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Changes in Highway Expenditures and Revenues in an Era of CAVs, Volume B: Road Users

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Changes in Highway Expenditures and Revenues in an Era of CAVs, Volume B: Road-user Costs

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16. Abstract

At the current time, road agencies and city authorities are considering various stimuli (legislations, policies, programs, and infrastructure investment projects) to support or facilitate electric, connected, and/or automation vehicle (ECAV) transportation. A candid and comprehensive assessment of such stimuli is possible only after due consideration of not only the benefits but also costs of each alternative option to each stakeholder. The road user, one of the key stakeholders of any stimulus, refers to an individual vehicle owner, user of a shared vehicle service, or commercial vehicle fleet owner. This report first presents a general evaluation framework that considers road user perspectives as an input. This framework could be used for ECAV-related appraisals of project investments, programs, and