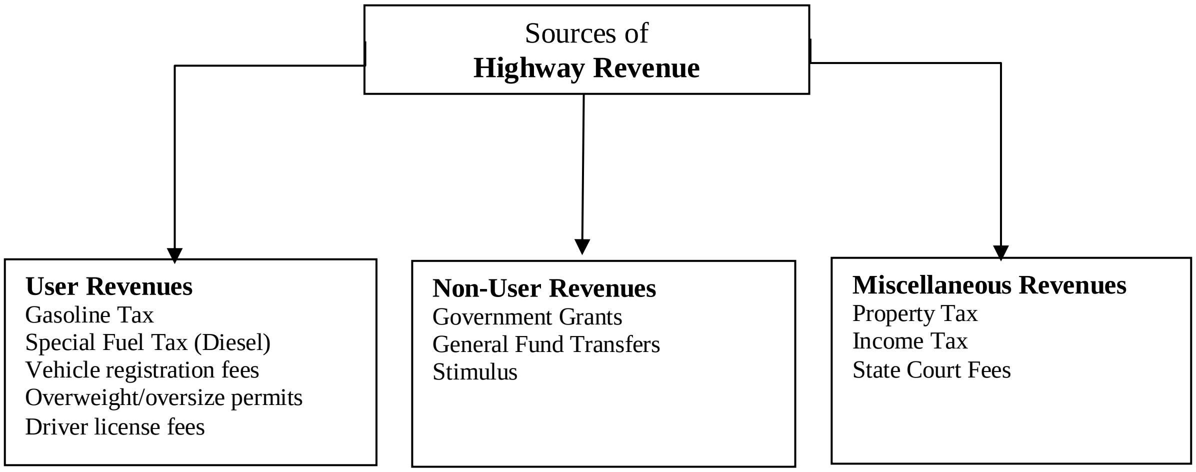


Figure 2.5: Typical highway revenue sources [adapted from (Agbelie et al., 2016)]

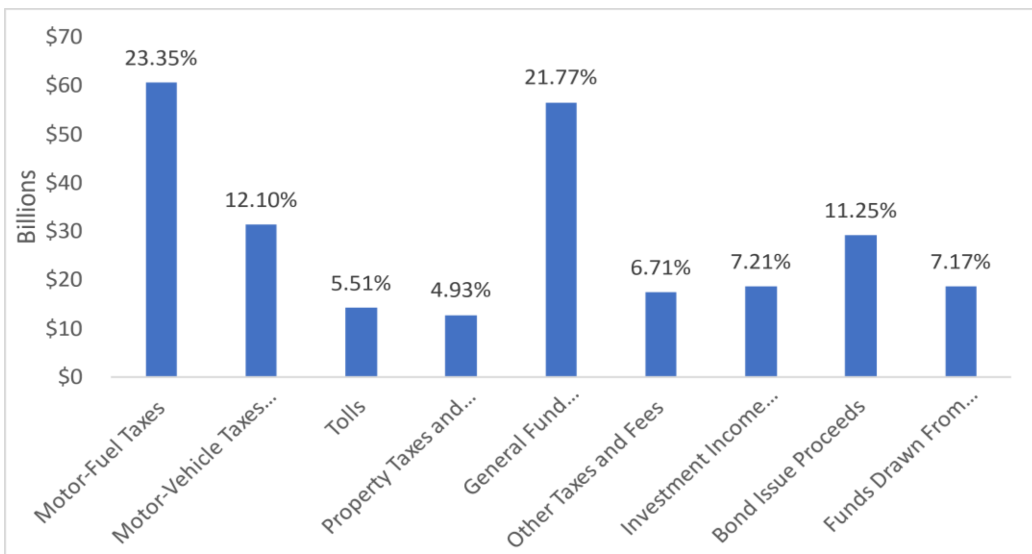


Figure 2.6: National highway revenue contributions by source (FHWA & FTA, 2019)

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, and stimulus from legislative acts in response to prevailing economic conditions, among others. However, these sources are inconsistent and cannot be relied upon to continue funding highway projects year after year. 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.

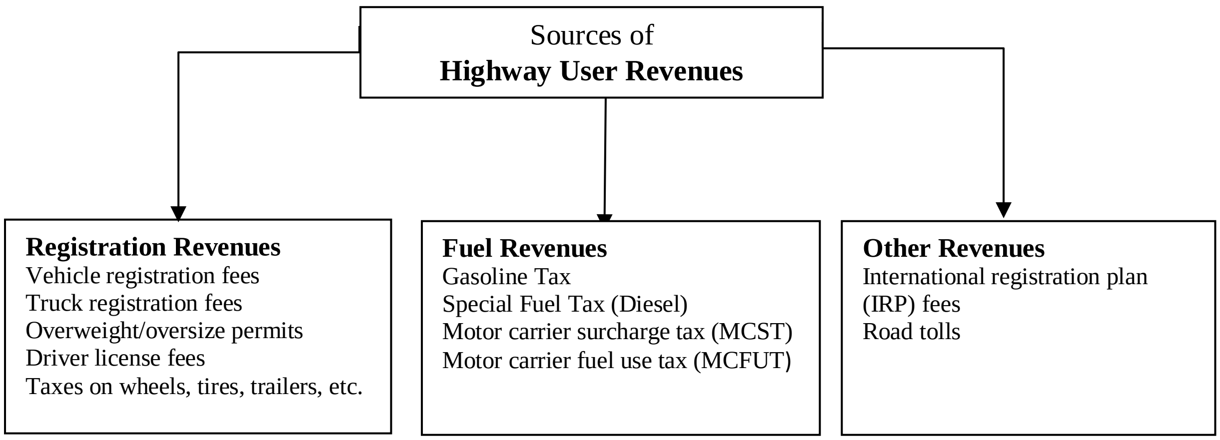


Figure 2.7: Composition of highway user revenues [adapted from (Agbelie et al., 2016)]

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 also on the total travel rates and fuel usage. These, 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 due to the well established inverse relationship between fuel efficiency and highway revenue. Tax rates and collection terms are established by the legislative bodies. As of the time of publishing of this report, the tax rates are 18 cents per gallon for gasoline and 16 cents per gallon for diesel at the state level in Indiana. At the federal level, the fuel taxes are 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, the fuel revenues can be estimated using equation (2.1), and following the procedure presented in Figure 2.8. A detailed explanation of each of the steps is outlined in Volovski et al. (2015).

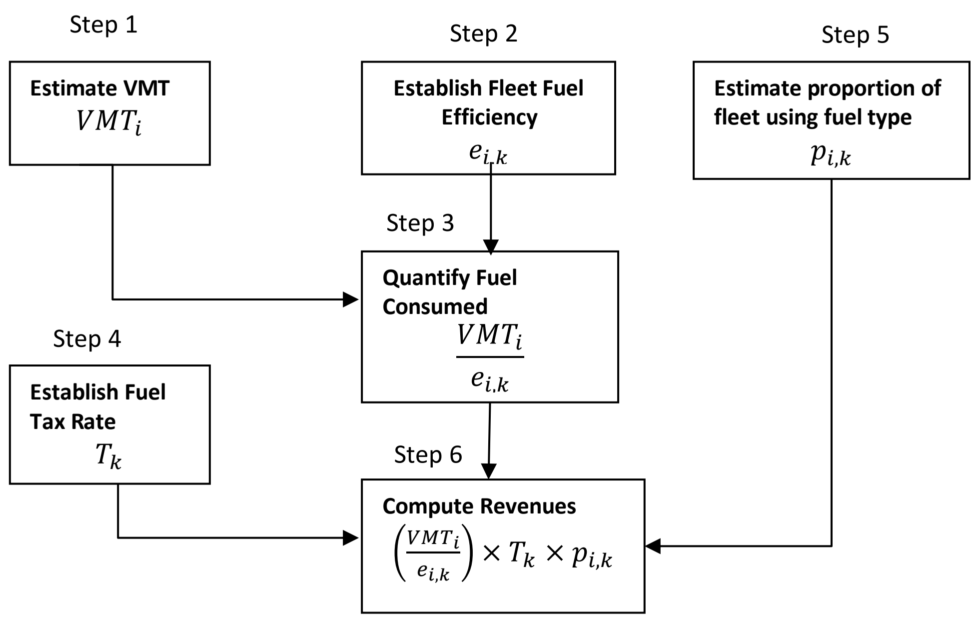


Figure 2.8: Steps to estimate/predict fuel tax revenues.

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 to 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 1 through 6 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 may be 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 reduced out-of-pocket costs, increased network connectivity, increased accessibility to social and economic centers, improved safety, reduced delays, and increased 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 where both the benefits and the costs of a transport system, program, initiative, or innovation are distributed among the current or prospective users. 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 are 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 be best 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. For example, the State of 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). The state of Nevada investigated the state's highway cost allocation with respect to the highway users (classified by vehicle type and weights) to make recommendations for tax rate changes and therefore reduce the disparity between payments and cost responsibilities for each class (Balducci et al., 2009). Also, the state of Oregon carried out a highway cost allocation study and suggested alternative fee schedules intended to minimize cross-subsidization across the vehicle classes, to improve equity among vehicle classes (ECONorthwest, 2014).

A desirable equity 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. Existing literature on highway cost allocation methods was reviewed and documented. The sources of published material on the subject included journal publications, conference publications, agency reports, and reports from management consultants and technology companies.

The literature review also provided evidence to suggest that the emerging vehicle technologies are poised to cause numerous impacts which include comfort, convenience, safety, reliability, and security. 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, increased power generation for vehicle electrification, cloud computing infrastructure, and smart highway and intersection features. These will require significant expenditures by highway agencies. On the other hand, electrification will cause drastic reductions in highway fuel-tax revenue. Therefore, the gap between highway revenue and expenditure, is expected to decrease.

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, the thickness incremental approach, and the performance-based approach. 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 superstructure – 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.

Highway revenue attribution and user equity were 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. 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. 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.

CHAPTER 3. METHODS

This chapter of the report presents the methodology adopted for analyzing 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 report are only for the state of Indiana.

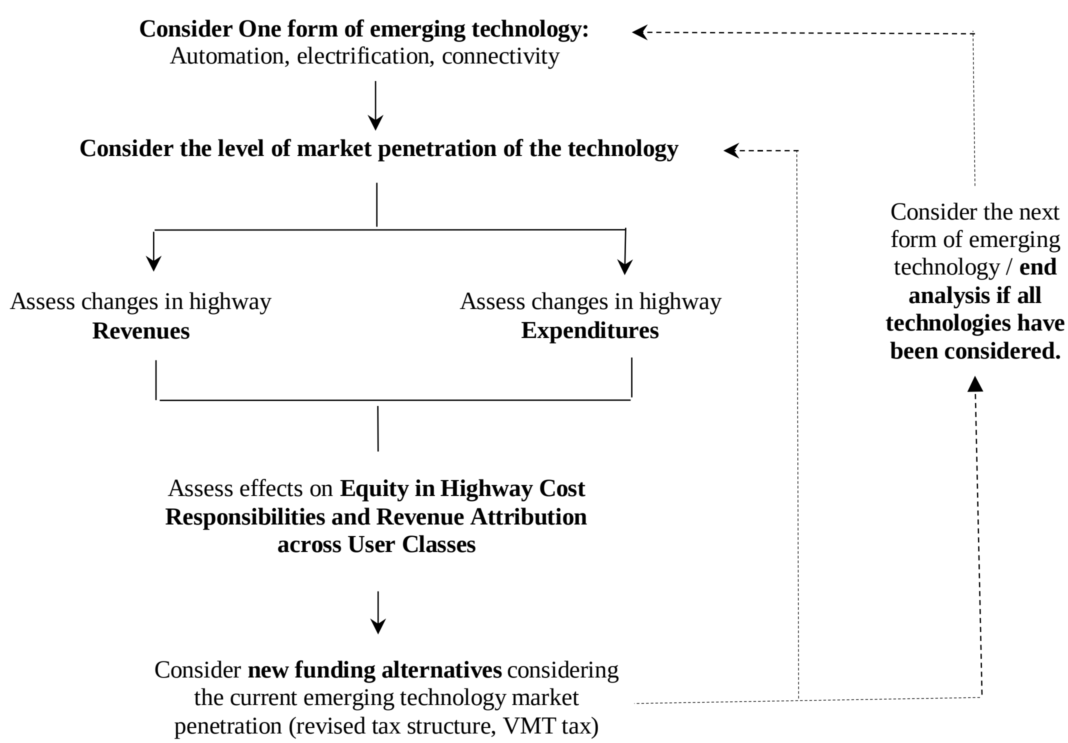


Figure 3.1 Study framework

3.1. Establishing the Base Case (Conventional) Scenario

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, the base case serves as a control scenario, ensuring that the impacts being assessed are primarily due to the emerging vehicle technologies in question. According 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 report, 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 report 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.

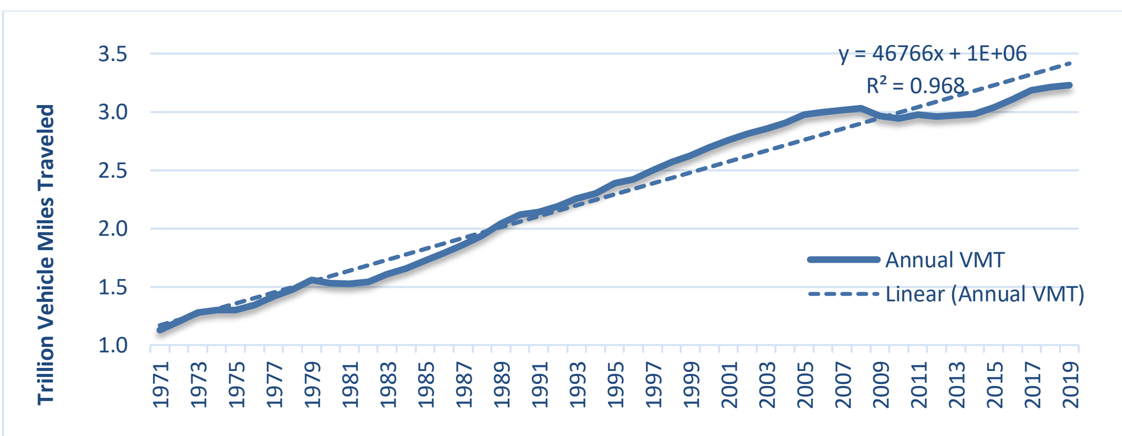


Figure 3.2: Annual VMT in US, 1971–2019 [adapted from (FHWA, 2020)]

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 report 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. Also, the topographical and climatic conditions prevailing in Switzerland may vary significantly from those in the Midwest United States.

In this study, the infrastructure expenditure vs. usage models were developed using US highway statistics data (provided by FHWA) on highway system usage and expenditures from 1994 through 2019. The following functional form was used for the infrastructure cost models:

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

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 presented in equations 3.2 and 3.3, respectively.

$$\ln(Cost_{common}) = \alpha_{common} + \beta_{common} \ln(VMT) \tag{3.2}$$

$$\ln(Cost_{attr}) = \alpha_{attr} + \beta_{attr} \ln(ton - miles) \tag{3.3}$$

As outlined in Section 2.3 of this report, 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 (3.4):

$$Cost = e^{\alpha} x^{\beta} \tag{3.4}$$

Due to lack of granular data for many of the years for which data were 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 report, the data in the model development were 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 are adopted from Volovski et al. (2015). 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 dataset 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 report 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 report represent the amounts for the fiscal year 2009 through 2012 and are presented in 2012 dollars. Highway expenditures refers to the funds spent on new construction and long-term stewardship of highway assets, and includes spending on pavements, bridges, and highway safety, and mobility. Highway 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 a 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) (Figure 3.3).

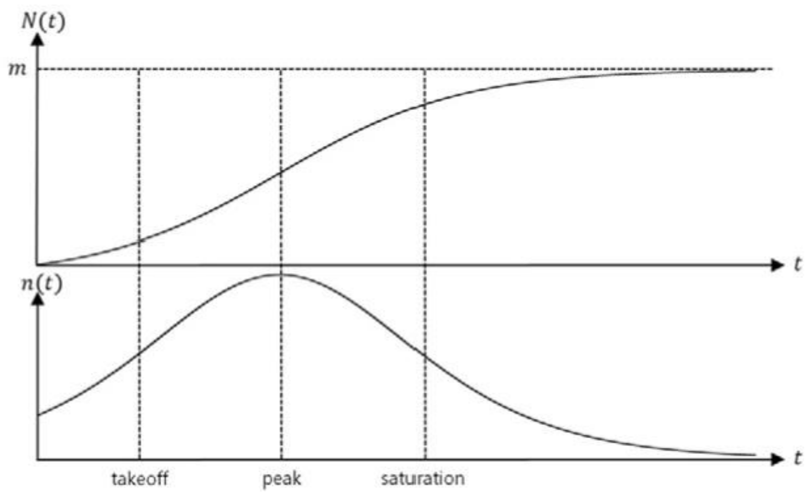


Figure 3.3: Bass model adopter curves (top – cumulative adopter; bottom – non-cumulative adopter (Kim & Hong, 2015).

Vehicle automation, electrification and connectivity are each expected to develop at different paces. The rate of their market penetration, 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 report. The rate of development of connectivity hinges on advances in wireless communication protocols and 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 penetration. 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 report analyzed at least 15 scenarios of supply and demand. This is illustrated in Table 3.1.

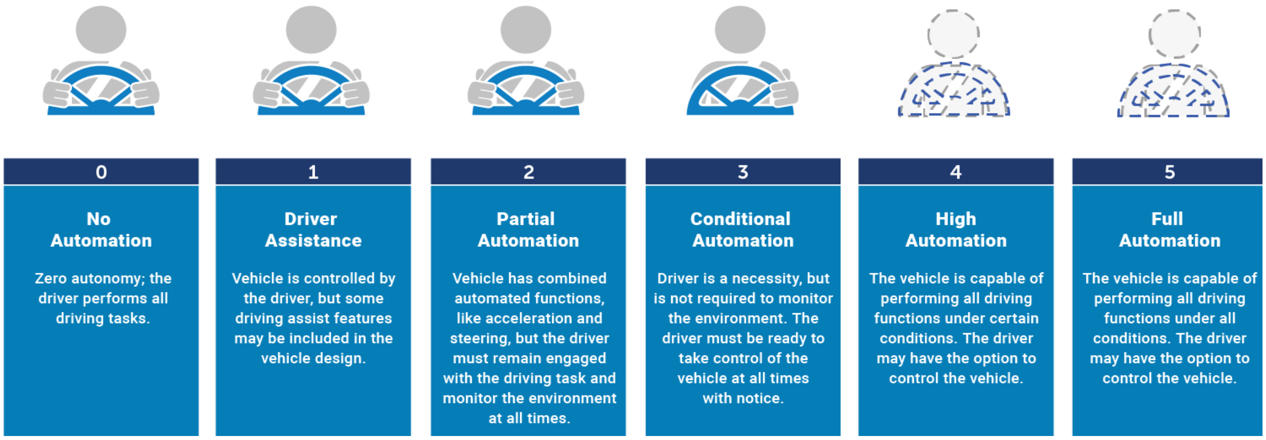


Figure 3.4 SAE automation levels (SAE, 2018)

Table 3.1: Scenarios of demand and supply analyzed in this report.

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

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 market penetration indicated.

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 et al., 2020a). Connectivity features include integrated smart apps, GPS, satellite navigation and 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 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).

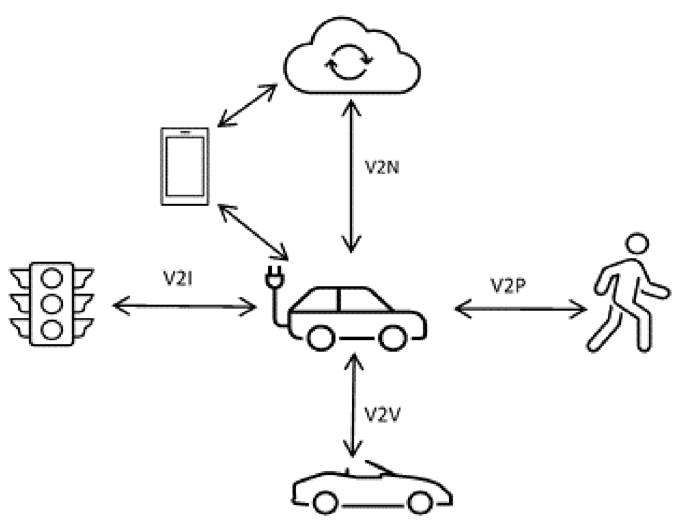


Figure 3.5: Schematic representation of different types of vehicle connectivity [adapted from (Heiden, 2019)].

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 to the 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).

However, under more controlled conditions 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; Zohdy & Rakha, 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).

3.4.1.(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. 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). The 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 report, 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 expected, however, to result in improved fuel efficiency for the connected vehicles, through platooning and adaptive cruise control. For the purpose of this report, 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; Zohdy & Rakha, 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.

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 Level 1 automation at least.

Governments and transportation agencies spend funds on several aspects of highway infrastructure. Several of these expenditures 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. The expenditures 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. Such increased capacities, in turn, may induce travel demand, thereby increasing the 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

Currently, 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). The 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 (for example, Audi, 2015; Bomey, 2018; Ford, 2020). Additionally, some non-traditional vehicle manufacturers (for example, Tesla), some mobility companies (for example, Uber and technology companies including 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 likely 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.

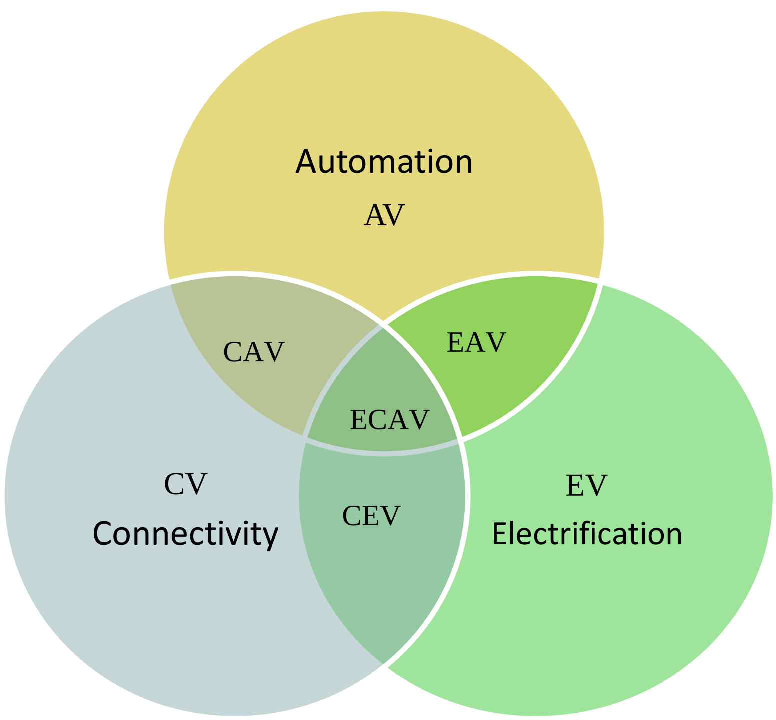
In forecasting autonomous vehicle adoption rates and market penetration, several factors on the demand and supply side must be considered. These include government regulation and incentives, affordability of the technology and its evolution over time, consumer willingness to pay and available levels 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 despite being on the market for about a decade (Mosquet et al., 2015).

Table 3.2: AV market penetration forecasts

Reference	Model/Approach	AV Level of automation forecast
		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 seems that the pursuit and tandem development of both technologies is driven by primarily by a confluence of market forces and to a smaller extent, their inherent interdependencies. Automation and electrification require different technologies and do not have the same motivating forces. However, they have a synergistic sibling relationship. The push towards electrification is mainly being driven by the move away from fossil fuels which is fueled by rising climate awareness (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, et al., 2020a; Ha, et al., 2020b). 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 combustion engines or electric vehicles that are not autonomous. 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 used in the analysis
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

Even though they rely on different technologies Vehicle automation and electric propulsion 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 logistics centers and rest stations along routes. Additionally, the authors noted that this may be suitable only 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 least, 50kW) and (3) a supporting intra-day energy infrastructure, e.g., battery swapping (Çabukoglu et al., 2018). Also, 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, it has been postulated that the gains resulting from transportation decarbonization would be negated by indirect emissions of generation, leading virtually no difference in overall carbon emissions (Çabukoglu et al., 2019). The authors 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, replacing diesel in heavy duty vehicles seems 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 report, 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.

3.4.3.(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. However, with the wide availability of driver assistance features in modern vehicles, it is hardly realistic to assume the complete absence of any automation in present-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 that will enable the drivers to locate charging stations within the network are expected to be present in these vehicles. With these technological 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 vehicles will be classified as human-driven vehicles, they will possess at least Level 2 automation by SAE automation standards (SAE, 2018).

For the purposes of this report, 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 the purposes of this report, 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. Furthermore, 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

3.4.3.(b) Automation with no Electrification

The second scenario considered in this report automation without electric propulsion. This scenario can also be considered a possible 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, 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, 2015). Furthermore, ride sharing may not have enough of a market share to offset the increase in VMT stemming from other competing effects.

Therefore, for this analysis, 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 as compared with a fully human-driven fleet at similar VMT levels.

3.4.3.(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 travel 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.

However, the combination of automation and electrification 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 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 no 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 vehicles with conventional vehicle efficiencies, it cannot be used for fuel revenue analysis. Consider the extreme case where all vehicles in the fleet are 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 common (Davis et al., 2014). 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). Nevertheless, for accounting purposes in this report, 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 (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

Some vehicle trips are made by drivers who do not derive direct personal benefits from the trip but undertake the trip so that their passengers can benefit (as suggested in 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 report) and earlier established assumptions on the level of CAV penetration.

It is rather difficult to ascertain accurately 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 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 personal vehicle 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. Fagnant 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%. Furthermore, 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, 2015). 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 et al., 2020), increased safety (Du et al., 2020), smoother traffic flow (Li 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, privately-owned AVs and AVs used for shipping and freight. For the present study, a modified version of the aforementioned set of assumptions is 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

Figure 3.7 is a simplified version of a figure earlier presented in this report, and presents the overall approach taken to evaluate the impact of new vehicle technologies on highway expenditures and revenues.

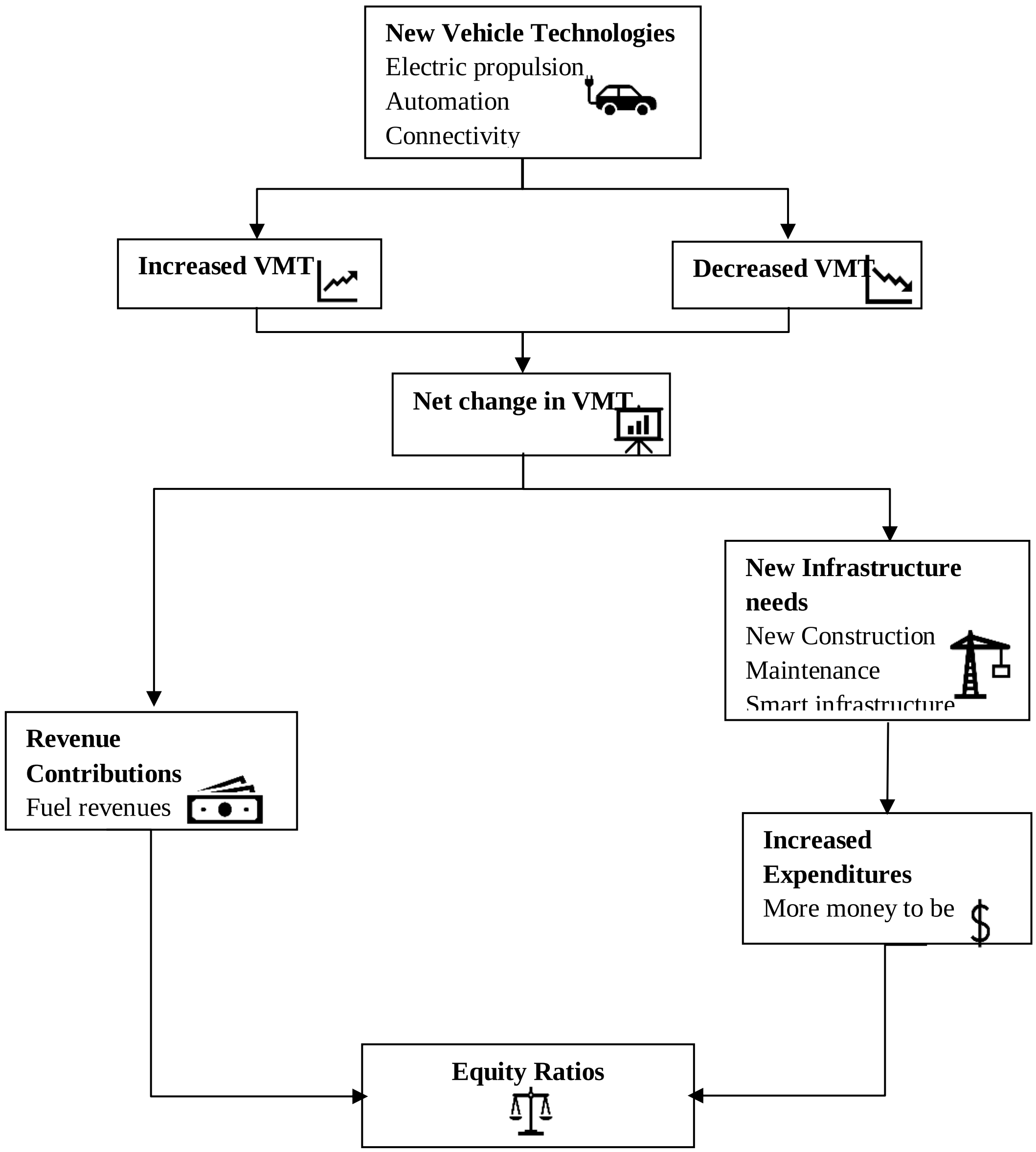


Figure 3.7 A generalized framework for evaluating the impacts of new vehicle technologies on highway revenues, expenditures, and user equity

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 report, 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, several expenditure categories including grading and earthwork expenditures, drainage and erosion control expenditures, pavement-related expenditures, and shoulder expenditures are considered. 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. The remaining costs are attributed to non-load and therefore, 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.

3.6.2. Bridge expenditures

Bridge expenditures can be expected to change in the era of CAV operations due to 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 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 this research to allocate the costs of new bridge construction. This procedure is explained in greater detail in Volovski et al. (2015).

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. Regarding 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 the case for new bridge construction, the ratio of load to non-load expenditures for 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 and are traditionally regarded as treatments that are independent of vehicle characteristics (size and weight). Therefore , these costs are allocated based on VMT. However, situations can sometimes arise where certain expenditure items such as right-of-way can be considered as being related to vehicle size, such as in determining the width of a single lane bridge. 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 report, 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.

Similar to 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.

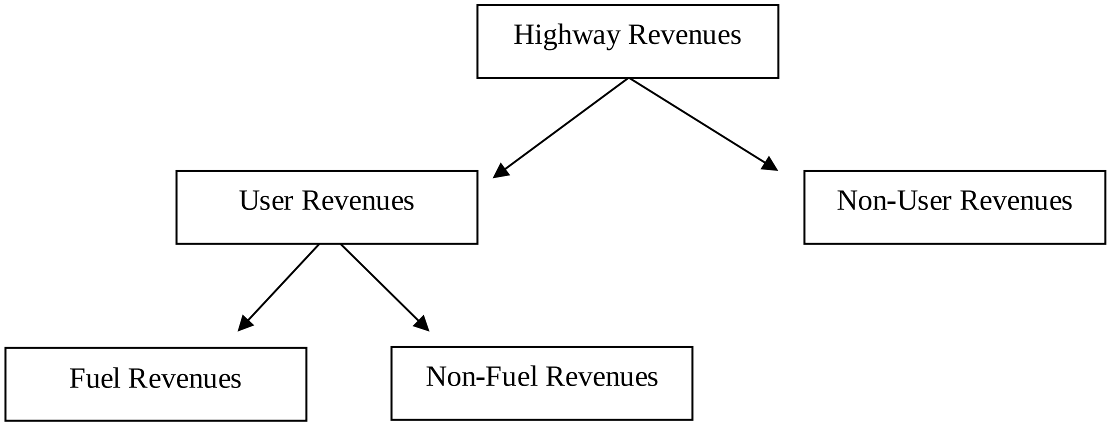


Figure 3.8: Highway revenue sources

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 on 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 report 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 – connectivity, automation, and/or electrification under consideration.

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 (3.5) below:

$$R_{i,k} = \left(\frac{VMT_i}{e_{i,k}}\right) \times T_k \times p_{i,k} \qquad (3.5)$$

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: a slow rate of adoption rate initially, followed by an accelerating adoption rate as the technology becomes less costly and more widely available, and then at the final stages, a decelerating rate of adoption as the market approaches saturation. In this study, the Bass Diffusion model is used to describe such adoption rate patterns.

The 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. 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. Further, at higher market penetration levels, there can be several 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. These changes in VMT, along with the need 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 use fuel gasoline and therefore will not contribute to the fuel revenues, thereby exacerbating the problem of revenue inadequacy.

CHAPTER 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 as a result, 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 a previous chapter of this report are presented in this section. This chapter also presents the modeling results for the infrastructure cost functions developed earlier in this report. 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 report 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 modeling 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 common cost 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. The intensity, and hence cost of these projects are mostly load dependent, and are therefore allocated 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 on average. 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 upkeep (repair or replacement), x is a measure of system usage, while α and β are model parameters to be estimated. For common costs, x represents VMT and for attributable costs, x 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 report used 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 the 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.

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

This section reports the anticipated and estimated impacts of emerging vehicle technologies on highway expenditures and revenues. The impacts are assessed for each scenario and across various 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, the user equity (and changes thereof) are then reported.

The impacts of the technologies are reported against an established base case scenario as detailed in Section 3.1. The impacts and infrastructure requirements may be different for each of the technologies at varying 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 establishes 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 report assumed 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 in the sections that follow.

a. Expenditures

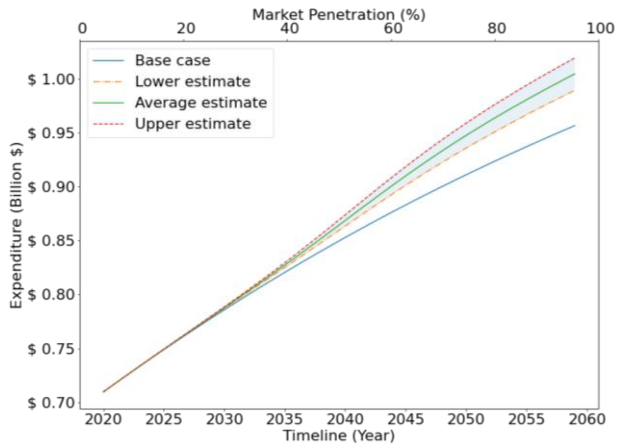
Vehicle connectivity is expected to be widely available in many cars starting in the 2020s to early 2030s (Heiden, 2019; Litman, 2017). Currently, almost all new cars being sold come equipped with connectivity, be it cell phone mirroring (Apple Carplay, Android Auto) or in-vehicle GPS navigation. Depending on the vehicle manufacturer, these features may be provided as standard or as premium base options. Vehicle connectivity technology can be expected to gain widespread market acceptance and use as the years go by. Therefore, this report 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 consequently, induced demand (increased overall travel) and ultimately, possible increase in highway expenditures compared with the base case, as shown in Figure 4.1.

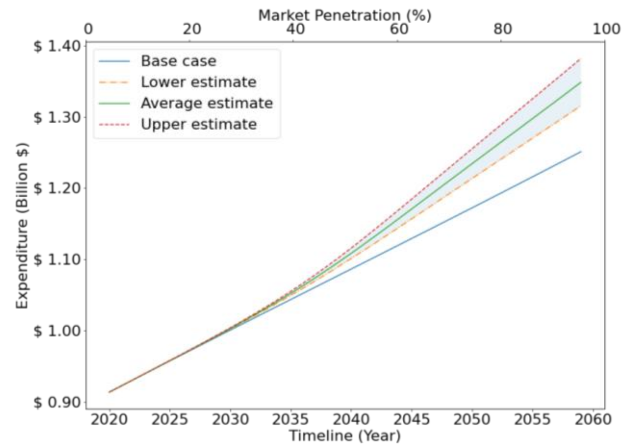
Table 4.1: Total annual highway expenditure estimates, CV-only scenario, from 2020s (low market penetration) to late 2050s (high market penetration)

	Total Annual Highway Expenditure for CV Scenario			
Year	Base Case	CV Lower estimate	CV Average	CV Upper Estimate
2020	$2,364,041,000	$2,364,041,000	$2,364,041,000	$2,364,041,000
2021	$2,388,489,000	$2,388,563,000	$2,388,601,000	$2,388,638,000
2022	$2,412,802,000	$2,412,985,000	$2,413,076,000	$2,413,168,000
2023	$2,436,979,000	$2,437,315,000	$2,437,483,000	$2,437,650,000
2024	$2,461,018,000	$2,461,565,000	$2,461,838,000	$2,462,111,000
2025	$2,484,916,000	$2,485,750,000	$2,486,166,000	$2,486,583,000
2026	$2,508,671,000	$2,509,890,000	$2,510,499,000	$2,511,108,000
2027	$2,532,284,000	$2,534,010,000	$2,534,873,000	$2,535,736,000
2028	$2,555,751,000	$2,558,141,000	$2,559,335,000	$2,560,529,000
2029	$2,579,074,000	$2,582,318,000	$2,583,939,000	$2,585,559,000
2030	$2,602,251,000	$2,606,583,000	$2,608,746,000	$2,610,909,000
2031	$2,625,282,000	$2,630,981,000	$2,633,828,000	$2,636,672,000
2032	$2,648,168,000	$2,655,564,000	$2,659,256,000	$2,662,945,000
2033	$2,670,908,000	$2,680,380,000	$2,685,107,000	$2,689,827,000
2034	$2,693,503,000	$2,705,477,000	$2,711,449,000	$2,717,411,000
2035	$2,715,955,000	$2,730,895,000	$2,738,342,000	$2,745,772,000
2036	$2,738,264,000	$2,756,662,000	$2,765,825,000	$2,774,964,000
2037	$2,760,431,000	$2,782,789,000	$2,793,914,000	$2,805,003,000
2038	$2,782,458,000	$2,809,265,000	$2,822,591,000	$2,835,867,000
2039	$2,804,347,000	$2,836,059,000	$2,851,808,000	$2,867,486,000
2040	$2,826,098,000	$2,863,118,000	$2,881,482,000	$2,899,751,000
2041	$2,847,715,000	$2,890,371,000	$2,911,507,000	$2,932,519,000
2042	$2,869,198,000	$2,917,737,000	$2,941,761,000	$2,965,625,000
2043	$2,890,552,000	$2,945,131,000	$2,972,113,000	$2,998,898,000
2044	$2,911,777,000	$2,972,469,000	$3,002,440,000	$3,032,174,000
2045	$2,932,876,000	$2,999,679,000	$3,032,634,000	$3,065,308,000
2046	$2,953,852,000	$3,026,700,000	$3,062,604,000	$3,098,183,000
2047	$2,974,707,000	$3,053,490,000	$3,092,285,000	$3,130,713,000
2048	$2,995,445,000	$3,080,017,000	$3,121,633,000	$3,162,839,000
2049	$3,016,068,000	$3,106,268,000	$3,150,625,000	$3,194,533,000
2050	$3,036,578,000	$3,132,238,000	$3,179,255,000	$3,225,787,000
2051	$3,056,980,000	$3,157,933,000	$3,207,532,000	$3,256,613,000
2052	$3,077,276,000	$3,183,366,000	$3,235,472,000	$3,287,033,000
2053	$3,097,469,000	$3,208,552,000	$3,263,100,000	$3,317,080,000
2054	$3,117,563,000	$3,233,511,000	$3,290,444,000	$3,346,789,000
2055	$3,137,559,000	$3,258,265,000	$3,317,533,000	$3,376,199,000
2056	$3,157,463,000	$3,282,833,000	$3,344,396,000	$3,405,349,000
2057	$3,177,276,000	$3,307,235,000	$3,371,063,000	$3,434,276,000
2058	$3,197,002,000	$3,331,492,000	$3,397,561,000	$3,463,015,000
2059	$3,216,645,000	$3,355,621,000	$3,423,916,000	$3,491,601,000

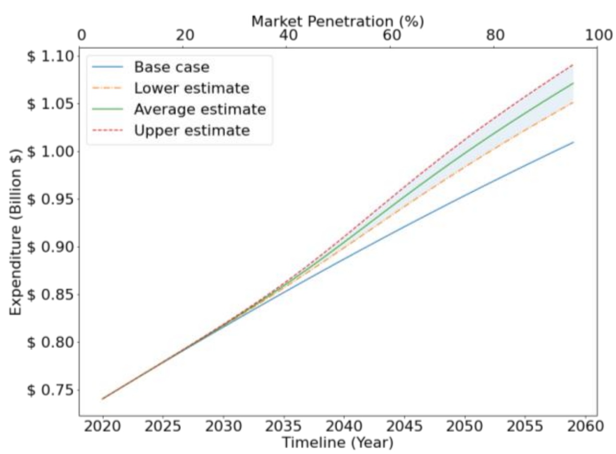
The trend is clearer when shown graphically, as depicted in Figure 4.1. For each of the vehicle classes, the early years following the introduction of the technology, the expenditures are close to the base case scenario, because not enough cars are equipped with the technology to have significant impacts. However, the cost begins to rise to levels higher than the base case as the market penetration increases. This is accompanied by an increase in the need for additional infrastructure to support not only the technology but also the increase in travel resulting from the technology. The disparity between the technology scenario and the base case, increases with time (as the technology's 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 far out into the prediction horizon.



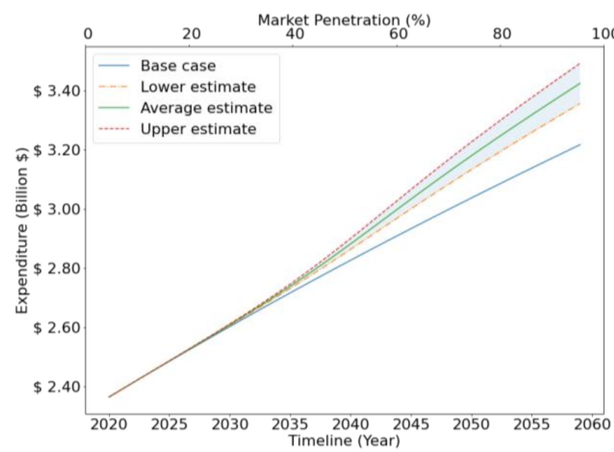
Passenger Cars



Light Trucks



Heavy Trucks



Total

Figure 4.1 Annualized total highway expenditures for the CV-only scenario from low to high market penetration

b. Revenues

Vehicle connectivity does not directly influence travel patterns and overall VMT. However, it could result in marginal gains in vehicle fuel economy. This is due in part to the benefits of enhanced 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 2 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 3.4.1.(a). 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.

At all three levels of market penetration of the technology, the differences in revenues between the base case and the technology level in question, is substantial. 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 the 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. Generally, 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.

Table 4.2: Total annual highway revenue estimates in the era of CV-only from 2020s (low market penetration) to late 2050s (high market penetration)

	Total Annual Revenue for CV Scenario			
Year	Base Case	Lower estimate	Average	Upper estimate
2020	$2,309,097,000	$2,309,097,000	$2,309,097,000	$2,309,097,000
2021	$2,330,607,000	$2,330,601,000	$2,330,616,000	$2,330,631,000
2022	$2,352,117,000	$2,352,104,000	$2,352,141,000	$2,352,178,000
2023	$2,373,627,000	$2,373,603,000	$2,373,671,000	$2,373,740,000
2024	$2,395,137,000	$2,395,097,000	$2,395,210,000	$2,395,323,000
2025	$2,416,647,000	$2,416,587,000	$2,416,760,000	$2,416,933,000
2026	$2,438,157,000	$2,438,068,000	$2,438,323,000	$2,438,578,000
2027	$2,459,667,000	$2,459,541,000	$2,459,904,000	$2,460,268,000
2028	$2,481,177,000	$2,481,003,000	$2,481,508,000	$2,482,014,000
2029	$2,502,687,000	$2,502,450,000	$2,503,141,000	$2,503,833,000
2030	$2,524,197,000	$2,523,880,000	$2,524,810,000	$2,525,739,000
2031	$2,545,707,000	$2,545,290,000	$2,546,522,000	$2,547,754,000
2032	$2,567,217,000	$2,566,677,000	$2,568,288,000	$2,569,898,000
2033	$2,588,727,000	$2,588,039,000	$2,590,117,000	$2,592,195,000
2034	$2,610,237,000	$2,609,372,000	$2,612,019,000	$2,614,667,000
2035	$2,631,747,000	$2,630,677,000	$2,634,007,000	$2,637,336,000
2036	$2,653,257,000	$2,651,954,000	$2,656,088,000	$2,660,223,000
2037	$2,674,767,000	$2,673,205,000	$2,678,273,000	$2,683,339,000
2038	$2,696,277,000	$2,694,436,000	$2,700,565,000	$2,706,693,000
2039	$2,717,787,000	$2,715,652,000	$2,722,966,000	$2,730,280,000
2040	$2,739,297,000	$2,736,860,000	$2,745,476,000	$2,754,090,000
2041	$2,760,807,000	$2,758,068,000	$2,768,086,000	$2,778,102,000
2042	$2,782,317,000	$2,779,284,000	$2,790,788,000	$2,802,287,000
2043	$2,803,827,000	$2,800,515,000	$2,813,566,000	$2,826,613,000
2044	$2,825,337,000	$2,821,765,000	$2,836,408,000	$2,851,043,000
2045	$2,846,847,000	$2,843,039,000	$2,859,296,000	$2,875,544,000
2046	$2,868,357,000	$2,864,337,000	$2,882,217,000	$2,900,085,000
2047	$2,889,867,000	$2,885,661,000	$2,905,158,000	$2,924,640,000
2048	$2,911,377,000	$2,907,010,000	$2,928,108,000	$2,949,188,000
2049	$2,932,887,000	$2,928,383,000	$2,951,059,000	$2,973,714,000
2050	$2,954,398,000	$2,949,778,000	$2,974,007,000	$2,998,210,000
2051	$2,975,908,000	$2,971,193,000	$2,996,947,000	$3,022,671,000
2052	$2,997,418,000	$2,992,626,000	$3,019,879,000	$3,047,097,000
2053	$3,018,928,000	$3,014,076,000	$3,042,802,000	$3,071,489,000
2054	$3,040,438,000	$3,035,541,000	$3,065,718,000	$3,095,850,000
2055	$3,061,948,000	$3,057,020,000	$3,088,628,000	$3,120,187,000
2056	$3,083,458,000	$3,078,512,000	$3,111,535,000	$3,144,504,000
2057	$3,104,968,000	$3,100,016,000	$3,134,441,000	$3,168,807,000
2058	$3,126,478,000	$3,121,531,000	$3,157,350,000	$3,193,103,000
2059	$3,147,988,000	$3,143,057,000	$3,180,262,000	$3,217,396,000

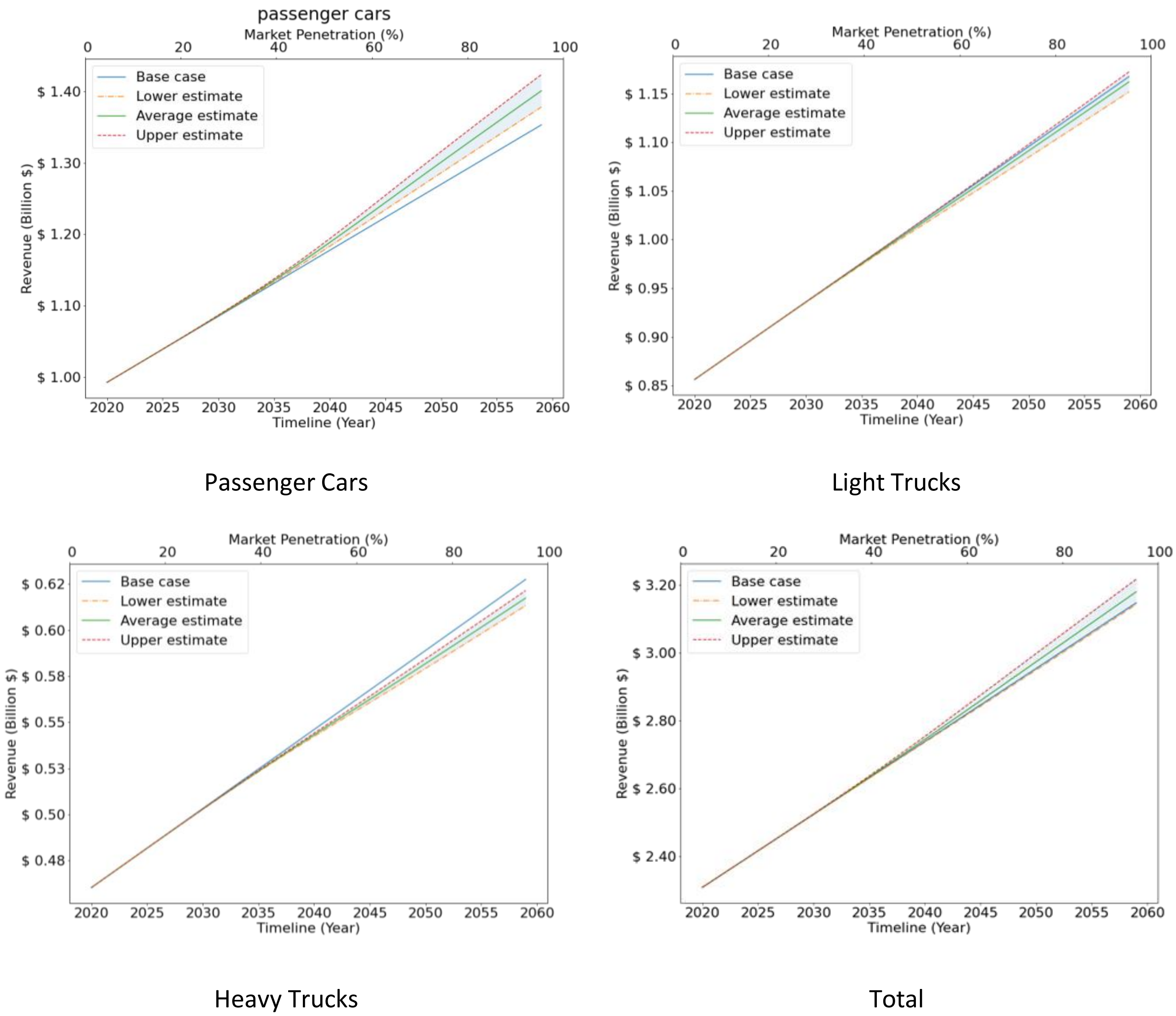


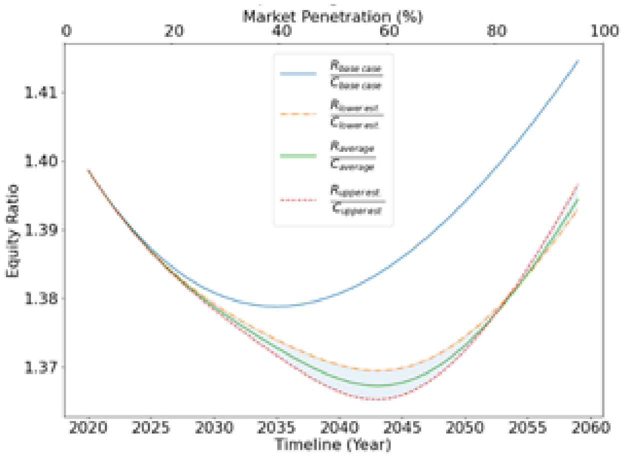
Figure 4.2: Total Annual Highway Revenues for the CV scenario, for different levels of market penetration

c. User Equity Analysis

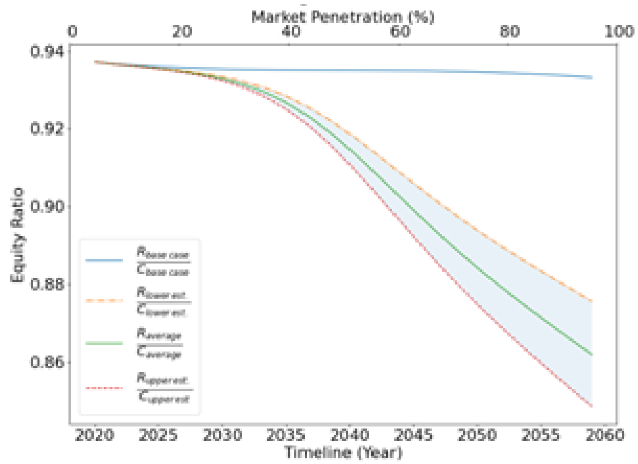
Equity ratios relate the share of revenue contributed by a given user group (vehicle class) to its cost responsibility. For each vehicle class, the contributed revenues and cost responsibility are expressed as percentages of the total values across all vehicle classes. Consequently, changes to expenditures or revenues reflect as changes in the 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 generally.

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 varying 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.

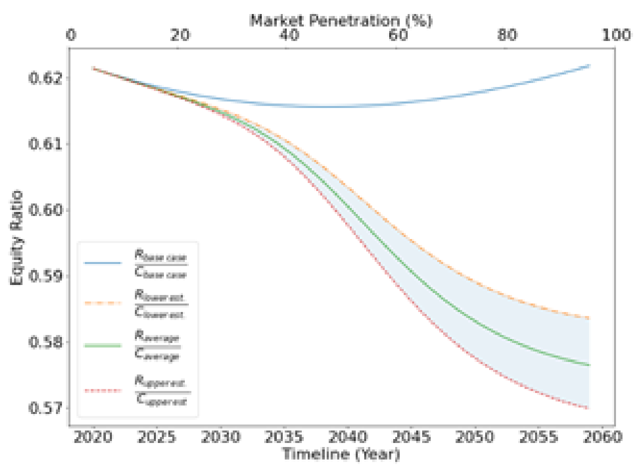
The overall decline in revenue contributions of each vehicle class is manifested by the results (decreases in equity ratios) across the classes. Across the various levels of market penetration of vehicle connectivity, the light and heavy-duty vehicle classes seem to be underpaying their share of the 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. Therefore, in the era for significant market penetration, there will exist a need to revise the user fee structure to reduce the exacerbation in user inequity in the highway system.



Passenger Cars



Light Trucks



Heavy Trucks

Figure 4.3: Equity Ratios for Connected Vehicles scenario for various levels of market penetration.

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 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 4.3.3.(b) of this report. Vehicle automation technology is assumed to be advanced enough (levels 4 and 5) by the 2040s, with mass market adoption taking place in the 2050s (Section 3.4, Table 3.2). Therefore, the analysis of vehicle automation impact 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.

The results of the analysis suggest that there will be significant disparity in highway expenditures between the AV scenario and the base case at all levels of market penetration. This disparity grows with the increasing level of market penetration and could 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 infrastructure repairs.

Furthermore, the increase in overall travel demand will necessitate investments in new infrastructure to support the growth. Additionally, investments in AV sibling technology (connectivity) and other smart infrastructure to support automation operations, will cause further increase in infrastructure expenditure.

Table 4.3: Total annual highway expenditure estimates in the AV-only era from 2040s (low market penetration) to late 2070s (high market penetration)

	Total Annual Highway Expenditures for AV Scenario			
Year	Base Case	Lower Estimate	Average	Upper Estimate
2040	$2,826,098,000	$2,826,098,000	$2,826,098,000	$2,826,098,000
2041	$2,847,715,000	$2,847,871,000	$2,847,949,000	$2,848,027,000
2042	$2,869,198,000	$2,869,580,000	$2,869,771,000	$2,869,962,000
2043	$2,890,552,000	$2,891,251,000	$2,891,601,000	$2,891,951,000
2044	$2,911,777,000	$2,912,915,000	$2,913,484,000	$2,914,053,000
2045	$2,932,876,000	$2,934,610,000	$2,935,477,000	$2,936,344,000
2046	$2,953,852,000	$2,956,383,000	$2,957,648,000	$2,958,912,000
2047	$2,974,707,000	$2,978,290,000	$2,980,080,000	$2,981,870,000
2048	$2,995,445,000	$3,000,400,000	$3,002,875,000	$3,005,348,000
2049	$3,016,068,000	$3,022,790,000	$3,026,147,000	$3,029,500,000
2050	$3,036,578,000	$3,045,551,000	$3,050,030,000	$3,054,503,000
2051	$3,056,980,000	$3,068,782,000	$3,074,670,000	$3,080,549,000
2052	$3,077,276,000	$3,092,590,000	$3,100,224,000	$3,107,845,000
2053	$3,097,469,000	$3,117,080,000	$3,126,851,000	$3,136,599,000
2054	$3,117,563,000	$3,142,356,000	$3,154,699,000	$3,167,007,000
2055	$3,137,559,000	$3,168,504,000	$3,183,895,000	$3,199,234,000
2056	$3,157,463,000	$3,195,586,000	$3,214,529,000	$3,233,397,000
2057	$3,177,276,000	$3,223,630,000	$3,246,639,000	$3,269,544,000
2058	$3,197,002,000	$3,252,623,000	$3,280,202,000	$3,307,640,000
2059	$3,216,645,000	$3,282,504,000	$3,315,127,000	$3,347,566,000
2060	$3,236,207,000	$3,313,172,000	$3,351,259,000	$3,389,116,000
2061	$3,255,692,000	$3,344,488,000	$3,388,393,000	$3,432,019,000
2062	$3,275,103,000	$3,376,290,000	$3,426,288,000	$3,475,959,000
2063	$3,294,442,000	$3,408,407,000	$3,464,689,000	$3,520,606,000
2064	$3,313,715,000	$3,440,673,000	$3,503,353,000	$3,565,637,000
2065	$3,332,922,000	$3,472,939,000	$3,542,060,000	$3,610,766,000
2066	$3,352,068,000	$3,505,082,000	$3,580,627,000	$3,655,756,000
2067	$3,371,156,000	$3,537,007,000	$3,618,917,000	$3,700,424,000
2068	$3,390,188,000	$3,568,653,000	$3,656,836,000	$3,744,647,000
2069	$3,409,168,000	$3,599,982,000	$3,694,330,000	$3,788,351,000
2070	$3,428,099,000	$3,630,982,000	$3,731,378,000	$3,831,508,000
2071	$3,446,983,000	$3,661,659,000	$3,767,987,000	$3,874,125,000
2072	$3,465,823,000	$3,692,030,000	$3,804,184,000	$3,916,230,000
2073	$3,484,622,000	$3,722,125,000	$3,840,006,000	$3,957,874,000
2074	$3,503,383,000	$3,751,975,000	$3,875,500,000	$3,999,112,000
2075	$3,522,108,000	$3,781,616,000	$3,910,716,000	$4,040,009,000
2076	$3,540,800,000	$3,811,085,000	$3,945,706,000	$4,080,626,000
2077	$3,559,462,000	$3,840,415,000	$3,980,517,000	$4,121,025,000
2078	$3,578,096,000	$3,869,639,000	$4,015,196,000	$4,161,263,000
2079	$3,596,703,000	$3,898,789,000	$4,049,784,000	$4,201,392,000

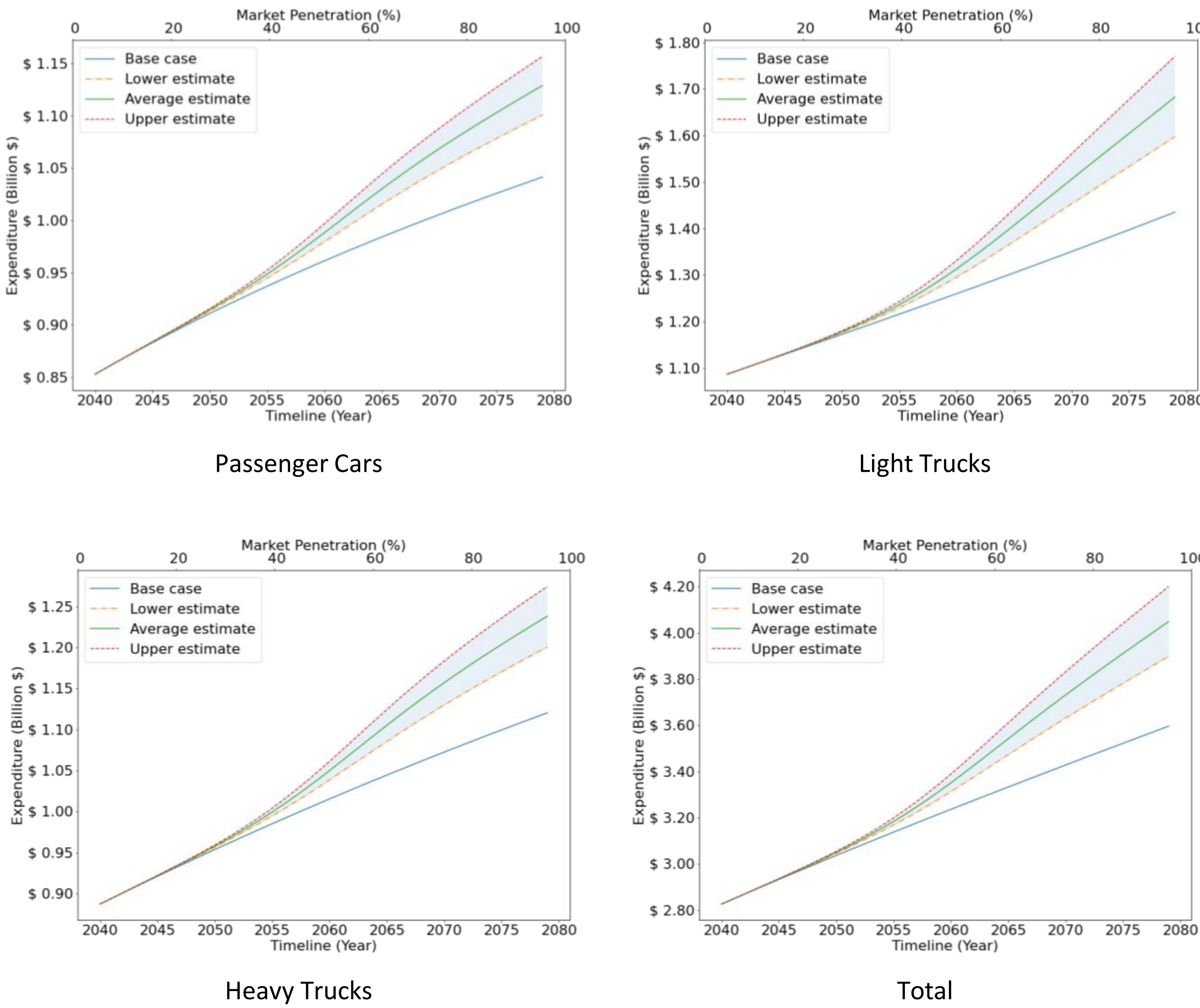


Figure 4.4: Total annual highway expenditures for AV-only scenario, from 2040s (low market penetration) to late 2070s (high market penetration)

b. <u>Highway Revenues</u>

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 generally slightly superior to that of non-automated vehicles. 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 to the base case, at all levels of market penetration.

Table 4.4: Total annual highway revenue estimates in the AV-only era, from 2040s (low market penetration) to late 2070s (high market penetration)

	Total Annual Revenues for AV Scenario			
Year	Base Case	Lower Estimate	Average	Upper Estimate
2040	$2,739,297,000	$2,739,297,000	$2,739,297,000	$2,739,297,000
2041	$2,760,807,000	$2,760,879,000	$2,760,915,000	$2,760,950,000
2042	$2,782,317,000	$2,782,494,000	$2,782,582,000	$2,782,670,000
2043	$2,803,827,000	$2,804,152,000	$2,804,315,000	$2,804,478,000
2044	$2,825,337,000	$2,825,870,000	$2,826,136,000	$2,826,402,000
2045	$2,846,847,000	$2,847,663,000	$2,848,071,000	$2,848,479,000
2046	$2,868,357,000	$2,869,555,000	$2,870,154,000	$2,870,753,000
2047	$2,889,867,000	$2,891,573,000	$2,892,425,000	$2,893,278,000
2048	$2,911,377,000	$2,913,749,000	$2,914,935,000	$2,916,121,000
2049	$2,932,887,000	$2,936,124,000	$2,937,742,000	$2,939,360,000
2050	$2,954,398,000	$2,958,742,000	$2,960,914,000	$2,963,086,000
2051	$2,975,908,000	$2,981,654,000	$2,984,527,000	$2,987,400,000
2052	$2,997,418,000	$3,004,915,000	$3,008,664,000	$3,012,412,000
2053	$3,018,928,000	$3,028,582,000	$3,033,409,000	$3,038,237,000
2054	$3,040,438,000	$3,052,710,000	$3,058,846,000	$3,064,982,000
2055	$3,061,948,000	$3,077,347,000	$3,085,047,000	$3,092,747,000
2056	$3,083,458,000	$3,102,531,000	$3,112,068,000	$3,121,604,000
2057	$3,104,968,000	$3,128,281,000	$3,139,937,000	$3,151,593,000
2058	$3,126,478,000	$3,154,594,000	$3,168,653,000	$3,182,711,000
2059	$3,147,988,000	$3,181,447,000	$3,198,176,000	$3,214,906,000
2060	$3,169,498,000	$3,208,789,000	$3,228,434,000	$3,248,080,000
2061	$3,191,008,000	$3,236,550,000	$3,259,321,000	$3,282,092,000
2062	$3,212,518,000	$3,264,646,000	$3,290,710,000	$3,316,774,000
2063	$3,234,028,000	$3,292,986,000	$3,322,465,000	$3,351,944,000
2064	$3,255,538,000	$3,321,478,000	$3,354,447,000	$3,387,417,000
2065	$3,277,048,000	$3,350,038,000	$3,386,533,000	$3,423,027,000
2066	$3,298,558,000	$3,378,595,000	$3,418,613,000	$3,458,631,000
2067	$3,320,068,000	$3,407,092,000	$3,450,604,000	$3,494,116,000
2068	$3,341,578,000	$3,435,488,000	$3,482,443,000	$3,529,398,000
2069	$3,363,088,000	$3,463,757,000	$3,514,092,000	$3,564,427,000
2070	$3,384,598,000	$3,491,886,000	$3,545,530,000	$3,599,174,000
2071	$3,406,108,000	$3,519,870,000	$3,576,751,000	$3,633,632,000
2072	$3,427,618,000	$3,547,715,000	$3,607,764,000	$3,667,812,000
2073	$3,449,128,000	$3,575,430,000	$3,638,581,000	$3,701,731,000
2074	$3,470,638,000	$3,603,028,000	$3,669,222,000	$3,735,417,000
2075	$3,492,148,000	$3,630,523,000	$3,699,711,000	$3,768,898,000
2076	$3,513,658,000	$3,657,932,000	$3,730,069,000	$3,802,206,000
2077	$3,535,168,000	$3,685,270,000	$3,760,321,000	$3,835,372,000
2078	$3,556,678,000	$3,712,552,000	$3,790,488,000	$3,868,425,000
2079	$3,578,189,000	$3,739,790,000	$3,820,591,000	$3,901,392,000

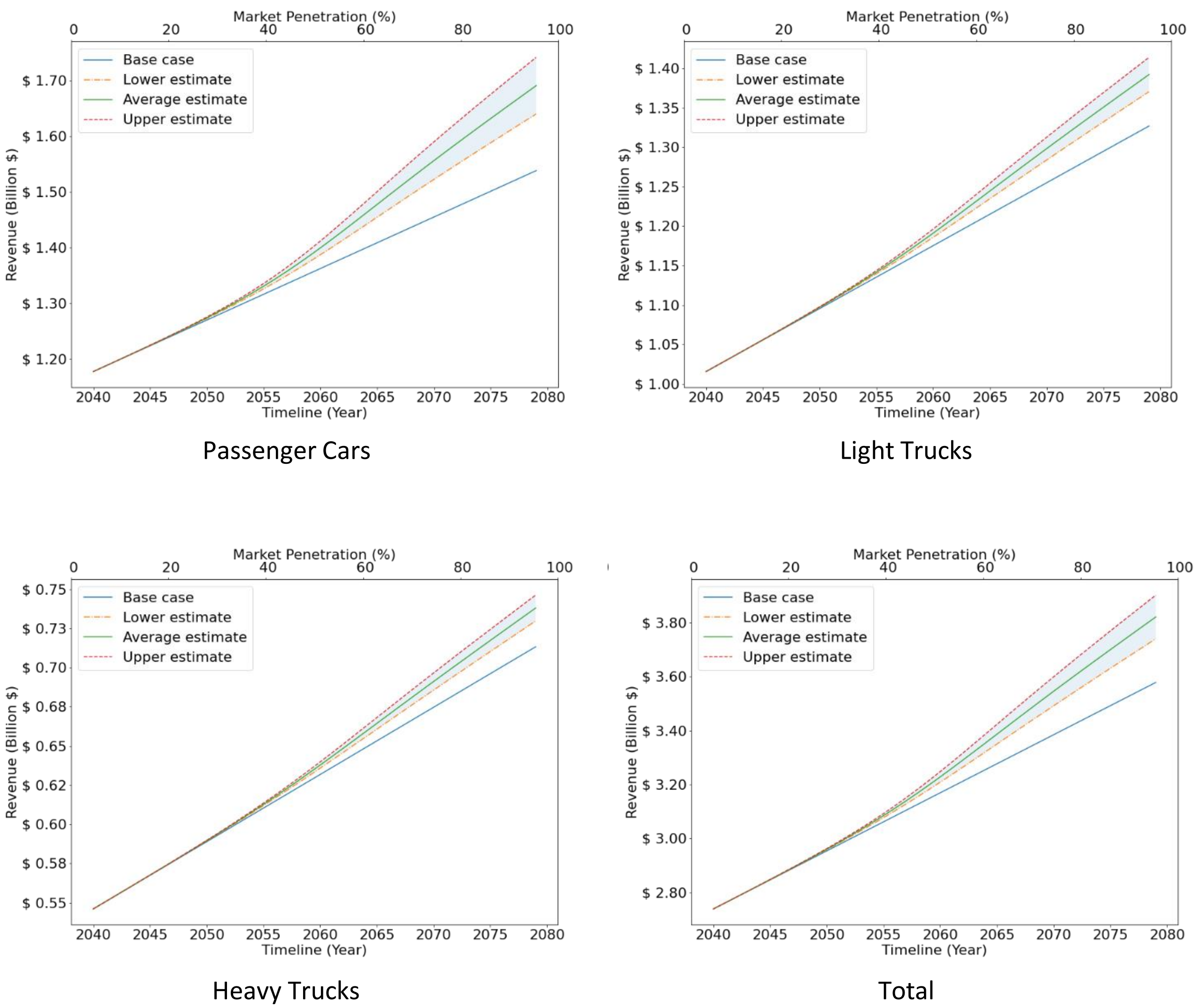
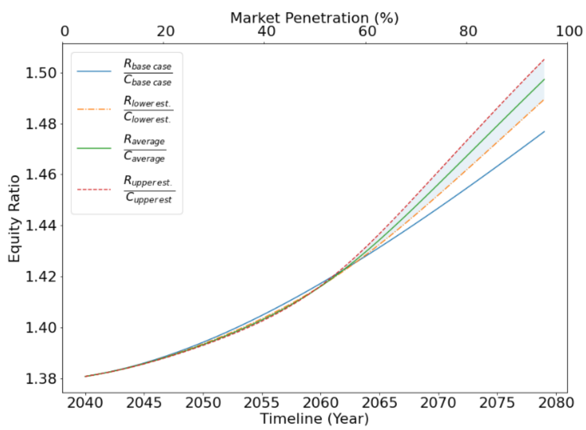


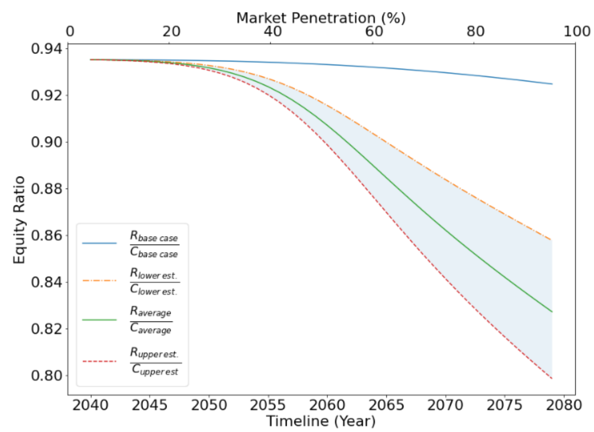
Figure 4.5: Total Annual Highway Revenues for the AV-only scenario, from 2040s (low market penetration) to late 2070s (high market penetration)

c. User Equity Analysis

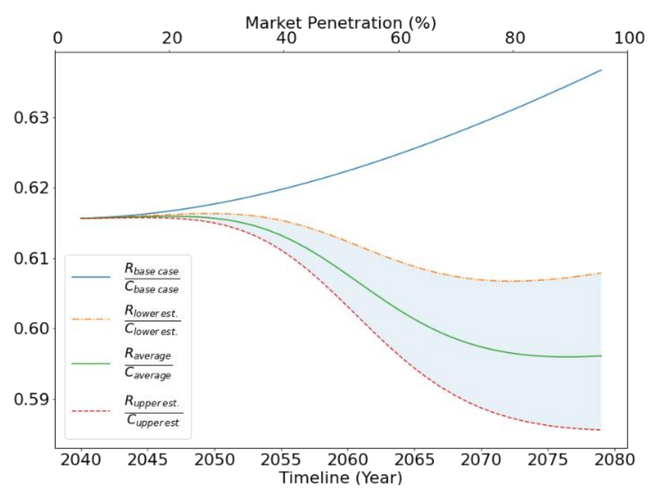
This section reports the equity ratios in the era of vehicle automation, and the changes thereof, based on the reported changes in expenditures and revenues reported in the previous section. These are summarized in Figure 4.6. The results indicate that across the various levels of market penetration, 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 cars 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.



Passenger Cars



Light Trucks



Heavy Trucks

Figure 4.6: Equity ratios for the AV-only scenario, from 2040s (low market penetration) to late 2070s (high market penetration)

4.3.3. Electric vehicles (EV)

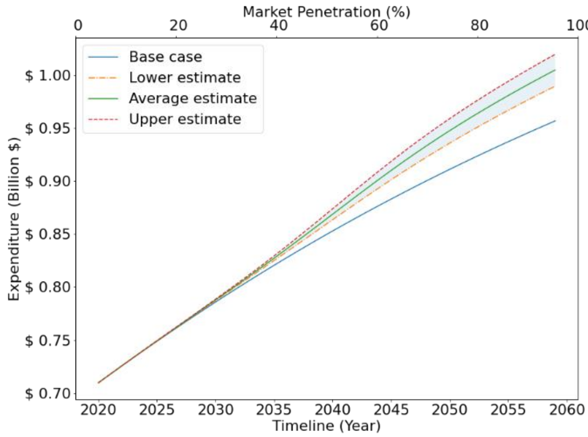
Vehicle electrification, and its impacts on highway expenditures and revenues are analyzed in two scenarios: automated electric vehicles and non-automated electric vehicles. Non-automated electric vehicles are already in use today. In addition, although EV costs are still high (and therefore impede mass market adoption), these costs have been reducing steadily (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 that anticipated for their automated-vehicle counterparts. The impacts of both automated and non-automated electric vehicles are reported in this section.

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

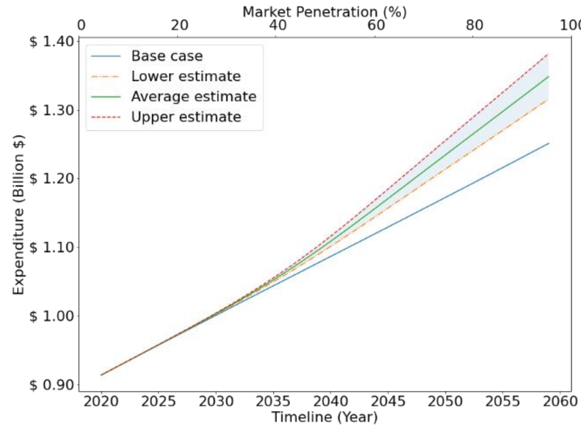
As described in Section 3.4.3.(a), the human-driven electric vehicle is being considered for analysis even though vehicle electrification and automation are expected to develop in tandem. The reason for this consideration is the difference in the technologies that drive automation and electrification. 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 important to consider the impacts of electric human-driven vehicles on highway expenditures and revenues. The scenarios and the anticipated impacts on highway travel patterns, expenditures and revenues are highlighted in Table 3.3.

i. Highway Expenditures

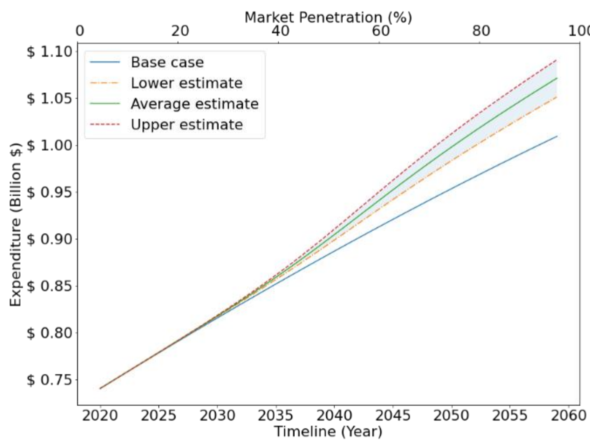
Vehicle electrification, *per se*, is not expected to significantly affect individual travel patterns. There is no reason to expect that people will travel more or less than usual simply because they own or operate an electric vehicle. Highway expenditures, however, are expected to increase because growing 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 in response to vehicle connectivity and low-level automation features. The impacts of electrification on highway expenditures are reported herein:



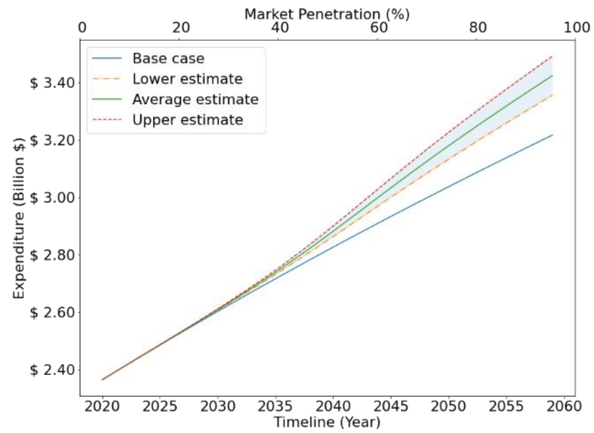
Passenger Cars



Light Trucks



Heavy Trucks



Total

Figure 4.7: Total annual highway expenditures for the EV-only scenario, from 2020s (low market penetration) to late 2050s (high market penetration)

Table 4.5: Total annual highway expenditures estimates in the era of EVs from 2020s (low market penetration) to late 2050s (high market penetration)

	Total Annual Expenditures for EV Scenario			
Year	Base Case	Lower Estimate	Average	Upper Estimate
2020	$2,364,041,000	$2,364,041,000	$2,364,041,000	$2,364,041,000
2021	$2,388,489,000	$2,388,563,000	$2,388,601,000	$2,388,638,000
2022	$2,412,802,000	$2,412,985,000	$2,413,076,000	$2,413,168,000
2023	$2,436,979,000	$2,437,315,000	$2,437,483,000	$2,437,650,000
2024	$2,461,018,000	$2,461,565,000	$2,461,838,000	$2,462,111,000
2025	$2,484,916,000	$2,485,750,000	$2,486,166,000	$2,486,583,000
2026	$2,508,671,000	$2,509,890,000	$2,510,499,000	$2,511,108,000
2027	$2,532,284,000	$2,534,010,000	$2,534,873,000	$2,535,736,000
2028	$2,555,751,000	$2,558,141,000	$2,559,335,000	$2,560,529,000
2029	$2,579,074,000	$2,582,318,000	$2,583,939,000	$2,585,559,000
2030	$2,602,251,000	$2,606,583,000	$2,608,746,000	$2,610,909,000
2031	$2,625,282,000	$2,630,981,000	$2,633,828,000	$2,636,672,000
2032	$2,648,168,000	$2,655,564,000	$2,659,256,000	$2,662,945,000
2033	$2,670,908,000	$2,680,380,000	$2,685,107,000	$2,689,827,000
2034	$2,693,503,000	$2,705,477,000	$2,711,449,000	$2,717,411,000
2035	$2,715,955,000	$2,730,895,000	$2,738,342,000	$2,745,772,000
2036	$2,738,264,000	$2,756,662,000	$2,765,825,000	$2,774,964,000
2037	$2,760,431,000	$2,782,789,000	$2,793,914,000	$2,805,003,000
2038	$2,782,458,000	$2,809,265,000	$2,822,591,000	$2,835,867,000
2039	$2,804,347,000	$2,836,059,000	$2,851,808,000	$2,867,486,000
2040	$2,826,098,000	$2,863,118,000	$2,881,482,000	$2,899,751,000
2041	$2,847,715,000	$2,890,371,000	$2,911,507,000	$2,932,519,000
2042	$2,869,198,000	$2,917,737,000	$2,941,761,000	$2,965,625,000
2043	$2,890,552,000	$2,945,131,000	$2,972,113,000	$2,998,898,000
2044	$2,911,777,000	$2,972,469,000	$3,002,440,000	$3,032,174,000
2045	$2,932,876,000	$2,999,679,000	$3,032,634,000	$3,065,308,000
2046	$2,953,852,000	$3,026,700,000	$3,062,604,000	$3,098,183,000
2047	$2,974,707,000	$3,053,490,000	$3,092,285,000	$3,130,713,000
2048	$2,995,445,000	$3,080,017,000	$3,121,633,000	$3,162,839,000
2049	$3,016,068,000	$3,106,268,000	$3,150,625,000	$3,194,533,000
2050	$3,036,578,000	$3,132,238,000	$3,179,255,000	$3,225,787,000
2051	$3,056,980,000	$3,157,933,000	$3,207,532,000	$3,256,613,000
2052	$3,077,276,000	$3,183,366,000	$3,235,472,000	$3,287,033,000
2053	$3,097,469,000	$3,208,552,000	$3,263,100,000	$3,317,080,000
2054	$3,117,563,000	$3,233,511,000	$3,290,444,000	$3,346,789,000
2055	$3,137,559,000	$3,258,265,000	$3,317,533,000	$3,376,199,000
2056	$3,157,463,000	$3,282,833,000	$3,344,396,000	$3,405,349,000
2057	$3,177,276,000	$3,307,235,000	$3,371,063,000	$3,434,276,000
2058	$3,197,002,000	$3,331,492,000	$3,397,561,000	$3,463,015,000
2059	$3,216,645,000	$3,355,621,000	$3,423,916,000	$3,491,601,000

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 cost 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.

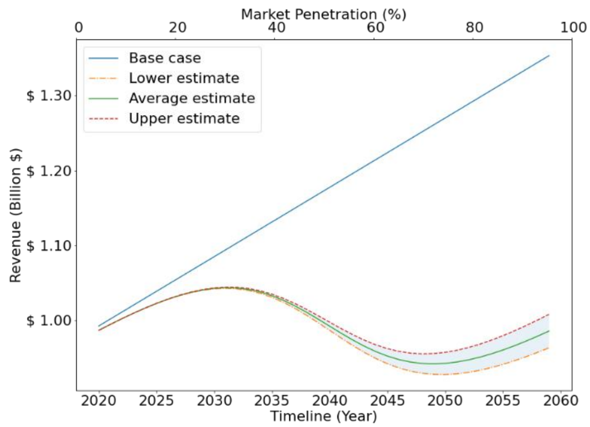
ii. Highway Revenues

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

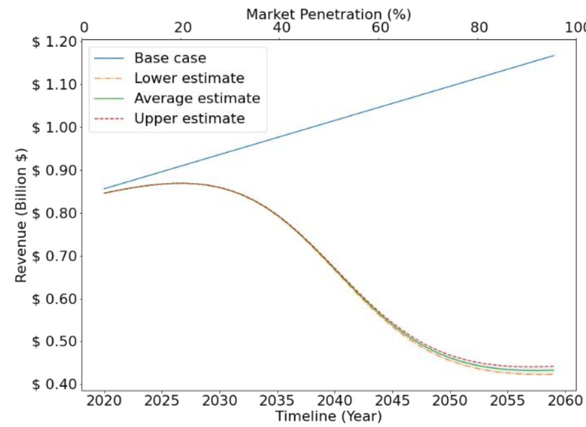
Table 4.6 and Figure 4.8 present the results of the impacts of non-automated electric vehicles on revenues. From Table 4.6, it can be observed that the total revenues generated under electric vehicles is significantly lower than that for the base case. At low market penetration levels, the revenues generated 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: Total annual highway revenue estimates in the era of EVs from 2020s (low market penetration) to late 2050s (high market penetration)

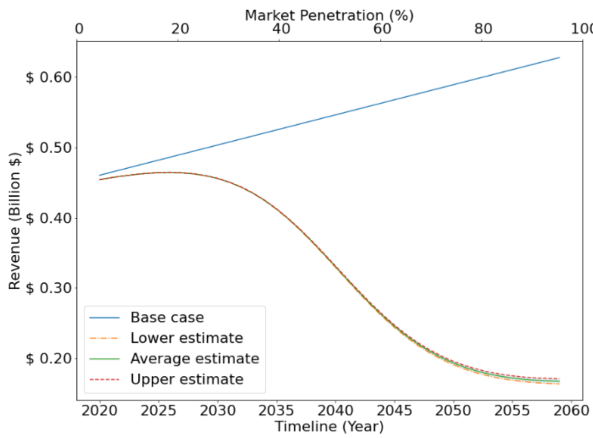
	Total Annual Highway Revenues for EV Scenario			
Year	Base Case	Lower Estimate	Average	Upper Estimate
2020	$2,309,097,000	$2,286,665,000	$2,286,665,000	$2,286,665,000
2021	$2,330,607,000	$2,302,969,000	$2,302,988,000	$2,303,003,000
2022	$2,352,117,000	$2,318,098,000	$2,318,144,000	$2,318,181,000
2023	$2,373,627,000	$2,331,803,000	$2,331,888,000	$2,331,957,000
2024	$2,395,137,000	$2,343,791,000	$2,343,929,000	$2,344,042,000
2025	$2,416,647,000	$2,353,716,000	$2,353,928,000	$2,354,101,000
2026	$2,438,157,000	$2,361,184,000	$2,361,495,000	$2,361,749,000
2027	$2,459,667,000	$2,365,744,000	$2,366,186,000	$2,366,549,000
2028	$2,481,177,000	$2,366,898,000	$2,367,512,000	$2,368,017,000
2029	$2,502,687,000	$2,364,109,000	$2,364,944,000	$2,365,634,000
2030	$2,524,197,000	$2,356,819,000	$2,357,937,000	$2,358,864,000
2031	$2,545,707,000	$2,344,477,000	$2,345,950,000	$2,347,178,000
2032	$2,567,217,000	$2,326,582,000	$2,328,495,000	$2,330,099,000
2033	$2,588,727,000	$2,302,732,000	$2,305,183,000	$2,307,249,000
2034	$2,610,237,000	$2,272,688,000	$2,275,784,000	$2,278,413,000
2035	$2,631,747,000	$2,236,433,000	$2,240,291,000	$2,243,592,000
2036	$2,653,257,000	$2,194,235,000	$2,198,975,000	$2,203,067,000
2037	$2,674,767,000	$2,146,680,000	$2,152,423,000	$2,157,429,000
2038	$2,696,277,000	$2,094,681,000	$2,101,542,000	$2,107,585,000
2039	$2,717,787,000	$2,039,440,000	$2,047,527,000	$2,054,724,000
2040	$2,739,297,000	$1,982,382,000	$1,991,784,000	$2,000,243,000
2041	$2,760,807,000	$1,925,035,000	$1,935,827,000	$1,945,641,000
2042	$2,782,317,000	$1,868,915,000	$1,881,150,000	$1,892,395,000
2043	$2,803,827,000	$1,815,401,000	$1,829,114,000	$1,841,847,000
2044	$2,825,337,000	$1,765,640,000	$1,780,849,000	$1,795,105,000
2045	$2,846,847,000	$1,720,488,000	$1,737,195,000	$1,752,995,000
2046	$2,868,357,000	$1,680,493,000	$1,698,689,000	$1,716,036,000
2047	$2,889,867,000	$1,645,908,000	$1,665,575,000	$1,684,459,000
2048	$2,911,377,000	$1,616,734,000	$1,637,849,000	$1,658,254,000
2049	$2,932,887,000	$1,592,777,000	$1,615,316,000	$1,637,215,000
2050	$2,954,398,000	$1,573,703,000	$1,597,638,000	$1,621,006,000
2051	$2,975,908,000	$1,559,091,000	$1,584,398,000	$1,609,204,000
2052	$2,997,418,000	$1,548,479,000	$1,575,134,000	$1,601,352,000
2053	$3,018,928,000	$1,541,396,000	$1,569,378,000	$1,596,981,000
2054	$3,040,438,000	$1,537,387,000	$1,566,679,000	$1,595,642,000
2055	$3,061,948,000	$1,536,027,000	$1,566,613,000	$1,596,918,000
2056	$3,083,458,000	$1,536,931,000	$1,568,800,000	$1,600,428,000
2057	$3,104,968,000	$1,539,756,000	$1,572,900,000	$1,605,837,000
2058	$3,126,478,000	$1,544,204,000	$1,578,615,000	$1,612,851,000
2059	$3,147,988,000	$1,550,014,000	$1,585,689,000	$1,621,216,000



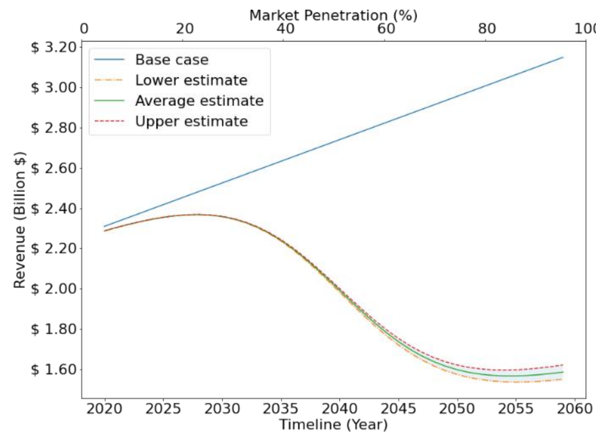
Passenger Cars



Light Trucks



Heavy Trucks



Total

Figure 4.8: Total annual highway revenues for the EV-only scenario

In all the scenarios considered, the rate of market penetration of the emerging technology is assumed to follow the sigmoid curve. As a result, the corresponding impacts follow a nonlinear response. Total highway revenues are composed of both fuel and non-fuel revenues. Each of these individual components depends on the VMT in a nonlinear way, which in turn depends on the market penetration rate. Therefore, the combined revenue may grow or decline at a given rate depending on which factors dominate. For example, Figure 4.8 suggests that revenues for passenger cars decline as the market penetration rate of electric vehicles increases. However, this decline is not monotonous as they begin to rebound around the 2050s. This is because as the VMT increases, part of this increased VMT can be attributed to new cars being purchased. This in turn results in an increase in non-fuel revenues (registrations, taxes, etc.). At a certain point, the rate of increase of these revenues outpaces the decline in fuel revenues resulting from electrification. A similar trend can be observed to a lesser extent in light-and heavy-duty trucks. Although this phenomenon is enough to reverse the decline in revenues, it is not enough to bridge the gap.

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 vehicle classes is similar to those observed in the cases of vehicle connectivity only and automation only. Passenger cars are observed to be overpaying their share while light-and heavy-duty trucks underpay. These changes in equity ratio reflect 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.

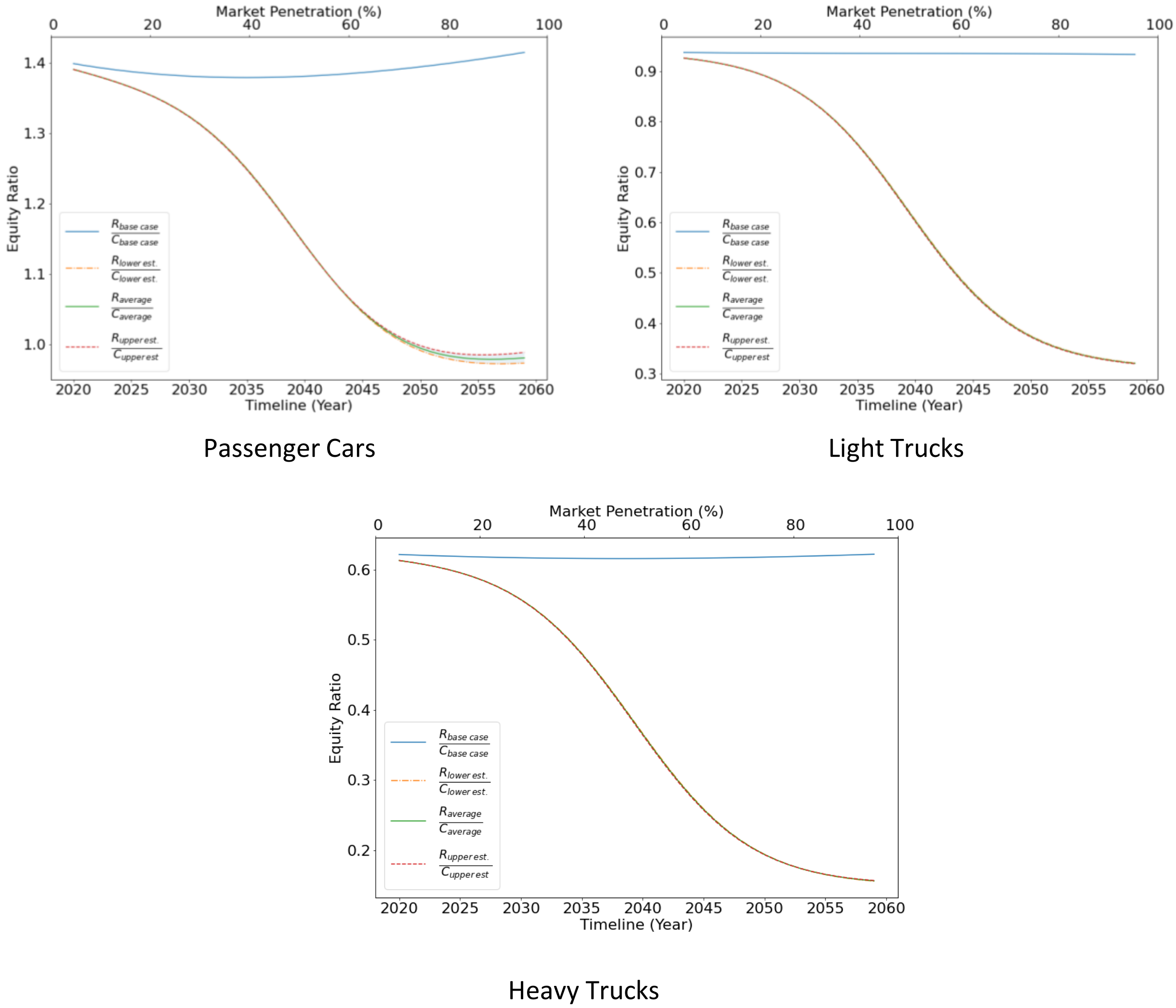


Figure 4.9: Equity ratios for the EV-only scenario

4.3.3.(b) Automated Electric Vehicles (EAVs)

Even though the two technologies (automation and electrification) are not interdependent, the timing of their developments is such that companies and vehicle manufacturers are investing in both simultaneously. It is realistic to have autonomous vehicles with electric propulsion.

To assess the impact of electric autonomous vehicles on highway expenditures and revenues, this study used the assumptions established in Section 3.4.3.(c): Vehicle automation is assumed to increase overall travel as outlined in Sections 3.4.3.(b) and 3.5: This study also assumes VMT increases of 10%, 15% and 20% due to low, moderate and high market penetration of vehicle automation, respectively. This assumption is reasonable due to the benefits of automation (see Sections 3.4 and 3.5). Also, AV cause (a) an increase in road capacity because they operate with smaller headways compared with human drivers, (b) reduced congestion that results from smooth driving and (c) potential for platooning. It has been suggested that these benefits cause induced demand, thus, increase in overall travel and VMT.

Electric propulsion is expected to impact the travel patterns only marginally 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 results for the various levels of market penetration.

i. Highway Expenditures

In the era of automated electric vehicles, the forecast highway travel patterns, and consequently highway expenditures are similar to those observed for 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 purposes of analytical simplicity, this report assumes that the changes in highway travel patterns and the resulting increase in highway expenditures will be nearly identical for automated electric vehicles as observed 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).

ii. Highway Revenues

In the era of automated electric vehicles highway revenues 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.4.3.3.(a).ii for the detailed results.

iii. User Equity Analysis

Automated electric vehicles represent the worst-case scenario of the emerging technologies in the context of highway expenditures and revenues, for two reasons. First, automation drive up the overall travel demand, and with it, expenditures on highway infrastructure development and upkeep. Second, electrification will significantly reduce the revenues generated from fuel tax. The combination of the two technologies results in the worst of any of the emerging technological scenarios, as evidenced by the equity ratios (Figure 4.10). The equity ratios for the scenario are much lower compared to the base case, for all vehicle classes. Similar to the trend observed in the non-automated electric vehicles scenario, the equity ratios are close to those of the base at very low EAV market penetration. As the market penetration increases, however, the equity ratios degrade sharply. Also, there is a sharp drop in revenues resulting from loss of fuel revenues due to electrification. The equity ratios suggest that in this scenario passenger cars overpay their share of the responsibility throughout the period of analysis, although the degree of overpay reduces with increasing EAV market penetration. Light and heavy-duty trucks EAV consistently underpay their share, and the degree of underpay worsens with increasing EAV market penetration.

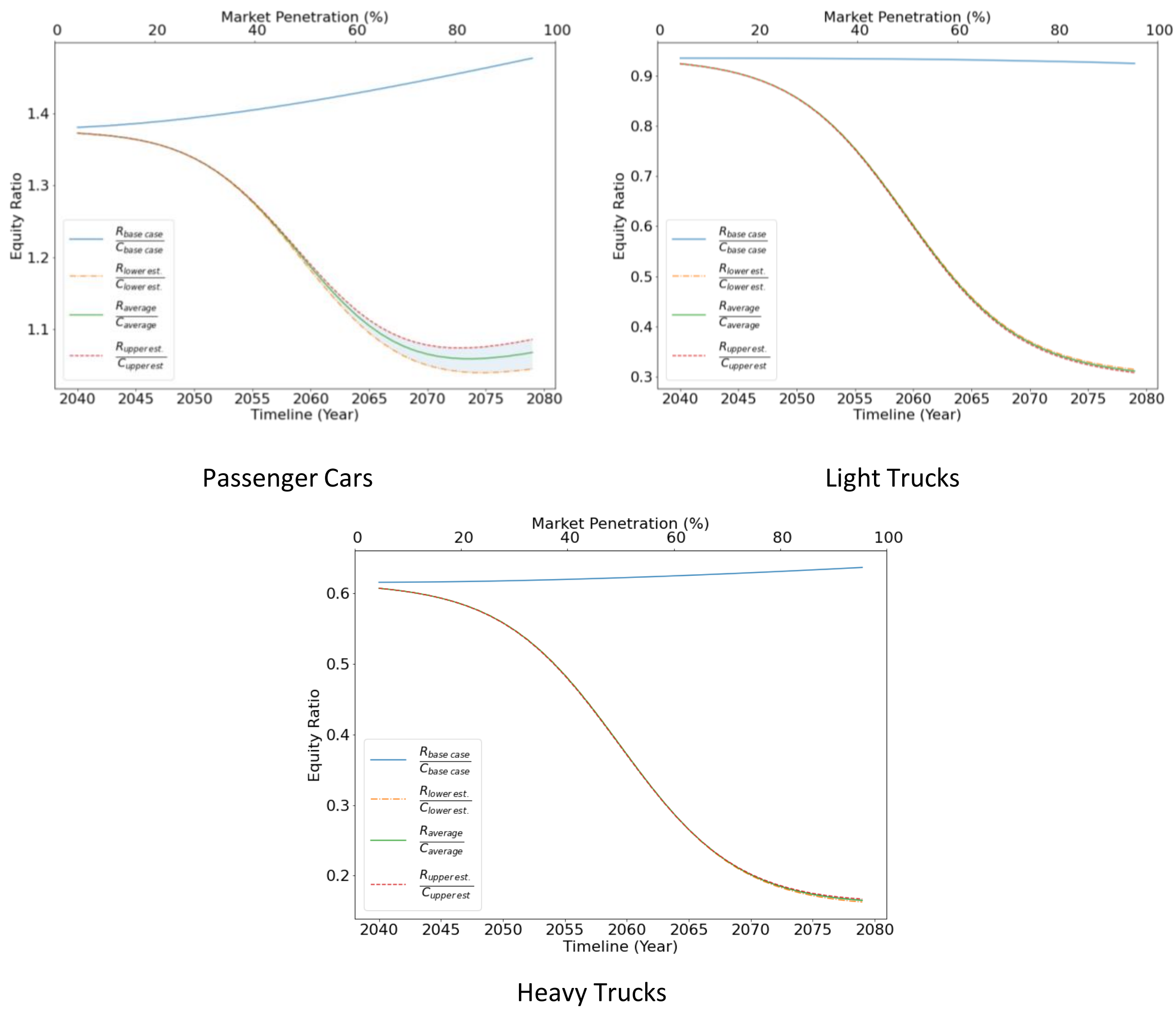


Figure 4.10: Equity ratios for the electric automated vehicle scenario, from 2020s (low market penetration) to late 2070s (high market penetration)

4.3.4. Connected and Automated Vehicles (CAV) (Gasoline powered)

In previous sections, this report documented how vehicle connectivity, automation, and electrification, separately or concurrently, could yield varying impacts on highway expenditures, revenues, and equity. In each case, this report 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 (but not electrified) 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, et al., 2020b; 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 et al., 2020b). The subsequent estimated changes due to autonomous vehicles are based on assumed AV market penetration and associated VMT and ESAL changes (see Sections Chapter 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, 2015). 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 in the CAV era will be driven by such investments as connectivity infrastructure, supporting infrastructure for vehicle automation (i.e., cloud computing, cloud storage and other network facilities, and smart highway installations (i.e., traffic lights and message signs). 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: Total annual highway expenditure estimates in the CAV era, from 2040s (low market penetration) to late 2070s (high market penetration)

	Total Annual Expenditures for CAV Scenario			
Year	Base Case	Lower Estimate	Average	Upper Estimate
2040	$2,826,098,000	$2,826,098,000	$2,826,098,000	$2,826,098,000
2041	$2,847,715,000	$2,847,886,000	$2,848,058,000	$2,848,229,000
2042	$2,869,198,000	$2,869,618,000	$2,870,038,000	$2,870,458,000
2043	$2,890,552,000	$2,891,321,000	$2,892,091,000	$2,892,860,000
2044	$2,911,777,000	$2,913,029,000	$2,914,281,000	$2,915,533,000
2045	$2,932,876,000	$2,934,783,000	$2,936,690,000	$2,938,596,000
2046	$2,953,852,000	$2,956,636,000	$2,959,418,000	$2,962,198,000
2047	$2,974,707,000	$2,978,648,000	$2,982,585,000	$2,986,518,000
2048	$2,995,445,000	$3,000,895,000	$3,006,337,000	$3,011,771,000
2049	$3,016,068,000	$3,023,462,000	$3,030,841,000	$3,038,206,000
2050	$3,036,578,000	$3,046,447,000	$3,056,291,000	$3,066,110,000
2051	$3,056,980,000	$3,069,960,000	$3,082,898,000	$3,095,794,000
2052	$3,077,276,000	$3,094,118,000	$3,110,889,000	$3,127,593,000
2053	$3,097,469,000	$3,119,036,000	$3,140,492,000	$3,161,841,000
2054	$3,117,563,000	$3,144,827,000	$3,171,921,000	$3,198,850,000
2055	$3,137,559,000	$3,171,586,000	$3,205,356,000	$3,238,884,000
2056	$3,157,463,000	$3,199,381,000	$3,240,924,000	$3,282,123,000
2057	$3,177,276,000	$3,228,241,000	$3,278,677,000	$3,328,642,000
2058	$3,197,002,000	$3,258,150,000	$3,318,578,000	$3,378,382,000
2059	$3,216,645,000	$3,289,044,000	$3,360,493,000	$3,431,152,000
2060	$3,236,207,000	$3,320,809,000	$3,404,199,000	$3,486,629,000
2061	$3,255,692,000	$3,353,293,000	$3,449,399,000	$3,544,389,000
2062	$3,275,103,000	$3,386,318,000	$3,495,749,000	$3,603,940,000
2063	$3,294,442,000	$3,419,697,000	$3,542,886,000	$3,664,765,000
2064	$3,313,715,000	$3,453,246,000	$3,590,461,000	$3,726,360,000
2065	$3,332,922,000	$3,486,802,000	$3,638,160,000	$3,788,272,000
2066	$3,352,068,000	$3,520,232,000	$3,685,724,000	$3,850,120,000
2067	$3,371,156,000	$3,553,431,000	$3,732,953,000	$3,911,605,000
2068	$3,390,188,000	$3,586,330,000	$3,779,712,000	$3,972,516,000
2069	$3,409,168,000	$3,618,890,000	$3,825,920,000	$4,032,718,000
2070	$3,428,099,000	$3,651,096,000	$3,871,542,000	$4,092,145,000
2071	$3,446,983,000	$3,682,955,000	$3,916,586,000	$4,150,786,000
2072	$3,465,823,000	$3,714,486,000	$3,961,082,000	$4,208,669,000
2073	$3,484,622,000	$3,745,719,000	$4,005,081,000	$4,265,850,000
2074	$3,503,383,000	$3,776,690,000	$4,048,645,000	$4,322,400,000
2075	$3,522,108,000	$3,807,439,000	$4,091,841,000	$4,378,401,000
2076	$3,540,800,000	$3,838,003,000	$4,134,735,000	$4,433,934,000
2077	$3,559,462,000	$3,868,420,000	$4,177,394,000	$4,489,077,000
2078	$3,578,096,000	$3,898,726,000	$4,219,876,000	$4,543,905,000
2079	$3,596,703,000	$3,928,954,000	$4,262,238,000	$4,598,481,000

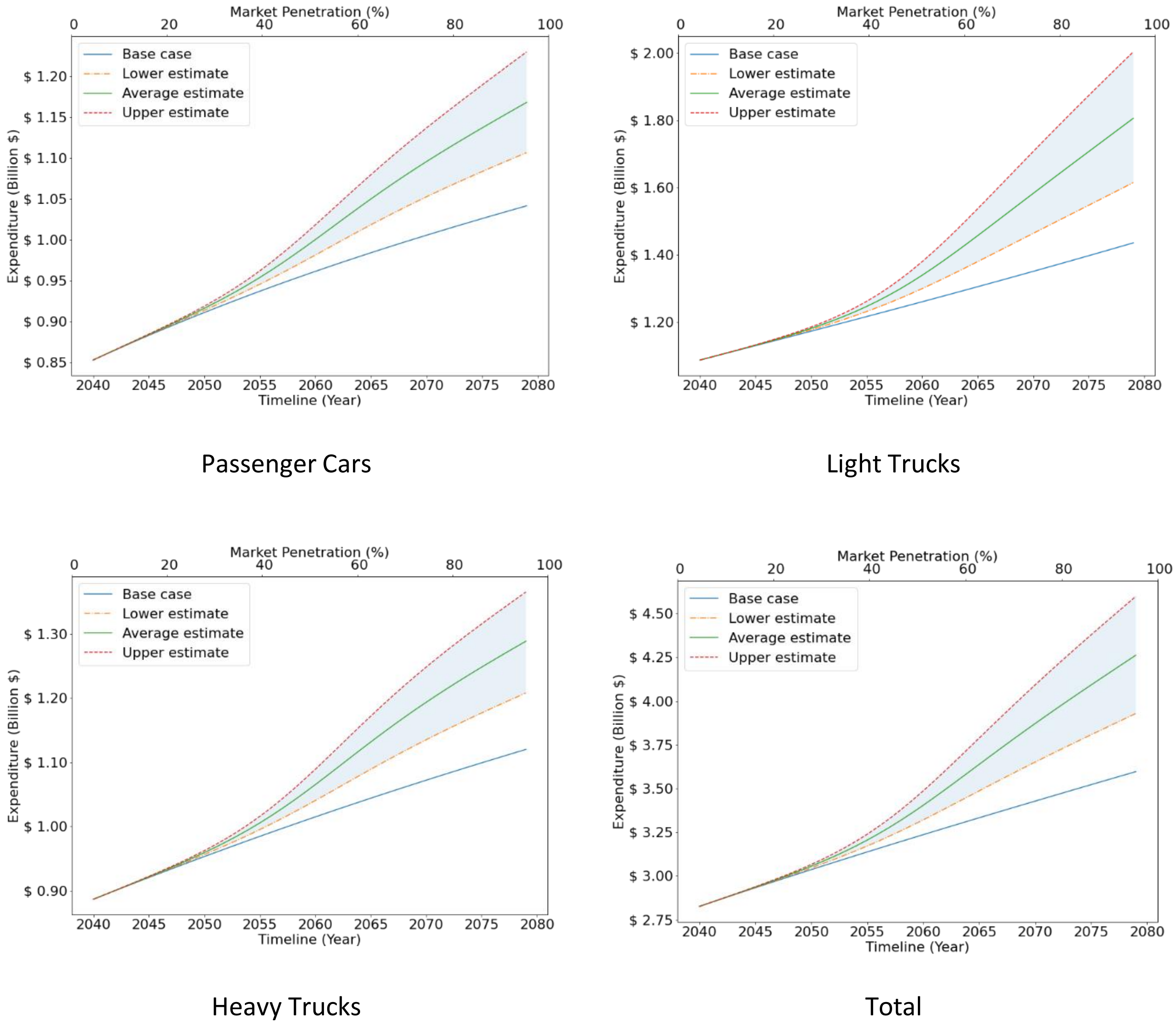


Figure 4.11: Total annual highway expenditures for the CAV scenario, for various levels market penetration

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: Total annual highway revenue estimates in the era of CAVs, from 2040s (low market penetration) to late 2070s (high market penetration)

	Total Annual Highway Revenues for the CAV Scenario			
Year	Base Case	Lower Estimate	Average	Upper Estimate
2040	$2,739,297,000	$2,739,297,000	$2,739,297,000	$2,739,297,000
2041	$2,760,807,000	$2,760,894,000	$2,761,024,000	$2,761,153,000
2042	$2,782,317,000	$2,782,532,000	$2,782,850,000	$2,783,168,000
2043	$2,803,827,000	$2,804,223,000	$2,804,810,000	$2,805,396,000
2044	$2,825,337,000	$2,825,985,000	$2,826,946,000	$2,827,906,000
2045	$2,846,847,000	$2,847,840,000	$2,849,312,000	$2,850,783,000
2046	$2,868,357,000	$2,869,815,000	$2,871,975,000	$2,874,134,000
2047	$2,889,867,000	$2,891,943,000	$2,895,018,000	$2,898,092,000
2048	$2,911,377,000	$2,914,264,000	$2,918,540,000	$2,922,813,000
2049	$2,932,887,000	$2,936,827,000	$2,942,658,000	$2,948,485,000
2050	$2,954,398,000	$2,959,685,000	$2,967,509,000	$2,975,324,000
2051	$2,975,908,000	$2,982,900,000	$2,993,243,000	$3,003,570,000
2052	$2,997,418,000	$3,006,540,000	$3,020,025,000	$3,033,482,000
2053	$3,018,928,000	$3,030,674,000	$3,048,022,000	$3,065,325,000
2054	$3,040,438,000	$3,055,366,000	$3,077,395,000	$3,099,350,000
2055	$3,061,948,000	$3,080,676,000	$3,108,282,000	$3,135,774,000
2056	$3,083,458,000	$3,106,649,000	$3,140,788,000	$3,174,756,000
2057	$3,104,968,000	$3,133,306,000	$3,174,963,000	$3,216,366,000
2058	$3,126,478,000	$3,160,645,000	$3,210,790,000	$3,260,573,000
2059	$3,147,988,000	$3,188,633,000	$3,248,182,000	$3,307,228,000
2060	$3,169,498,000	$3,217,211,000	$3,286,982,000	$3,356,074,000
2061	$3,191,008,000	$3,246,292,000	$3,326,974,000	$3,406,762,000
2062	$3,212,518,000	$3,275,772,000	$3,367,899,000	$3,458,879,000
2063	$3,234,028,000	$3,305,541,000	$3,409,482,000	$3,511,987,000
2064	$3,255,538,000	$3,335,489,000	$3,451,453,000	$3,565,659,000
2065	$3,277,048,000	$3,365,513,000	$3,493,564,000	$3,619,507,000
2066	$3,298,558,000	$3,395,527,000	$3,535,609,000	$3,673,208,000
2067	$3,320,068,000	$3,425,463,000	$3,577,425,000	$3,726,510,000
2068	$3,341,578,000	$3,455,273,000	$3,618,898,000	$3,779,239,000
2069	$3,363,088,000	$3,484,924,000	$3,659,956,000	$3,831,285,000
2070	$3,384,598,000	$3,514,402,000	$3,700,564,000	$3,882,599,000
2071	$3,406,108,000	$3,543,702,000	$3,740,718,000	$3,933,176,000
2072	$3,427,618,000	$3,572,830,000	$3,780,433,000	$3,983,045,000
2073	$3,449,128,000	$3,601,799,000	$3,819,742,000	$4,032,259,000
2074	$3,470,638,000	$3,630,623,000	$3,858,685,000	$4,080,882,000
2075	$3,492,148,000	$3,659,322,000	$3,897,307,000	$4,128,989,000
2076	$3,513,658,000	$3,687,914,000	$3,935,656,000	$4,176,652,000
2077	$3,535,168,000	$3,716,418,000	$3,973,776,000	$4,223,945,000
2078	$3,556,678,000	$3,744,852,000	$4,011,712,000	$4,270,936,000
2079	$3,578,189,000	$3,773,231,000	$4,049,503,000	$4,317,688,000

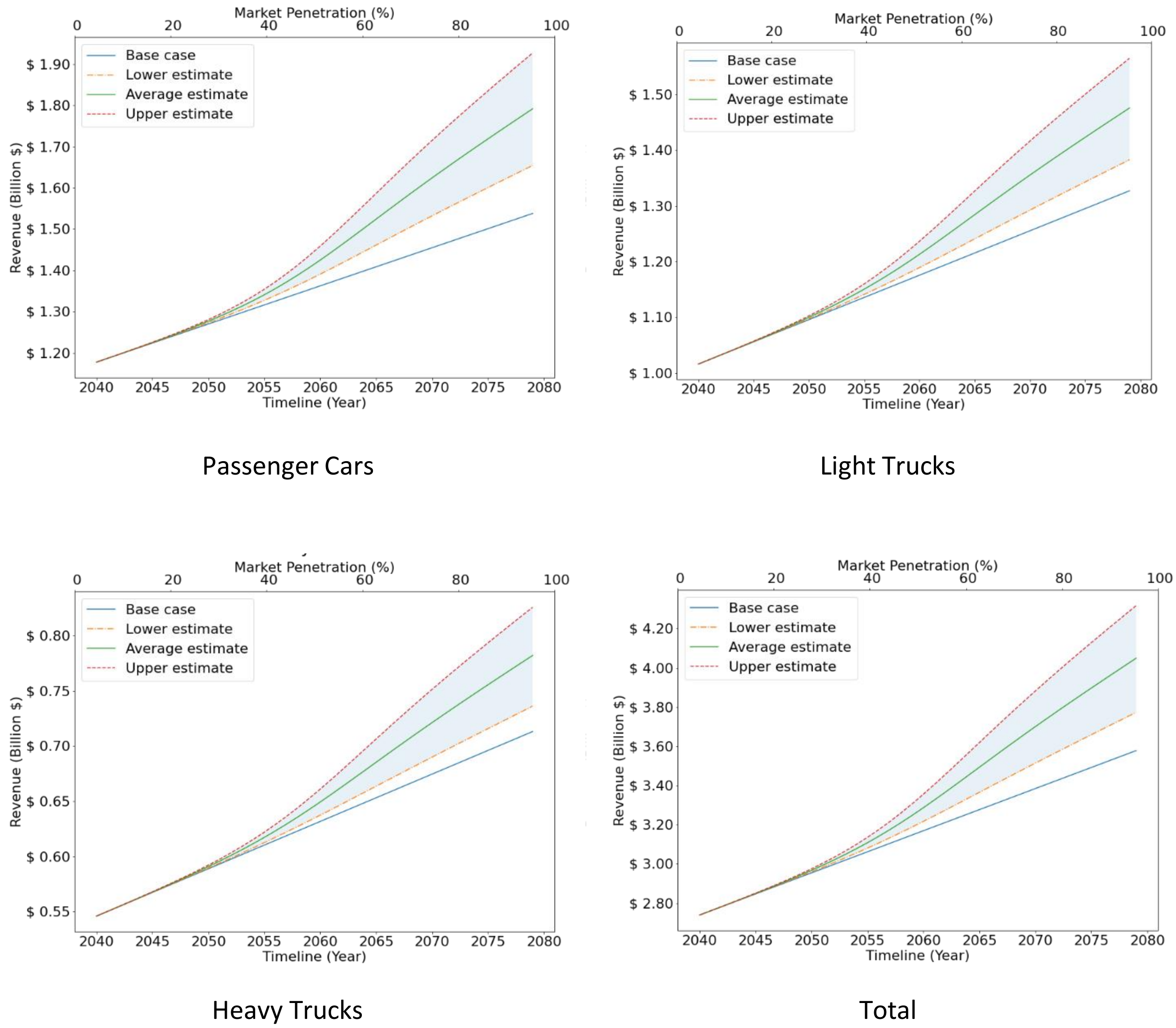


Figure 4.12: Total annual highway revenues for CAV scenario from low market penetration through high market penetration.

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. It is observed that for passenger cars, the equity ratios in the CAV scenario are higher than the base, indicating that the overpay degree for passenger cars is higher for this scenarios compared with the base case. This increase in equity could be attributed to the increased VMT under this scenario, along with the synergistic effects of automation and connectivity, leading to an amplification of their effects. The trend is reversed for light and heavy-duty trucks where the equity ratios are lower for the 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 to passenger cars, generally. This results in the equity ratios declining with increased market penetration because the revenues decline due to increased fuel efficiency. The VMT does not grow fast enough for the non-fuel revenues to counteract the decrease in fuel revenues, the expenditures grow faster than the revenues, therefore resulting in declining equity ratios.

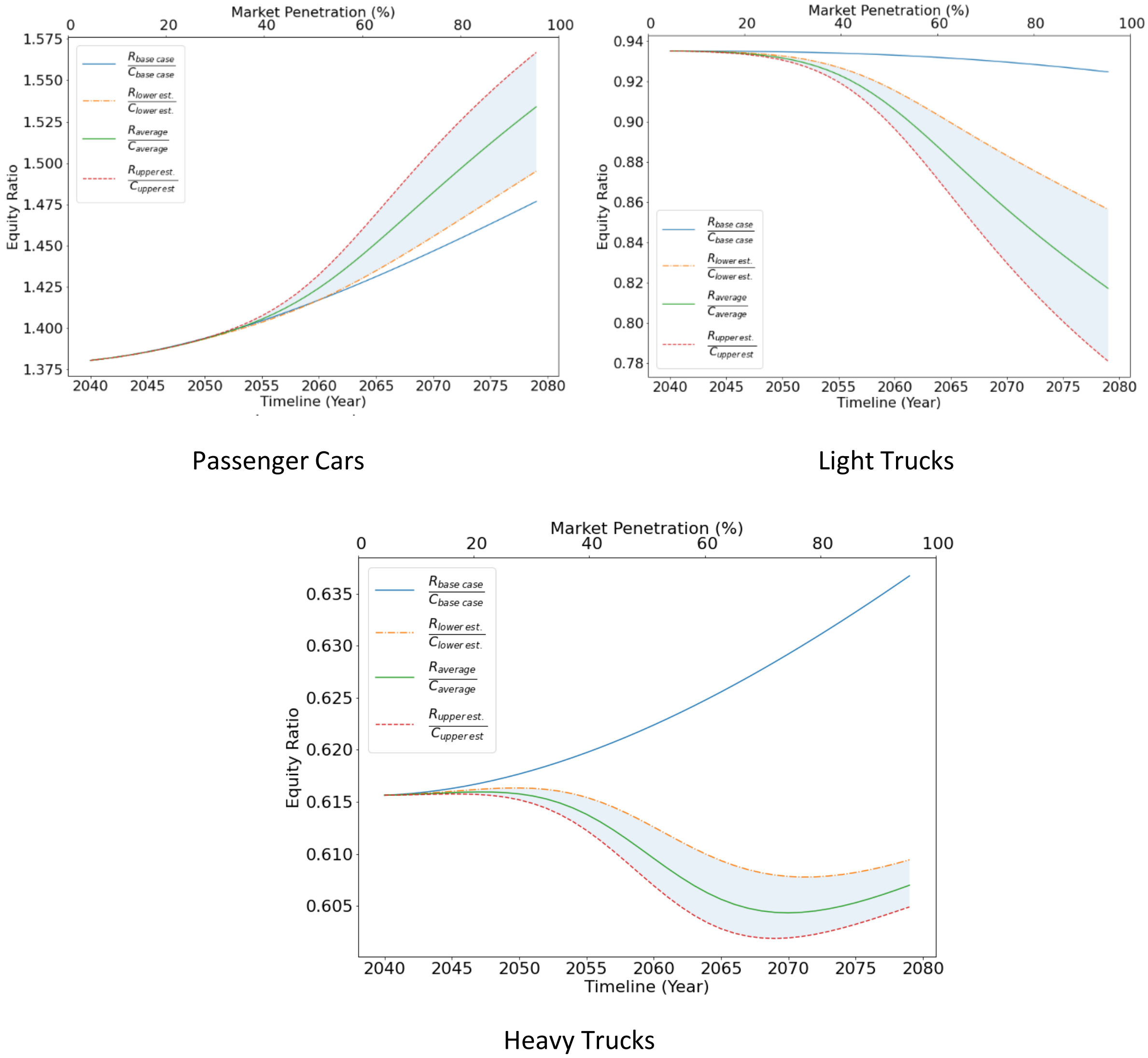


Figure 4.13: Equity ratios for the CAV scenario

4.3.5. Electric, connected, and automated vehicles (ECAVs)

Electric, connected, and automated vehicles (ECAVs) represent the emerging technologies paragon, that is, the integration of all three vehicle technologies. In previous sections of this chapter, these technologies are evaluated as standalone or pairwise in their deployment. 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 manufactured vehicles. The impacts explored for scenarios discussed in earlier sections (pertaining to the individual technologies) also apply here in the ECAV scenario. 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, et al., 2020b), 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 than each individual technology. By extension, vehicle electrification will also promote or exacerbate some of these beneficial or adverse impacts, respectively. The analysis of ECAVs therefore applies the effects of all the individual technologies and amplifies or reduces the sum of effects. The results of this analysis are presented in the sections below.

(a) Highway Expenditures

The impacts of electric propulsion, automation, and connectivity (ECAV) on highway expenditures are like 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 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: Total annual highway expenditure estimates, ECAVs, from 2040s (low market penetration) to late 2070s (high market penetration)

	Total Annual Highway Expenditures for ECAV Scenario			
Year	Base Case	Lower Estimate	Average	Upper Estimate
2040	$2,826,098,000	$2,826,098,000	$2,826,098,000	$2,826,098,000
2041	$2,847,715,000	$2,847,980,000	$2,848,136,000	$2,848,307,000
2042	$2,869,198,000	$2,869,847,000	$2,870,229,000	$2,870,648,000
2043	$2,890,552,000	$2,891,741,000	$2,892,440,000	$2,893,210,000
2044	$2,911,777,000	$2,913,712,000	$2,914,850,000	$2,916,101,000
2045	$2,932,876,000	$2,935,824,000	$2,937,557,000	$2,939,462,000
2046	$2,953,852,000	$2,958,154,000	$2,960,682,000	$2,963,461,000
2047	$2,974,707,000	$2,980,796,000	$2,984,373,000	$2,988,304,000
2048	$2,995,445,000	$3,003,864,000	$3,008,808,000	$3,014,238,000
2049	$3,016,068,000	$3,027,489,000	$3,034,191,000	$3,041,550,000
2050	$3,036,578,000	$3,051,819,000	$3,060,757,000	$3,070,565,000
2051	$3,056,980,000	$3,077,023,000	$3,088,765,000	$3,101,643,000
2052	$3,077,276,000	$3,103,274,000	$3,118,490,000	$3,135,164,000
2053	$3,097,469,000	$3,130,753,000	$3,150,209,000	$3,171,511,000
2054	$3,117,563,000	$3,159,626,000	$3,184,181,000	$3,211,039,000
2055	$3,137,559,000	$3,190,037,000	$3,220,625,000	$3,254,048,000
2056	$3,157,463,000	$3,222,085,000	$3,259,692,000	$3,300,745,000
2057	$3,177,276,000	$3,255,813,000	$3,301,444,000	$3,351,211,000
2058	$3,197,002,000	$3,291,194,000	$3,345,833,000	$3,405,385,000
2059	$3,216,645,000	$3,328,124,000	$3,392,699,000	$3,463,049,000
2060	$3,236,207,000	$3,366,428,000	$3,441,772,000	$3,523,844,000
2061	$3,255,692,000	$3,405,875,000	$3,492,693,000	$3,587,292,000
2062	$3,275,103,000	$3,446,192,000	$3,545,050,000	$3,652,841,000
2063	$3,294,442,000	$3,487,096,000	$3,598,407,000	$3,719,907,000
2064	$3,313,715,000	$3,528,309,000	$3,652,343,000	$3,787,921,000
2065	$3,332,922,000	$3,569,585,000	$3,706,482,000	$3,856,365,000
2066	$3,352,068,000	$3,610,720,000	$3,760,507,000	$3,924,800,000
2067	$3,371,156,000	$3,651,558,000	$3,814,178,000	$3,992,877,000
2068	$3,390,188,000	$3,691,993,000	$3,867,324,000	$4,060,341,000
2069	$3,409,168,000	$3,731,964,000	$3,919,844,000	$4,127,028,000
2070	$3,428,099,000	$3,771,447,000	$3,971,691,000	$4,192,850,000
2071	$3,446,983,000	$3,810,449,000	$4,022,866,000	$4,257,778,000
2072	$3,465,823,000	$3,848,998,000	$4,073,402,000	$4,321,832,000
2073	$3,484,622,000	$3,887,137,000	$4,123,353,000	$4,385,063,000
2074	$3,503,383,000	$3,924,916,000	$4,172,789,000	$4,447,543,000
2075	$3,522,108,000	$3,962,392,000	$4,221,784,000	$4,509,354,000
2076	$3,540,800,000	$3,999,621,000	$4,270,414,000	$4,570,579,000
2077	$3,559,462,000	$4,036,656,000	$4,318,753,000	$4,631,298,000
2078	$3,578,096,000	$4,073,547,000	$4,366,867,000	$4,691,587,000
2079	$3,596,703,000	$4,110,342,000	$4,414,819,000	$4,751,510,000

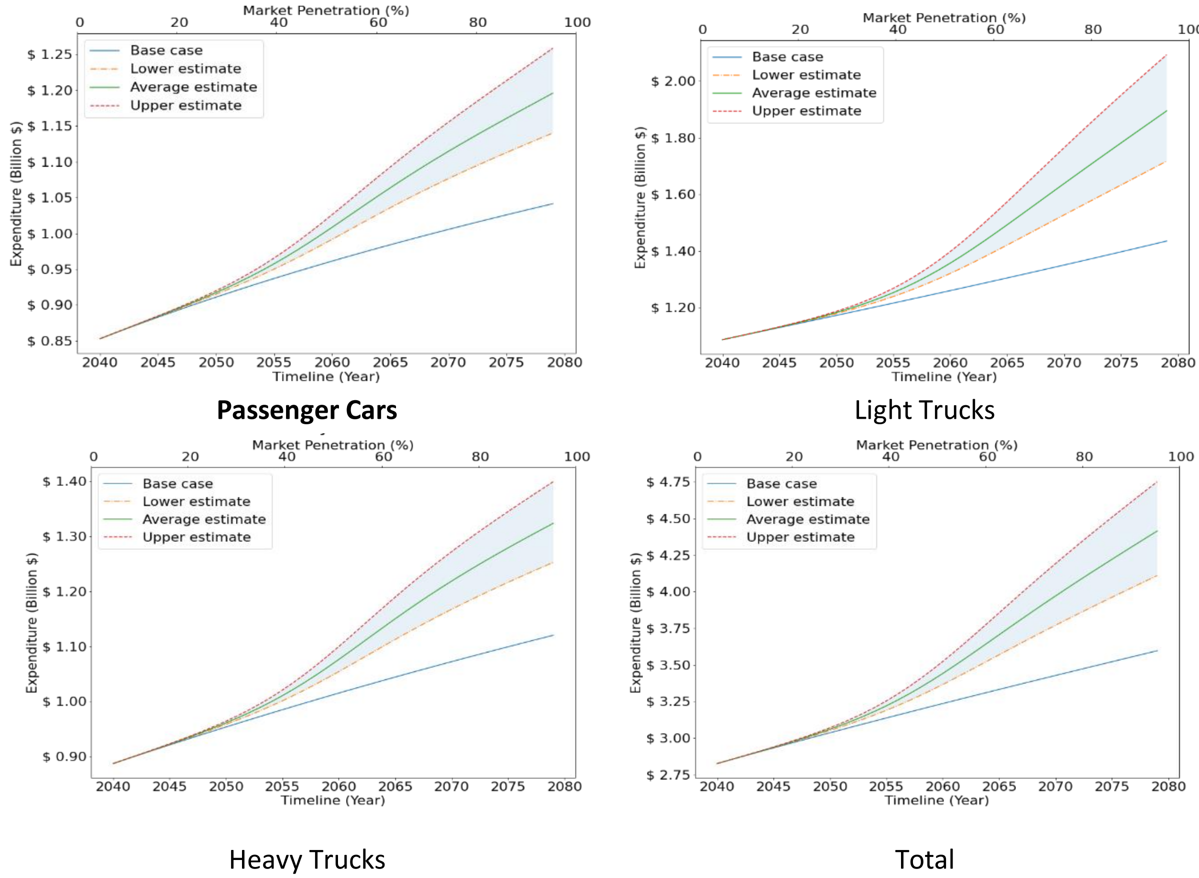


Figure 4.14: Total annual highway expenditures, ECAV scenario, from low to high market penetration

(b) Highway Revenues

For the ECAV scenario, highway expenditures are much closer to those for the CAV scenario but the revenues are much closer to those under the EV scenario. This is largely because the disparity in revenues between the ECAV scenario and the base case are driven primarily by loss of fuel revenues due to electrification. At low MP, the disparity in revenues between the base case and the ECAV scenario is minimal. However, this disparity grows as MP increases from low-moderate or high levels. The non-fuel revenues, however, are higher for the ECAV scenario compared to the base case for all MP levels. This is due to the increase in travel demand resulting from market adoption of the new technologies, which leads to new vehicle purchases which contribute to registration fee revenues and related taxes. Overall, the fall in revenues in the ECAV scenario are driven mostly by fuel revenue losses due to electrification. At low MP (10-30%), fuel revenues are 70-90% of those of the base case. At high MP however, this falls to 10-20% of the base case revenues. Therefore, as MP increases, revenues become more reliant on non-fuel sources, as evidenced by the slight increase in revenues from passenger cars as MP increases.

Table 4.10: Total annual highway revenue estimates, ECAVs, from 2040s (low market penetration) to late 2070s (high market penetration)

	Total Annual Highway Revenues for ECAV Scenario			
Year	Base Case	Lower Estimate	Average	Upper Estimate
2040	$2,739,297,000	$2,712,687,000	$2,712,687,000	$2,712,687,000
2041	$2,760,807,000	$2,728,236,000	$2,728,369,000	$2,728,518,000
2042	$2,782,317,000	$2,742,490,000	$2,742,817,000	$2,743,182,000
2043	$2,803,827,000	$2,755,183,000	$2,755,785,000	$2,756,457,000
2044	$2,825,337,000	$2,766,008,000	$2,766,990,000	$2,768,086,000
2045	$2,846,847,000	$2,774,605,000	$2,776,103,000	$2,777,775,000
2046	$2,868,357,000	$2,780,563,000	$2,782,752,000	$2,785,193,000
2047	$2,889,867,000	$2,783,422,000	$2,786,520,000	$2,789,973,000
2048	$2,911,377,000	$2,782,673,000	$2,786,950,000	$2,791,716,000
2049	$2,932,887,000	$2,777,774,000	$2,783,557,000	$2,790,001,000
2050	$2,954,398,000	$2,768,164,000	$2,775,845,000	$2,784,401,000
2051	$2,975,908,000	$2,753,298,000	$2,763,331,000	$2,774,502,000
2052	$2,997,418,000	$2,732,682,000	$2,745,582,000	$2,759,938,000
2053	$3,018,928,000	$2,705,930,000	$2,722,261,000	$2,740,425,000
2054	$3,040,438,000	$2,672,820,000	$2,693,177,000	$2,715,806,000
2055	$3,061,948,000	$2,633,360,000	$2,658,346,000	$2,686,101,000
2056	$3,083,458,000	$2,587,845,000	$2,618,038,000	$2,651,550,000
2057	$3,104,968,000	$2,536,895,000	$2,572,814,000	$2,612,647,000
2058	$3,126,478,000	$2,481,465,000	$2,523,539,000	$2,570,157,000
2059	$3,147,988,000	$2,422,815,000	$2,471,361,000	$2,525,101,000
2060	$3,169,498,000	$2,362,434,000	$2,417,645,000	$2,478,708,000
2061	$3,191,008,000	$2,301,939,000	$2,363,886,000	$2,432,338,000
2062	$3,212,518,000	$2,242,939,000	$2,311,588,000	$2,387,383,000
2063	$3,234,028,000	$2,186,917,000	$2,262,151,000	$2,345,154,000
2064	$3,255,538,000	$2,135,119,000	$2,216,769,000	$2,306,790,000
2065	$3,277,048,000	$2,088,490,000	$2,176,360,000	$2,273,184,000
2066	$3,298,558,000	$2,047,644,000	$2,141,536,000	$2,244,947,000
2067	$3,320,068,000	$2,012,879,000	$2,112,608,000	$2,222,406,000
2068	$3,341,578,000	$1,984,215,000	$2,089,619,000	$2,205,630,000
2069	$3,363,088,000	$1,961,452,000	$2,072,397,000	$2,194,479,000
2070	$3,384,598,000	$1,944,230,000	$2,060,611,000	$2,188,653,000
2071	$3,406,108,000	$1,932,091,000	$2,053,828,000	$2,187,748,000
2072	$3,427,618,000	$1,924,522,000	$2,051,562,000	$2,191,302,000
2073	$3,449,128,000	$1,921,000,000	$2,053,306,000	$2,198,832,000
2074	$3,470,638,000	$1,921,015,000	$2,058,569,000	$2,209,862,000
2075	$3,492,148,000	$1,924,089,000	$2,066,886,000	$2,223,942,000
2076	$3,513,658,000	$1,929,789,000	$2,077,833,000	$2,240,660,000
2077	$3,535,168,000	$1,937,726,000	$2,091,032,000	$2,259,646,000
2078	$3,556,678,000	$1,947,561,000	$2,106,149,000	$2,280,574,000
2079	$3,578,189,000	$1,959,000,000	$2,122,897,000	$2,303,162,000

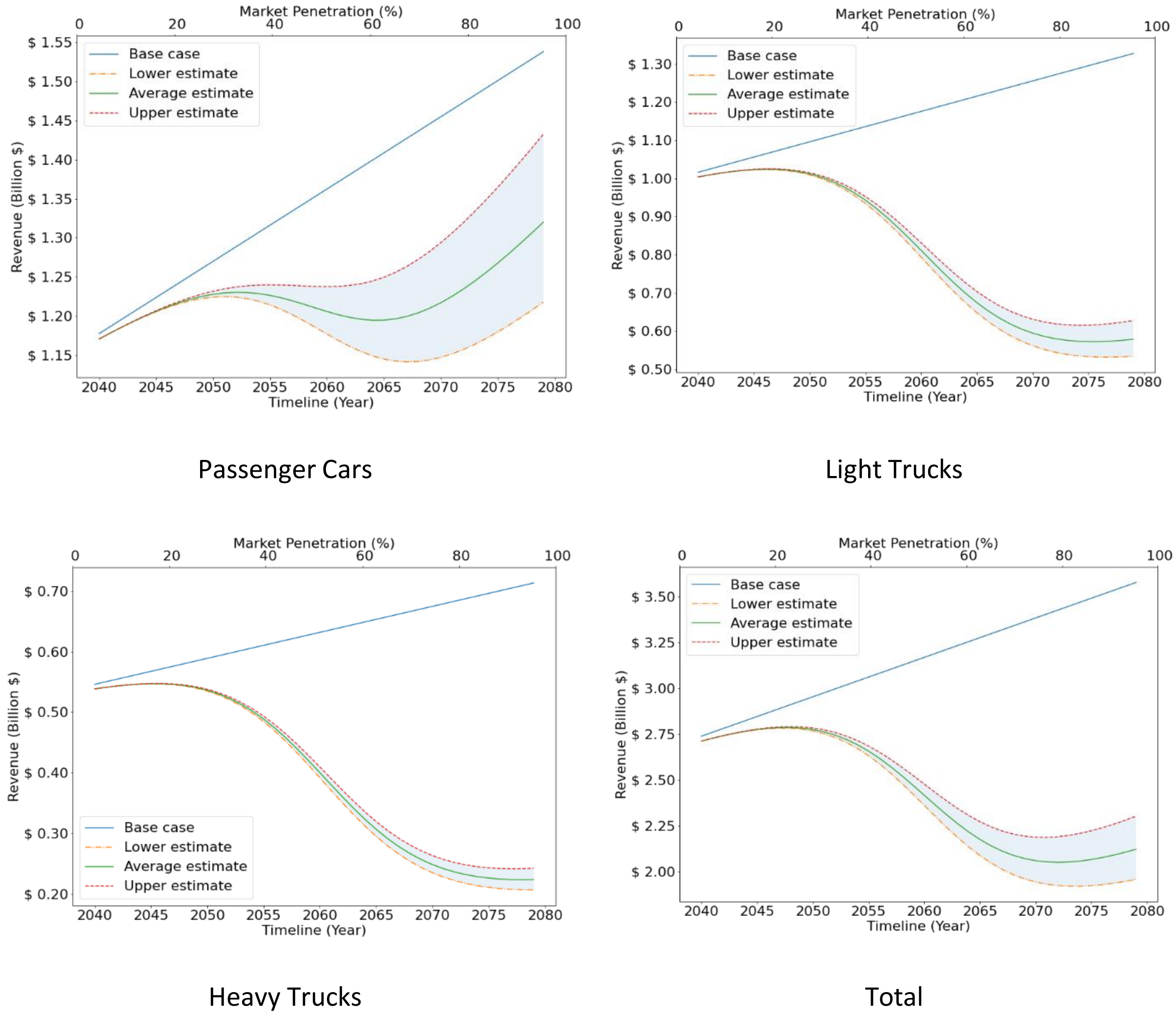
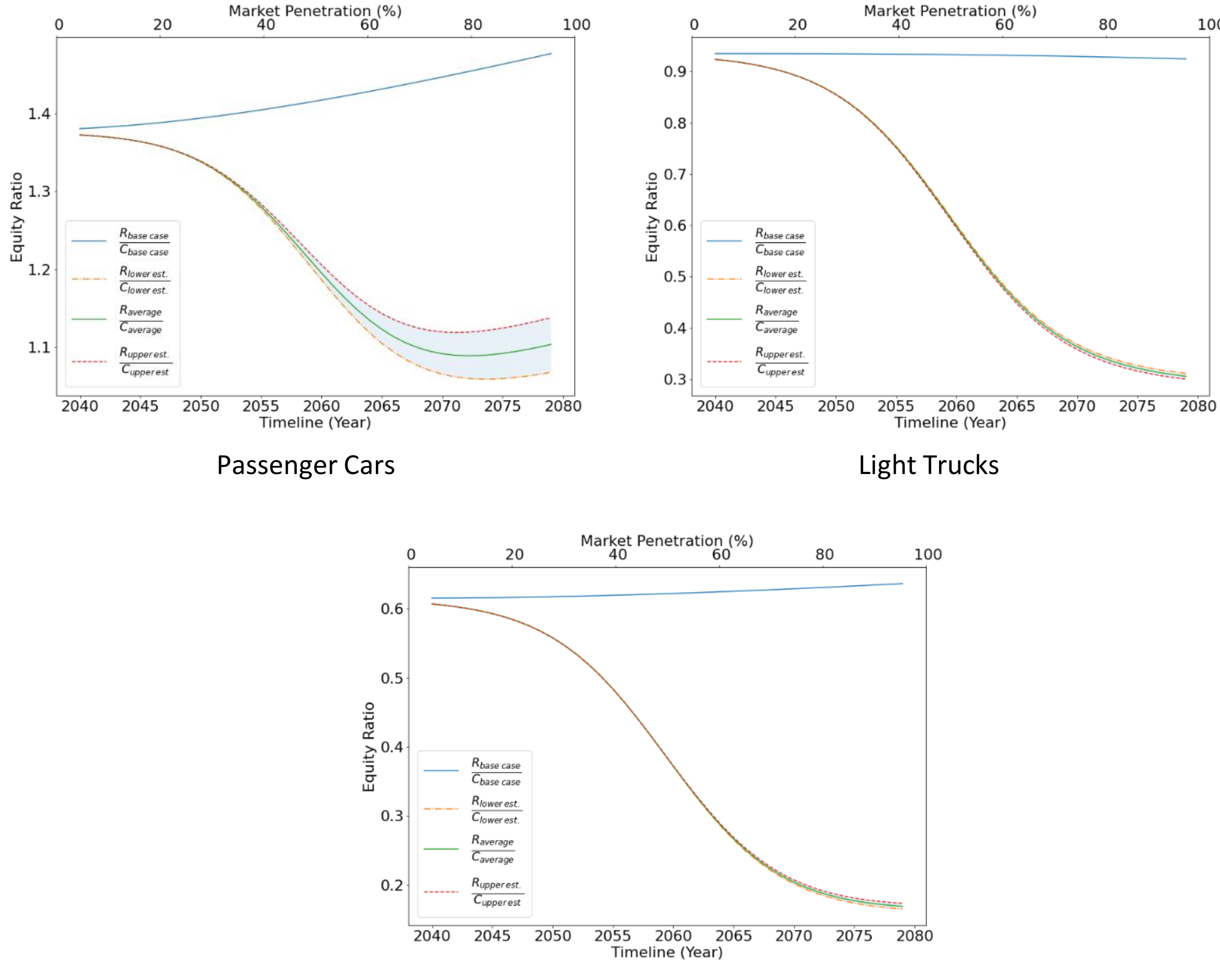


Figure 4.15: Total annual highway revenues for the ECAV scenario from low through high market penetration

(c) User Equity

Under ECAV, the equity ratios depict a trend similar to those observed for 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 highway agencies will face an urgent need to revise the user fee structure to address such inefficiency and inequity.



Heavy Trucks

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. 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 is expected to have more severe impacts on highway expenditures compared with connectivity. This disparity grows with the increasing level of market penetration and can be attributed in part to the increased overall travel that is to be expected with vehicle automation. This increase in system usage results in faster deterioration of the infrastructure which will then require more frequent repair and hence, expenditure. 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. Highway expenditures due to electric vehicles are expected to be impacted similarly to connected vehicles in terms of scale. Highway revenues, however will be impacted significantly in the ECAV 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.

CHAPTER 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 (Peterson Foundation, 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 been improving consistently over the last few decades, and the use of alternative fuels is 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, 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 report measures the increases in highway expenditures and expected shortfalls in highway funding and other challenges. This is important at this time as the transportation industry prepares to transition towards a new transportation terrain that features these new emerging technologies. This report 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 in the prospective era of electric, connected, and autonomous vehicles. To address the likely shortfalls in revenue due to emerging technologies, the report 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., but it also creates new travel patterns such as ride sharing that could have profound implications for the current revenue streams. Additionally, these new patterns could have numerous implications for equity demographic and transportation opportunities and access for various segments of the population. Other technologies, such as electrification, threaten to eliminate significant portions of the tax revenue base, namely fuel taxes. Therefore, this report proposes a revision to the current user fee structure that will help mitigate these issues.

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 report, it was evident that some vehicle classes, i.e., passenger cars irrespective of AV-EV-CV scenarios will be consistently overpaying their fair share of highway cost responsibility. It was also observed that other classes, such as the-light and heavy-duty are consistently underpaying their fair share of the costs incurred. The main reason for this disparity is the difference in their relative share of travel (vehicle- miles). As a class, passenger cars' total VMT is several times more than that of light and heavy trucks. Also, because the current user fee structure charges a flat tax per gallon of fuel used, vehicle classes that have more miles of travel, pay more in total taxes compared to 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 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 other truck-related taxes, evidence of previous studies suggest that these fees have been inadequate to offset the deficit.

To address this issue, this report 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 report 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 tax and inflation indexed tax.

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 market penetration. 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. 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, the 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) likelihood of public acceptance. The cost of implementation may require further research to be precisely ascertain. However, a simple implementation could rely on 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 cost 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 could 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 report 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 scenario are represented in the figure. Section 5.2.1 of this report addresses the moderate ECAV scenario with the revised user fee structure. Section 5.3 presents additional illustrations of the proposed user fee structure application.

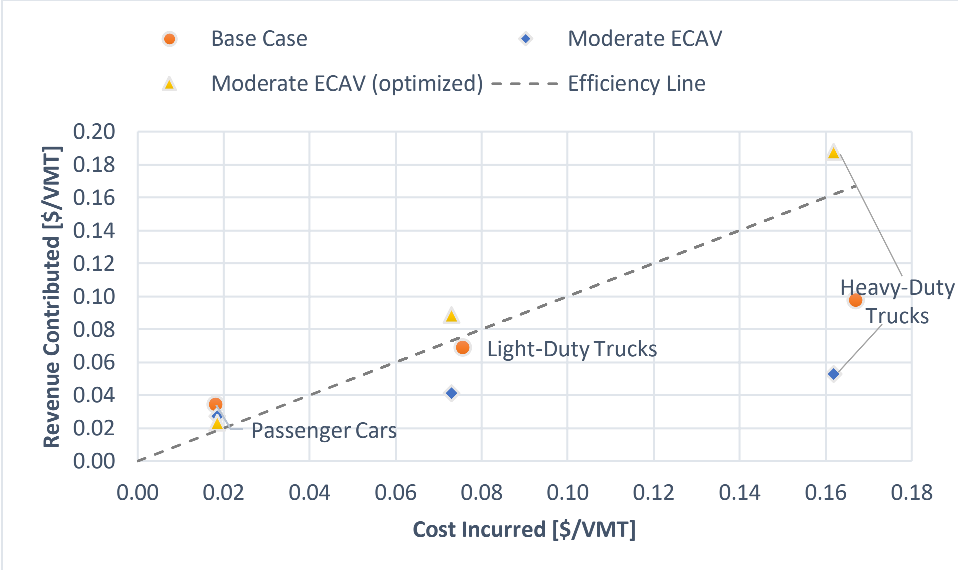


Figure 5.1: Revenue-expenditure efficiency comparison across the vehicle classes

Although this comparison is presented here for the three highway user groups used in this report, 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 report. 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, while 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 because 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 an 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 traditional 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 at CV different levels of market penetration

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 are 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 et al., 2020a).

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 in 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, smaller headways, smoother driving capabilities, etc. are expected to yield an increase in road capacity. As suggested and demonstrated in the literature and discussed in Section 3.5 of this report, 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 report. 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 4.3.3.(b). 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 at AV different levels of market penetration

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

5.3.3.(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 gasoline/diesel fuel, they are expected to make no contributions to the fuel tax and therefore result in significant decreases in current levels of fuel tax highway revenues.

At low market penetrations, approximately three in ten cars on the road are expected to be electric, meaning that the fuel tax revenue potential will become only 70% of what it would have been had the cars not been electric, although their nonfuel revenue contribution will be the same as non EVs. 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 using fuel and thus paying fuel taxes, further reducing the fuel tax revenue potential to just 10% of the base case. This decrease in revenue is necessarily due to cars not buying fuel, 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 could be implemented as a one-time fee paid 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 at non-automated EV different levels of market penetration

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

5.3.3.(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 for both passenger cars and heavy vehicles. The exact amounts to which the VMT may increase for passenger cars and heavy vehicles may vary, and simplifying assumptions are made. 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 the 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 the sum of effects of the two scenarios. It is possible that the increase in expenditures under the combined scenario exceeds that of automation alone considered in earlier chapters, and that the decrease in revenues fall below that of electrification considered previously. It is difficult to ascertain the degree of the synergy because 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 4.3.3.(b), 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 5.3.3.(a) or an EV fee – pay-as-you-charge, for example ($/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 at automated EV, different levels of market penetration

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 induces moments and stresses within the members. This pattern of repeated stresses in the members, even though within design limits, tends cause faster deterioration of the members. 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 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 in 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 at ECAV different levels of MP

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 report. 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 1's equity ratio may change from 1.3 to 1.1, and Group 3's ratio may change from 0.6 to 0.8. However, it is difficult to quantify the improvement in the system equity following this change.

This report 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 report 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.

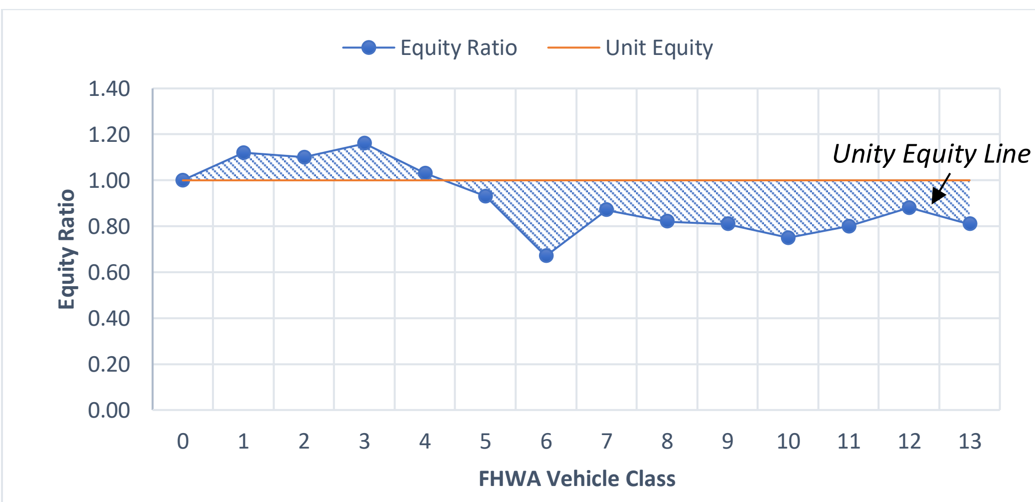


Figure 5.2: Equity Ratios for 13 FHWA vehicle classes (based on Volovski et al., 2015)

By quoting the value of the shaded area in Figure 5.2, one could compare user equity across multiple systems or across different times. The improvement in equity ratios across the system can be presented as percentage change of this area between the pre-intervention and post-intervention periods.

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 report. 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 report 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 indicates 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 4.3.3.(a) 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 highway revenues and expenditures for non-automated electric vehicles and connected vehicles at low market penetration.

Vehicle Class	Expenditures	Revenues	Equity Ratio	Modified Equity Ratio
		Non-Automated EV at low market penetration		
Passenger Cars	$948,234,000	$1,512,674,000	1.83	1.60
Light Duty Trucks	$1,666,118,000	$1,156,113,000	0.88	0.69
Heavy Duty Trucks	$1,373,581,000	$598,043,000	0.58	0.44
System Total	$3,987,935,000	$3,266,832,000	1.00	0.82
		Connected Vehicles at low market penetration		
Passenger Cars	$966,370,000	$1,693,497,000	1.82	1.75
Light Duty Trucks	$1,697,296,900	$1,444,417,000	0.89	0.85
Heavy Duty Trucks	$1,401,319,000	$773,521,000	0.57	0.55
System Total	$4,064,987,000	$3,911,436,000	1.00	0.96

The results of analysis based on the traditional Equity Ratio suggest 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 underpaying 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 the 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, it can be inferred that the system is operating with a 20% deficit overall. 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 demonstrates the superior efficacy of the modified equity ratio as a metric for assessing system equity and efficiency in the context of highway cost allocation.

5.5. Vehicle Classification for Highway Expenditure and Revenue Reporting

As has been shown in this report, wide adoption of ECAVs will generally result in increased VMT. 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. Repeated loading exacerbates 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 construction.

Notwithstanding the fact that any increase in VMT will likely have a similar effect on infrastructure, ECAVs are expected to exacerbate these impacts. For human-driven vehicles, minute deviations from the lane center line 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. This will promote passenger comfort but will have adverse 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 ECAV's anticipated disproportionate cost responsibility and their inability to generate additional revenue relative to conventional vehicles, it is difficult to justify the classification of ECAVs using the same scheme as is done for conventional vehicles. Furthermore, many of these vehicles may likely be electric, meaning their revenue contributions will be far less than that of their conventional counterparts. It seems reasonable, therefore, to argue that such imbalance in cost responsibility and revenue contribution warrants a new classification scheme for ECAVs, different from that currently used for conventional vehicles. For the purposes of highway expenditure and revenue assessment and reporting, it is suggested to classify ECAVs as a subcategory within each class. For example, using the traditional (FHWA vehicle classification) scheme as a basis, vehicles equipped with emerging vehicle technologies can be denoted with a suffix to represent the transportation technology type. For example, an automated passenger car can be denoted as class 2-A (the letter "A" representing automation) and an electric bus can be denoted as class 4-E. Adopting such a classification would simplify the accounting and reporting of highway expenditure and revenues 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 study explored the impacts of emerging vehicle technologies (automation, electrification, and connectivity) on highway finance(expenditures, revenues, and equity) only. The wider impacts, some beneficial and others adverse, extend beyond highway finance, and will ripple through several societal structures, including mobility and travel patterns, and 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) .

Most road traffic accidents can be attributed to human error (NHTSA, 2008). Therefore, 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 fewer. Lighter vehicles will lead to higher 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 undertaken by individuals. This is in part because individuals that cannot currently drive (children, the elderly and disabled individuals) will be able to take trips using 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. 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 demand for electricity. 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 report explored these impacts as they pertain to highway financing and duly recognizes that there exist other non-financial impacts. Each of the technologies (and their combinations thereof) could have specific impacts that may affect other systems and sectors.

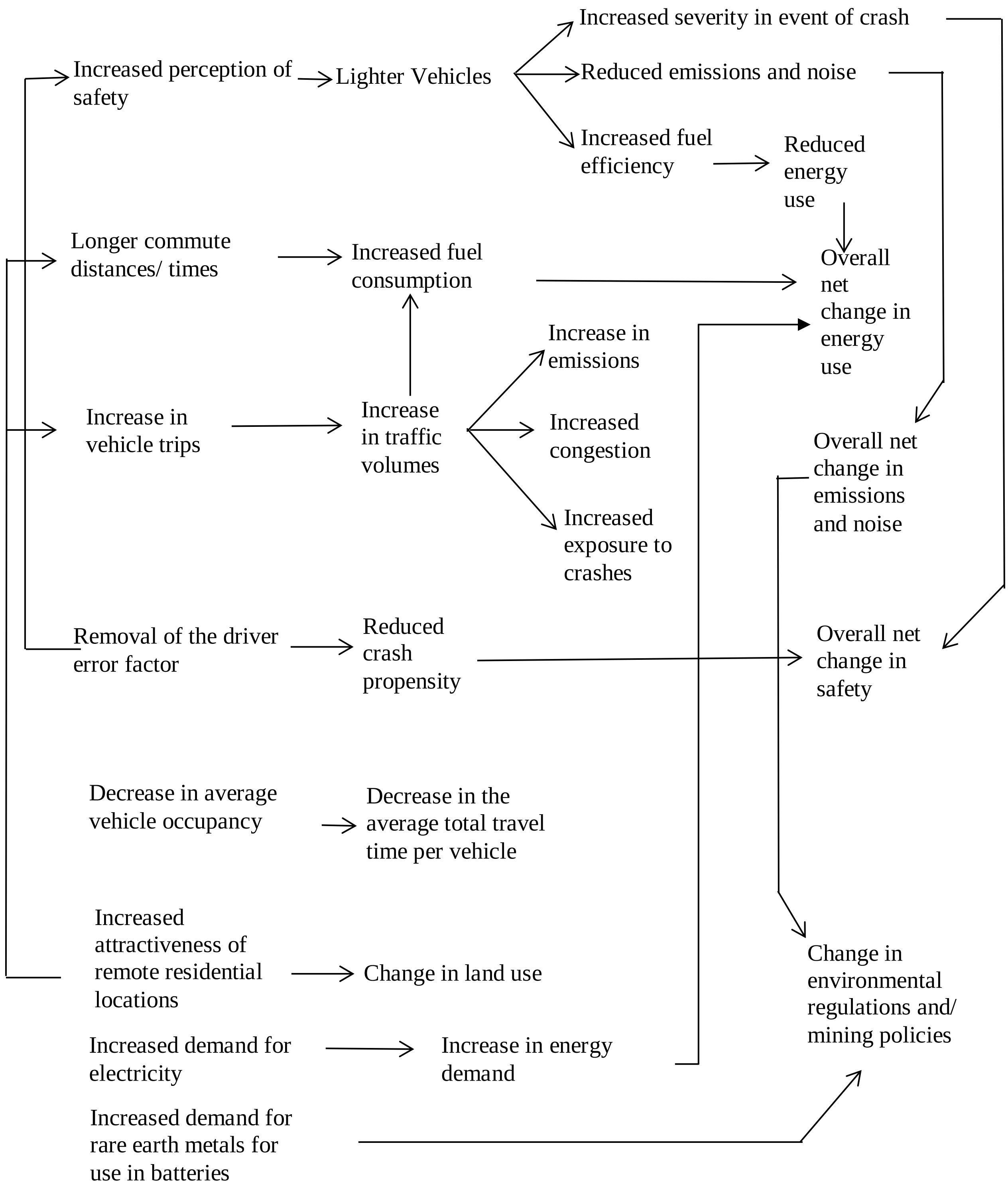


Figure 5.3: Broader impacts of vehicle automation, connectivity, and electrification [adapted from Labi et al. (2015)]

5.7. Chapter Summary

This chapter discussed in detail the implications and potential solutions to the fiscal impact of emerging vehicle technologies presented in Chapter 4 of this report. 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 for electric vehicles. The combination of the variable tax scheme and distance-based tax can address the current and persistent shortfall in revenue and the system inequity in cost allocation. Also, it can address the long-term decline in fuel tax due to vehicle electrification. This chapter also illustrated the application of the variable tax scheme to different scenarios of emerging vehicle technologies at various levels of market penetration.

The chapter also discussed highway user equity and presented 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 system equity is measured as the area bounded by the equity plot and the horizontal axis. 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 (MER). The MER is computed by comparing the actual dollar amounts instead of their proportions of revenues contributed and costs incurred (proportions). This modification allows the equity ratio to convey information about not only the system equity 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 can be considered warranted due to 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.

CHAPTER 6. FISCAL IMPACTS OF EVS AND CURRENT TRENDS IN EV CHARGING MECHANISMS AND FEES

6.1 Introduction

The dominant source of highway transportation funding is revenues from motor fuel taxes. With increasing vehicle electrification and other alternative fuels for propulsion, motor fuel tax revenues continue to decline. As such, state and local governments seek to estimate the revenue losses due to vehicle electrification and to identify solutions to address such revenue loss. This often involves the development of new fee structures for vehicles that use electricity and other alternative fuels for propulsion. After estimating the loss in fuel tax revenue due to EV use, the corresponding annual fee to impose on EVs to recover such lost revenues, can be established. This is the amount that is to be charged to each EV in order to recover the lost fuel tax revenue due to EV adoption, also referred to as the "recovery fee" in Figure 6.1 (Konstantinou, et.al, 2022). Agency may consider recovery fees as not a permanent solution but an interim arrangement, as arrangements could impair EV market penetration. It is worth noting that in some situations, EV owners have resisted EV taxes, arguing that their vehicles have an environmental benefit that is not captured in highway user fee design.

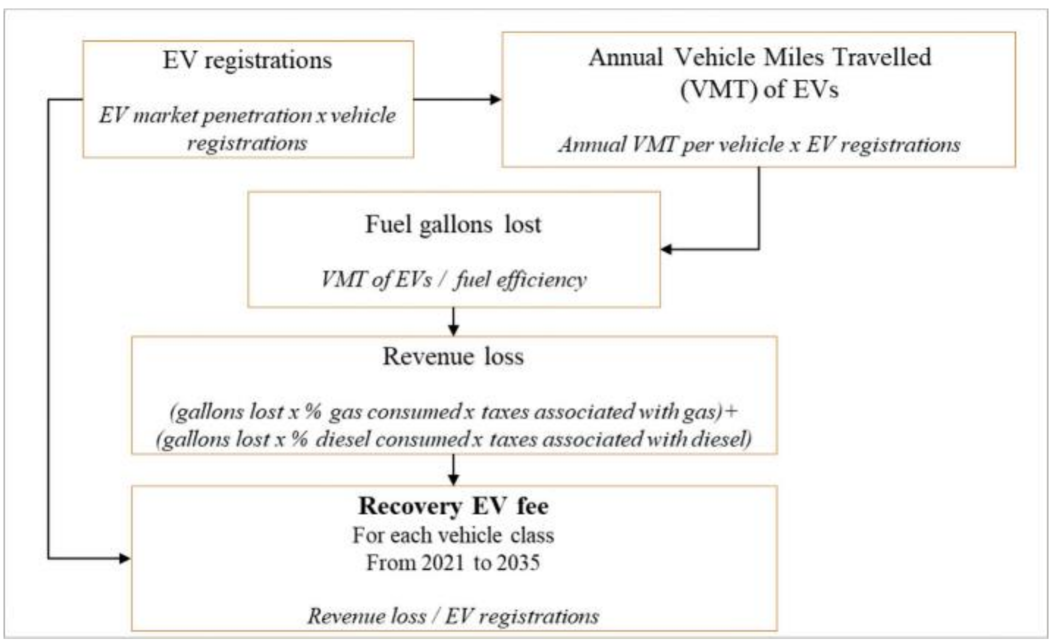


Figure 6.1 Methodology to calculate recovery fee for EVs.

In sum, it is generally desired that the implementation of EV fees must not only ensure sufficient revenue but also support EV adoption. It is also useful to consider vehicle class and weight in fee design, to account for damage caused to the operating efficiency (due to vehicle size) and infrastructure (due to vehicle weight). Vehicle use statistics show that the tax revenue for each unit VMT (vehicle mile traveled) is decreasing steadily, due to the increased fuel efficiency. For example, in 1994, the average fuel economy for a passenger car was 20.7 miles/gal (MPG) and the state and federal tax per VMT was 3.2 cents; and in 2018, the average fuel economy for a passenger car was 24.4 miles/gal and the state and federal tax per VMT was 2.1 cents (Ulrik Boesen, 2020). This chapter discusses a few potential mechanisms for electric charging, and presents the variations in EV fees across various states in the US (including an EV annual registration fee and EV registration fee broken into periodic payments, VMT Fee, and a Pay-as-you-charge ($/kWh) fee. The sections below discuss, for each charging mechanism, the key features, advantages, disadvantages, and policy considerations.

6.2 Electric Charging Mechanisms

6.2.1 Annual EV-registration fee

At certain states, an EV fee is paid once annually. These fees are associated not with highway use but rather, vehicle ownership. Therefore, annual EV fee could be serving as a more reliable revenue source compared with use-based fees or taxes (in this case, the reliability seems to be guaranteed because vehicle ownership is not expected to decline significantly in the foreseeable future). The annual EV registration fees is the charging mechanism used at most states that have adopted EV fees. The advantage of this charging mechanism is that it is consistent with the existing system of vehicle registration revenue generation. Therefore, this mechanism is expected to require minimal public education and outreach, and is less costly to implement. A key disadvantage of this mechanism is that the fee is paid upfront and the amount may be too much to pay, from the perspective of certain low-income users. In addition, this charging fee structure could stall the growth of EV market penetration, particularly for larger vehicle classes that consume more fuel and therefore will have a higher EV fee in order for the highway agency to recover revenues lost when these vehicles use electricity. Also, this fee structure does not take into consideration, the extent of highway use, and its future sustenance is not guaranteed. Modifications to existing fee structures may be needed to address any disparities between EV road use and EV fees. For example, EV users with high mileage may have a lower amount charged per mile compared to those with low mileage. In addition, fee designers need to recognize that fee increases over time may contravene EV purchase incentives from federal and state governments. The high EV fee burden, if made annually, could be lowered through payments made periodically (for example, quarterly, monthly, bi-weekly, or even weekly).

The current trends adopted in the states show that as of May 2023, thirty-four (34) states have passed legislation on EV fees (TIAC, 2023a). At Colorado, Hawaii, Michigan, and South Dakota, the EV and plug-in hybrid EV (PHEVs) annual fee ranges from $50 to $240 (indexed). The state of Utah has an annual charge of $120 per vehicle and they have an optional road user charge program, along with the fee on charging stations. The state of Montana has implemented the free based on the class of vehicles. The annual EV registration fee, excluding plug-in hybrids, vary according to vehicle class. Class 1 vehicles incur a fee of $130, while Class 2 vehicles are charged $190. Class 3 vehicles face an annual fee of $340, and Class 4 vehicles bear a higher cost of $1,100. For plug-in hybrids, the annual registration fees are as follows: Class 1 vehicles – $70; Class 2 vehicles – $100; Class 3 vehicles – $210; Class 4 vehicles – $700. The case is similar in Missouri. The state of Michigan charges $140 for lighter vehicles and for EVs exceeding a weight threshold of 8,000 lbs., the fee is $240. The current amount of fee charged across various states as of May 2023 is shown in Figure 6.2 below.

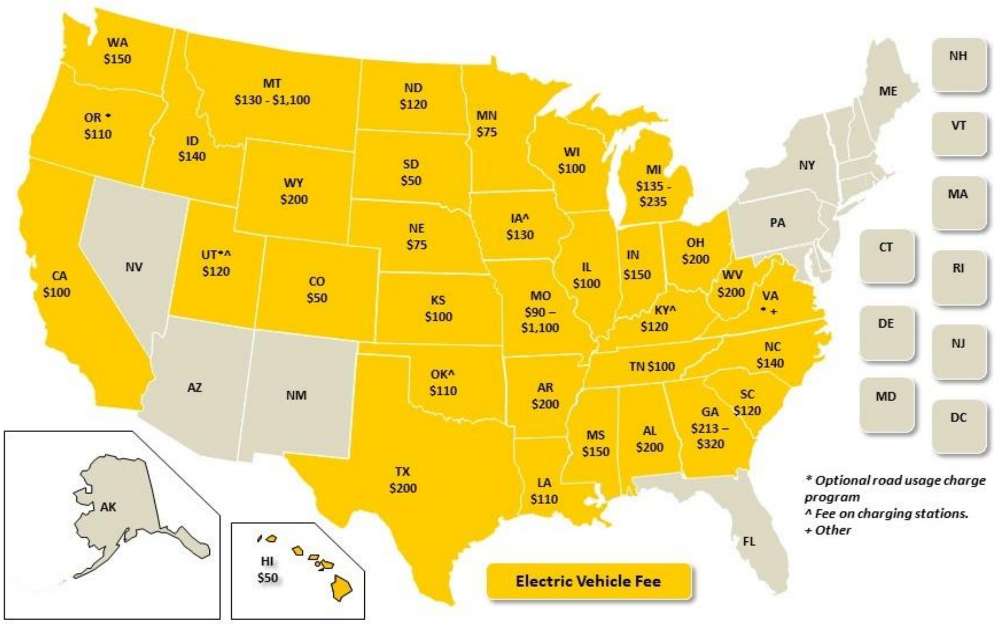


Figure 6.2 States that are experimenting an annual registration fee for EVs (Source: www.transportationinvestment.org)

6.2.2 Vehicle miles per travel (VMT) fee

The VMT fee, also known as the Road Usage Charge (RUC), $/mile, is a mileage-based user fee. This fee is advantageous because it can be spread across several periods, therefore minimizing the burden. However, it has been argued that VMT fees do not address the full range of impacts of each vehicle class on the highway system. VMT fees may fail to encourage electric vehicle adoption for relative long distance trips, and therefore may fail to garner the requisite public support and acceptance from both urban and rural drivers. In addition, road use monitoring because of VMT fee implementation, may cause privacy-related concerns. Further, the acquisition and deployment of technologies for vehicle tracking, account management, and transaction charging may lead to high costs of administration. Appropriate design of the VMT is required to address potential user disparity between urban and rural drivers. Also, this charging mechanism may require specific VMT-fee designs that incentivize behavior that enhances fuel efficiency. From an overall systemwide perspective, EVs could be made to have lower VMT fees because they improve air quality and reduce emissions. Nevertheless, VMT-based EV fees will need to be established only through a holistic evaluation of the considerations including revenue adequacy, climate, administration costs, and other considerations. It is also argued that a fee applied directly to the extent of road use, could, to some extent, account for the externalities associated with highway transportation operations. Further, when combined with weight-based fees, this mechanism could help develop fair rate structures that account for the multi-faceted impacts of EVs.

As of January 2023, four states – Virginia, Hawaii, Utah, and Oregon – have fully operational RUC programs in place. Connecticut has a dedicated program tailored for commercial trucks. Additionally, numerous other states are currently running pilot programs or conducting studies to delve into this subject further. Oregon's OReGO program enables participants to pay a -mile-based fee instead of the state motor fuel tax (TIAC, 2023b). The current rate is 1.8 cents/mile, and participants receive a credit for the fuel tax they have paid. Utah's RUC program charges participants 1.52 cents/mile and has a "Road Usage Charge Program Special Revenue Fund." This amount has a maximum limit (which is, the state's flat registration fee). Hawaii imposes a fee of 0.8 cents/mile for electric vehicles (EVs), or EV owners can choose to pay a flat annual fee of $50. Virginia's "Mileage Choice Program" serves as an alternative to its "Highway Use Fee," which levies a fixed annual rate on fuel-efficient and electric vehicles. Participants opting for the Mileage Choice program forego the use fee but have a mileage-based fee capped at what they would have paid as the Highway Use Fee. This per-mile rate is calculated based on the average mileage driven annually by a Virginian, which is approximately 11,600 miles. The states implementing the RUC (VMT fee) program are shown in Figure 6.3.

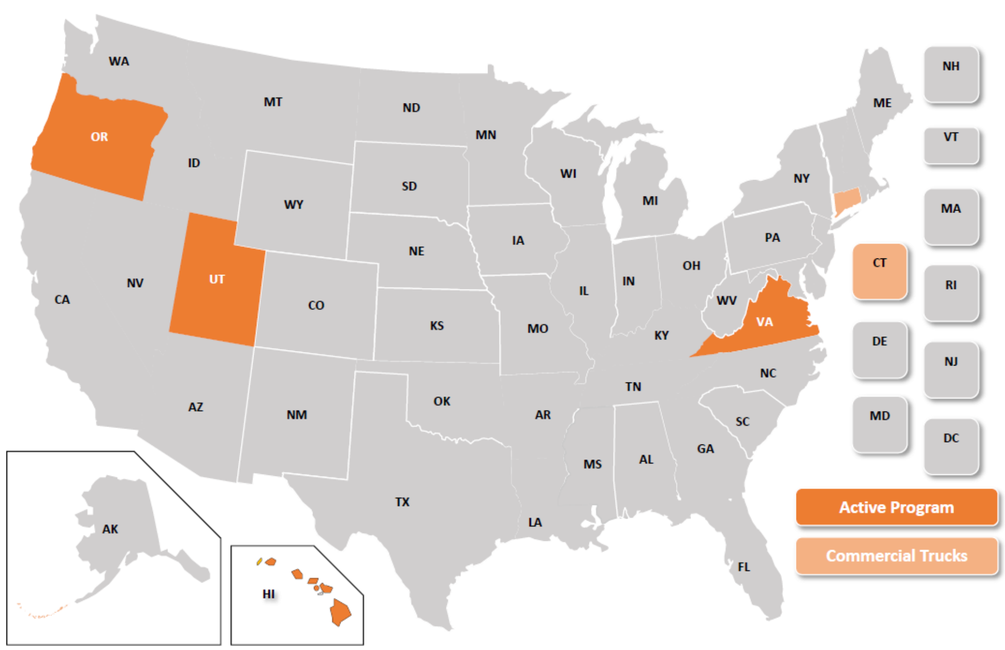


Figure 6.3 States that are experimenting VMT Fee program (Source: www.transportationinvestment.org)

6.2.3 Pay-as-you-charge ($/kWh)

Regarding this mechanism, the EV recovery fee is converted to fee on the amount of electricity used to charge an EV, measured in $/kWh. The costs can be paid at the time of charging, similar to gasoline refueling where the vehicle energy purchaser pays at the pump. Public familiarity with gasoline refueling could facilitate widespread public adoption and agency implementation of PAYC fees. This mechanism has a primary disadvantage in that EV charging mostly occurs at the residence of the EV user, and it is challenging to separate household electricity use from the electricity used to charge the EV. Also, citizens may be unwilling to pay state taxes for charging their EVs at their residences or at their places of work.

Further, the fee may also not be as representative compared to a weight-based measure, regarding the accounting for vehicle impacts on the roadway. Administering a PAYC structure may require measurement of EV electricity consumption using on-vehicle technology and submetering or smart chargers. Utilities may need to establish new tariff structures to reward or penalize certain charging-related behaviors such as, off- and on-peak charging, and these could reduce EV user charging cost and promote adoption. It will be useful to develop institutional protocols among the various parties – utilities, regulators, and the local/state road agencies to remit payments to the state's revenue collection agencies in an effective and efficient manner.

As of May 2023, seven states have taken measures to implement or explore a per-kilowatt hour excise tax on electric vehicle charging. These states include Oklahoma, Iowa, Pennsylvania, Kentucky, Minnesota, Utah, and Georgia. In Oklahoma, starting January 1, 2024, a three-cent tax per kilowatt-hour will be imposed on charging electric vehicles (TIAC, 2022b). Additionally, the bill introduces registration fees for electric vehicles based on their weight and type. It also offers an income tax credit for the taxes paid, with the credit not exceeding the electric vehicle's registration fee. Iowa has initiated an excise tax on hydrogen fuel, effective January 1st, 2020, and introduced a per-kilowatt-hr excise tax on electric power beginning July 1, 2023. In Pennsylvania, the excise tax rate on electric power, as of 2022, is 1.72 cents per kilowatt-hour. Kentucky has implemented a per-kilowatt hour excise tax on electric vehicle power, starting January 1, 2023, at a rate of $0.03 per kilowatt-hour. Figure 6.4 presents a diagram showing the states that have implemented the per kilowatt hour excise tax program.

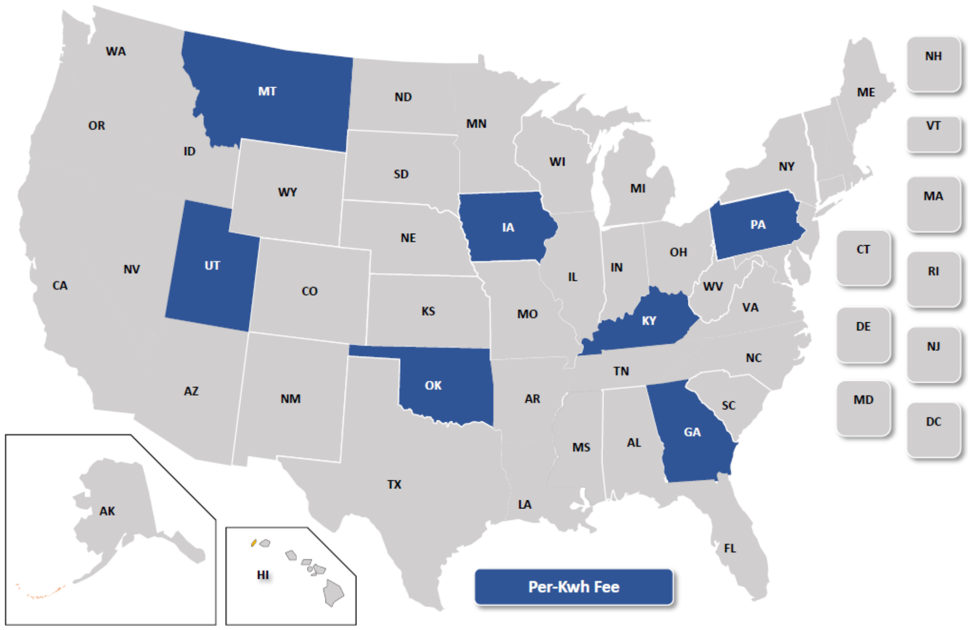


Figure 6.4 States that are experimenting a pay-as-you-charge program (Source: www.transportationinvestment.org)

6.3 Legislative Actions and the Way Forward

Several states are currently in discussions regarding alternative sources of funding due to the declining revenues from motor fuel taxes. These discussions are part of a larger legislative landscape, with 224 bills being considered across 39 states (as of July 2023), notably, 37 of which are specifically focused on EV fees. These conversations are taking place against the backdrop of a nationwide trend towards increasing EV adoption. This is particularly significant for states that heavily rely on gas taxes and registration fees as their primary sources of highway infrastructure funding.

Also, discussions on federal tax collection are underway. The Infrastructure Investment and Jobs Act (IIJA) directs the USDOT to support state-level pilots while establishing a national pilot program for $/mile road-use fees. The pilot program is authorized by the IIJA (which has authorized $50 million for the pilot over 5 years). The pilot will address design, resting, public acceptance, implementation, and financial sustainability. It will address the need for additional revenue for funding surface transportation infrastructure and will recommend requisite policies towards the adoption and implementation of a national $/mile user fee (EnoTrans, 2023).

As the transportation landscape transitions towards EV technologies and alternative fuels, it is prudent to develop realistic and equitable plans to address the fuel tax revenue decline. Experience has shown that policymakers are well served when they exercise caution in establishing timelines for these alternative approaches, because imbalances that makes owning an EV more expensive compared to an ICEV, could hinder adoption rates.

Potential barriers to implementation should encompass concerns related to sustainability, costs, and privacy, while policy considerations should encompass implementation processes, partnerships, and equity. It is also critical to consider the distribution of the charging fee collection, given that for ICEVs, gas purchases typically occur weekly or bi-weekly. Most literature endorse the exploration of progressive approaches to compensate for the loss of fuel tax revenue. For example, agencies could consider raising the gas tax as EV adoption rises or implementing higher road tolls for ICEVs. These could be considered as part of an overall strategy.

6.4 Chapter Summary

This chapter outlined and summarized the fiscal impacts of EVs and some measures that are currently being implemented to ensure revenue efficiency for transportation systems across the country. Some measures already implemented include VMT fees for electric vehicles, pay-as-you-charge mechanisms, and annual registration fees. These and other measures are in various stages of implementation to help reduce the revenue deficit anticipated due to increased adoption of EVs and therefore loss of fuel tax revenue.

CHAPTER 7. CONCLUDING REMARKS

7.1. Synopsis of the Research

This report addressed the impacts and consequences of emerging vehicle technologies on three key aspects of 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 report highlighted the gaps in the literature, particularly, the consideration of emerging vehicle technologies in highway cost allocation. The study accounts for the need for infrastructure investments that are expected to accommodate emerging vehicle technologies and the expenditures to address this need. From the revenue perspective, increasing CAV and EV operations will cause highway revenues (earned typically from vehicle fuel tax and registrations) to fluctuate due to reduced demand for vehicle ownership (will decrease revenue) and increased amount of travel (will increase revenue if travel mostly uses gasoline or other appropriately-taxed fuel).

The study proposed new models for estimating the cost of highway infrastructure construction and upkeep based on the 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 report recommended revisions to the current user fee structure that would improve system efficiency and reduce inequity in the near term and the long term.

7.2. Recap of the Problem Statement and Major Findings

The emergence and adoption of vehicle connectivity, automation, and electric propulsion are likely to exacerbate the current and eminent crisis facing highway financing. First, 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 most previous studies on 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 traditional 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. The study addressed the expenditure and revenue impacts associated with the emerging technologies impacts of vehicles electrification, connectivity and autonomy.

The results of the research suggest that CAVs will significantly change travel patterns, leading to increased system usage which in turn will result in increased wear and tear on highway infrastructure. This, with the need for new infrastructure to support and accommodate the new technologies, increased highway expenditure. At the same time, CAVs are expected to have significantly improved fuel economy compared with their human-driven counterparts, leading to a decrease in fuel consumption per vehicle, and ultimately, reduced fuel revenues. Furthermore, the growing prominence of EVs exacerbate this problem. This report analyzed the impacts of emerging vehicle technologies at varying levels of market penetration. In total, this report 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 small percentage (translating to a few hundred million dollars) to as high 20%. A similar trend was seen for the revenues, and consequently, the user equity.

7.3. Contributions of this Research

To address the aforementioned shortfalls in highway revenues stemming from the adoption of new vehicle technologies, this report proposed a revision to the current user fee structure. This revision contains two major parts designed to address system efficiency and equity in the near and long term. For the near term, this report 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 transition period, this report recommended supplementing the fuel tax with a distance-based VMT tax, applicable to electric vehicles. This report 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, in this report, a method was proposed for comparing the performance of highway user groups in a manner that is transferable across different systems and times. 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 report recommended an updated vehicle classification for the purposes of highway cost allocation and revenue attribution. Based on the disproportionate cost responsibility and the lower ability of ECAVs to generate revenue compared with conventional vehicles, this research recommended that ECAVs be classified as a subcategory within each traditionally defined class, class for the purpose of accounting and reporting of highway expenditures, revenues and equity. Using the FHWA vehicle classification as a basis, each vehicle equipped with at least one of the emerging vehicle technologies could be considered a sub-class within each traditional class, with a suffix to represent the technology.

7.4. Study Limitations and Direction for Future Research

This research focused on the impacts of emerging vehicle technologies on highway expenditures, revenues, and user equity, and proposed solutions to address any identified adverse impacts. It is recognized, however, that while the study's recommendations may be optimal from a highway financing perspective, they may compete (and probably, even conflict directly) with prescriptions or initiatives at other sectors of the economy. This is because economies of states are complex and have multiple interdependent elements. For example, 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 report place 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 interests of the trucking industry who seek to reduce their average transport costs (Volovski et al., 2015). Enforcing these proposals therefore can have ramifications for the state's economy. Therefore, future research could explore the impacts of implementing these proposals on the state's private sector and ultimately, economic output and also examine the impact of this study's recommendations on commercial trucking, truck operating weights of trucks on the roads, and their axle configurations. Furthermore, future studies may compare each state's infrastructure performance relative to the investments (Everett et al., 2013; Everett et al., 2014). This is to identify states that are efficient with their resources and identify what can be learned from them. Similarly, those that are considered inefficient may evaluate their administrative processes and adopt superior management strategies and infrastructure stewardship.

Finally, this report 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 additional data, models can be developed to estimate the costs by infrastructure type such as bridge and pavement (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.

CHAPTER 8. SYNOPSIS OF PERFORMANCE INDICATORS

8.1 USDOT Performance Indicators Part I

During the study period for this project, three (3) transportation-related courses and a study abroad course were offered that was taught by the PIs. The study abroad course was titled “Automation and Connectivity for Sustainable Development of Resilient Infrastructure in Singapore”. This is an undergraduate course worth 3 credit hours, and had 16 students in that class. One of the courses had a teaching assistant who is also associated with this research project. Three (3) graduate students and two PIs participated in the research project during the study period. During the study period, one (1) transportation-related advanced degree (doctoral) program and one (1) transportation-related M.S. program utilized the CCAT grant funds from this research project to support the graduate student in the programs. One graduate student earned his M.S. in 2020 and started his Ph.D. in 2020. The student earned the prestigious national Eisenhower transportation fellowship on two occasions, and Fall 2021 Graduate Student Engagement Award, given by Purdue University’s Lyles School of Civil Engineering. The second graduate student will complete his Ph.D. in 2023, and the third graduate is still working towards her Ph.D.

8.2 USDOT Performance Indicators Part II

Research Performance Indicators:

Two (2) published journal articles and eight (8) conference presentations were produced from this project. These include the Transportation Research Board’s 101st and 102nd Annual Meetings held in Washington, D.C. in 2022 and 2023 respectively, the ASCE International Conference on Transportation and Development (ASCE-ICTD) at Alexandria, VA; the Next Generation Transport Systems (NGTS) Conference at West Lafayette, IN; the AISIM Symposium at University of Texas, Austin, TX; the ASCE International Conference on Transportation and Development (ICTD) 2022, Seattle, WA; the Center for Transportation Asset & Infrastructure Management Conference (CIAMTIS), US Region 3 UTC, at Morgan State University/Penn State University, Baltimore, MD; and the Road School Conference, West Lafayette, IN. The research from this research project was disseminated to 340 people in attendance (from industry, government, and academia) through the 8 conference presentations.

Leadership Development Performance Indicators:

This research project generated 3 academic engagements and 2 industry engagements. The PIs held positions in 2 national organizations that address issues related to this research project. One of the CCAT students who worked on this project holds a membership position in an ASCE national-level technical committee (ASCE Transportation and Development Institute’s Committee for Economics and Finance) that is related to the subject of this study.

Education and Workforce Development Performance Indicators:

The methods, data and/or results from this study are being incorporated into the syllabus for the Fall 2022, Spring 2023, and Fall 2023 versions of the following courses at Purdue University: (a) CE 561: Transportation Systems Evaluation, a mandatory graduate level course at Purdue's transportation engineering graduate programs (average 10 students at each course offering), (b) CE 299: Smart Mobility, an optional undergraduate level course at Purdue' civil engineering B.S. program, (average 12 students), and (c) CE 398: Introduction to Civil Engineering Systems, a mandatory undergraduate level course at Purdue University's civil engineering program, (average 85 students at each course offering). These students will soon be entering the workforce. Thereby, the research helped enlarge the pool of people trained to develop knowledge and utilize at least a part of the technologies developed in this research, and to put them to use when they enter the workforce.

Collaboration Performance Indicators:

There was collaboration with other agencies at the state level (the Indiana Department of Transportation); the federal level (FHWA's Center for Excellence for Project Finance or the "Build America Center"); and 2 institutions (Morgan State University and Penn State University).

The outputs, outcomes, and impacts are described in Chapter 9.

CHAPTER 9. STUDY OUTCOMES AND OUTPUTS

9.1. Outputs

9.1.1. Publications, Conference papers, Presentations

Publications

(a) Innovation and Emerging Technologies.
Title of publication: Emerging transportation innovations: Promises and pitfalls
Full citation: Labi, S., Sinha, K.C. (2022). Emerging transportation innovations: Promises and pitfalls, Innovation and Emerging Technologies 9, 2240001,
https://www.worldscientific.com/doi/10.1142/S2737599422400011

(b) Konstantinou, T., Labi, S., Gkritza, K. (2023). Assessing highway revenue impacts of electric vehicles using a case study, Research in Transportation Economics, Volume 100, 101248,
https://doi.org/10.1016/j.retrec.2022.101248

Presentations

(i) Keck Distinguished Lecture, University of Illinois Urbana Champaign
Title of presentation: Charging Mechanisms for Road Use: An Interface between Engineering and Public Policy.
Full citation: Sinha, K.C. (2018). *Charging mechanisms for road use: An interface between engineering and public policy*, Keck Distinguished Lecture, April 12, 2018, University of Illinois Urbana Champaign, Urbana, IL.

(ii) ASCE International Conference on Transportation and Development (ASCE-ICTD)
Title of presentation: Anticipated changes in highway agency expenditures and revenues, and user equity in the CAV era.
Full citation: Saeed, T.U., Alabi, B.N.T., Miralinaghi, M., Volovski, M., Agbelie, B., Labi, S., Sinha, K.C. (2019). *Anticipated changes in highway agency expenditures and revenues, and user equity in the CAV era*, Presented at the ASCE International Conference on Transportation and Development, Alexandria, VA, USA.

(iii) Next Generation Transport Systems (NGTS) Conference Presentation
Title of presentation: Economic and Financial Implications of EV Infrastructure and Operations.
Full citation: Mwamba I. C., Labi S. (2020). *Economic and financial implications of electric vehicle infrastructure and operations*, Presented (virtual) at the 2nd Annual Conference on Next Generation Transport Systems. West Lafayette, IN, USA.

(iv) AISIM Conference Presentation
Title of presentation: Assessing and Quantifying the Impacts of Vehicle Automation, Electrification, and Connectivity on Highway Expenditures, Revenues, and User Equity.
Full citation: Mwamba I. C. (2021). *Assessing and quantifying the impacts of vehicle automation, electrification, and connectivity on highway expenditures, revenues, and user equity*, Presented at the 16th Annual Inter-University Symposium on Infrastructure Management (AISIM). Austin, Texas, USA. **Best Presentation Award**, AISIM 16 (2021).

(v) TRB Conference Presentation
Title of presentation: Assessing and Quantifying the Impacts of Vehicle Automation, Electrification, and Connectivity on Highway Expenditures, Revenues, and User Equity.
Full citation: Mwamba, I. C., Labi, S. (2022). *Assessing and quantifying the impacts of vehicle automation, electrification, and connectivity on highway expenditures, revenues, and user equity*, Presented at the 101st Transportation Research Board (TRB) Annual Meeting. Washington, DC., USA. January 2022.

(vi) ASCE ICTD Conference Presentation
Title of presentation: Addressing Financial Challenges of Transportation Infrastructure: Infrastructure Financing and Electric Vehicles.
Full citation: Mwamba, I. C., Labi, S., Sinha, K.C. (2022). *Addressing financial challenges of transportation infrastructure: infrastructure financing and electric vehicles*. Presented at the ASCE International Conference on Transportation and Development (ICTD) 2022. Seattle, Washington, USA.

(vii) Center for Transportation Asset & Infrastructure Management Conference (CIAMTIS), US Region 3 UTC, Morgan State University
Title of presentation: Efficiency & equity of highway cost allocation: Threats & opportunities in the age of vehicle autonomy, connectivity, and electric propulsion.
Full citation: Mwamba, I. C., Labi, S (2021). *Efficiency & equity of highway cost allocation: Threats & opportunities in the age of vehicle autonomy, connectivity, and electric propulsion*, Transportation Asset & Infrastructure Management Conference, US Region 3 UTC, Morgan State University, MD, USA.

(viii) Purdue Road School Conference Presentation
Title of presentation: Highway Financing in the Era of ECAVs: Equity Implications of Distance-Based User Fee Structures.
Full citation: Mwamba, I. C., Labi, S. (2023). *Highway financing in the era of ECAVs: Equity implications of distance-based user fee structures.* Accepted for presentation at the 109th Road School Conference, Purdue University, West Lafayette, IN, USA.

9.1.2. Other Outputs

(a) Other

Other products of this research are as follows:

- Frameworks, models, and data to be used in CAV-related instruction, in the Fall 2022, Spring 2023, and Fall 2023 versions of the following courses at Purdue University:
  - CE 561 (Transportation Systems Evaluation), a graduate-level mandatory course at Purdue's transportation engineering M.S. and Ph.D. programs,
  - CE 299 (Smart Mobility), an undergraduate-level elective course at Purdue' civil engineering B.S. program, and
  - CE 398 (Introduction to Civil Engineering Systems), a undergraduate-level mandatory course at Purdue University's civil engineering program
  - CE 597 (Next-generation Transportation), a Purdue graduate course that will be offered in Fall 2024, and annually thereafter.
- Research material and datasets to support future research related to the economic and financial aspects of next generation transportation and smart mobility (electric propulsion, vehicle automation, and transportation connectivity).
- Thesis Publication

  Title of publication: Vehicle Autonomy, Connectivity and Electric Propulsion: Consequences on Highway Expenditures, Revenues, and Equity.

  Full citation: Mwamba, C. I. (2022). *Vehicle Autonomy, Connectivity, and Electric Propulsion: Consequences on Highway Expenditures, Revenues, and Equity*. M.S. Thesis, Purdue University Graduate School. https://doi.org/10.25394/PGS.18070484.v1

9.2. Outcomes

This project produced outcomes that could influence road transportation system finance and cost allocation policies. These are:

- Increased understanding and awareness of the impacts of growing demand of CAVs on the infrastructure revenue, finance, and equity across vehicle classes,
- Consideration of the frameworks developed in this study for long-term infrastructure needs assessment and revenue projections.
- More reliable and robust long-term infrastructure financial planning (by road agencies) accounts for the emergence of advanced technologies including vehicle electrification, automation, and connectivity.

9.3. Impacts

9.3.1 Prospective revision of highway user fees

This report establishes a novel user fee structure designed to address highway finance and cost allocation problems associated with prospective deployment and operations of ECAVs. It has been shown through, multiple highway cost allocation studies and reports that some user groups, typically, passenger cars and other similar vehicles contribute more in highway revenues than the infrastructure repair costs for which they are responsible. At the same time, user groups on the other end of the classification spectrum, typically, trucks underpay their fair share of the cost responsibility. The current user fee structure levies the same fuel tax rate to all vehicle classes despite their disparate contributions to infrastructure deterioration. Although heavy vehicles are charged additional fees such as heavy vehicle surcharges, they are not enough to make up for the disparity. This report proposed a new user fee structure employing a *variable tax scheme*. The variable tax scheme applies a different fuel tax rate to each vehicle class, determined under given constraints to ensure optimal system efficiency and user equity. Furthermore, the variable tax scheme also provides a mode of transition to a distance-based tax as the transportation industry moves towards electric vehicles. This can be charged to electric vehicles at the charging station in the same way as the fuel tax is applied ($/kWh) or levied as a distance based VMT tax. Using the tools presented in this report, governments can set maximum allowable tax rates and other constraints as applicable and solve the associated decision, to problem identify tax rates for each vehicle class that will optimize system efficiency and ensure equity.

9.3.2 Increased awareness of highway system financial inefficiency and inequity

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. The traditional method of reporting user equity allows for individual user group assessment but does not offer a simple way to assess system-wide performance (see Section 5.4.1 of this report). For example, after adjusting the user fee structure, analyses may show the resulting changes in equity ratios across the user groups. For example, one user group's equity ratio may change from 1.3 to 1.1, and another's may change from 0.6 to 0.8. However, it is difficult to quantify the improvement in the system equity following this change. As such, this study proposed a method to assess and report system-wide equity and the changes thereof. The system-wide equity (or inequity) can be represented as the area between the prevailing equity ratio and the ideal equity ratio. A large area means a high deviation from the unit (ideal) 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 calculating the value of the shaded area, 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.

9.3.3 A novel way to assess highway system financial efficiency and equity – The modified equity ratio (MER)

The concept of equity ratios 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 report proposed a modified interpretation of the equity ratio, which will indicate both system efficiency and equity, referred to as the *Modified Equity Ratio* (MER). The MER accounts not only for the proportions of revenues and costs that each user contributes and incurs, respectively, but rather the actual contribution and cost incurred. Unlike the traditional equity ratio, the modified equity ratio indicates 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 indicates 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 entire system.

The outcomes documented in this report shed light on some of the biggest challenges currently facing highway financing: declining revenues and increasing expenditures. Declining revenues can be attributed to increasing fuel efficiency of vehicles and the declining purchasing power of the dollar as inflation rises. Furthermore, the emergence and growth of the demand for alternative fuels and modes of propulsion further exacerbates this problem. On the other hand, increasing VMT has led to increased highway expenditures on the upkeep of highway infrastructure. The need for new infrastructure to accommodate the ever-increasing demand exacerbates this situation. The prospective wide adoption of CAVs is expected to incur significant expenditure on the provision and maintenance of highway infrastructure. At the same time, the prominence of electric propulsion is likely to result in a decline of fuel revenues, leading to an overall reduction in total highway revenues.

Not only has this report shed light on the extent to which these impacts might affect highway financing but has also proposed potential remedies to help address these shortfalls. Using the outcomes of this research, highway agencies can make informed decisions and policies that will both prepare for the growing adoption of CAVs. These might include modification and/or retrofitting of current infrastructure, investing in construction of new infrastructure, etc. Further, highway agencies may need to revise their user fee structure in anticipation of (or response to) revenue changes engendered by wide adoption of EVs and CAVs. Overall, this research provides valuable information for agencies and policy makers to improve the financial sustainability of the highway transportation system.

9.4. Challenges and lessons learned

Over the course of this project, several challenges were encountered. One of the biggest was lack of access to sufficient data. The basic elements of this report are predicated on the estimates of highway expenditures and revenues, and projections of demand, development, and market adoption rates of emerging vehicle technologies. Obtaining data on highway expenditures and revenues from states is a rather laborious and time-consuming process, often mired in regulatory and bureaucratic hurdles. This report relied in part on the readily available highway statistics series published by the Federal Highway Administration. While sufficient for the coarse analyses undertaken in this project, more granular data would be necessary for more detailed analyses in future research. For example, to estimate the future cost of highway infrastructure at a given level of system usage, this research developed cost models using highway statistics data. However, due to the coarse nature of the available data, the resulting models can only provide general estimates of the infrastructure cost. To estimate costs for specific portions such as bridges, pavements, signage, etc., granular data on past expenditures on the relevant items would need to available in significant enough quantities to allow for reliable models to be developed.

Furthermore, this report documents some shortcomings that were identified with the equity ratio as used in traditional reporting to State and Federal governments. Although the equity ratio is widely used, its definition as a ratio of percentages makes it prone to misinterpretation. Therefore, this report encourages future researchers in this subject to question the status quo and to re-evaluate the efficacy of long standing norms of equity measurement and other concepts. As this report suggests, some of the universally accepted norms may need revision.

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APPENDIX

CCAT PROJECT TITLE: Changes in Highway Expenditures and Revenues in an Era of CAVS

Published Related Work

Labi, S., Sinha, K.C. (2022). Emerging transportation innovations: Promises and pitfalls, Innovation and Emerging Technologies 9, 2240001.
https://www.worldscientific.com/doi/10.1142/S2737599422400011

Abstract

Rapid growth in information and communication technologies has spawned a number of major innovations in transportation area, including automation and connectivity. At the same time, the advancement in battery technology has accelerated the electrification of transportation vehicle propulsion. This paper, focusing on highway-oriented surface transportation, examines the current development of these innovations, along with their synergies, benefits, pitfalls, trends, possible barriers to deployment, and wider impacts.

Konstantinou, T., Labi, S., Gkritza, K. (2023). Assessing highway revenue impacts of electric vehicles using a case study,
Research in Transportation Economics, Volume 100, 101248
https://doi.org/10.1016/j.retrec.2022.101248

Abstract

Increasing electric vehicle (EV) adoption poses serious concerns about the long-term adequacy of highway revenues. This paper addresses not only the fuel tax revenue loss across all vehicle classes but also proposes alternative funding mechanisms to recover the loss. Data on average vehicle miles travelled per vehicle, fuel taxes, vehicle registrations, fuel efficiency and consumption are used. The case study location is Indiana, U.S., and analysis period is 2021–2035. The optimal annual fees to recover the loss for each battery EV class range from $241 (in 2021) to $342 (in 2035) for automobiles, $344 to $435 for light-duty trucks, $1246 to $1488 for buses, $969 to $1243 for single-unit trucks, $6192 to $7321 for combination trucks, and $26 to $35 for motorcycles. For the most likely scenario (5% EV market penetration (EVMP) for light-duty vehicles and 30% EVMP for medium-/heavy-duty vehicles), the statewide fuel tax revenue decreases by 21% from 2030 to 2035. The paper also discusses a vehicle-miles-travelled fee and a pay-as-you-charge fee. The study framework is designed to facilitate replication in other states, and the results can provide useful information for assessing the adequacy of the existing revenue models and efficacy of prospective mitigation measures.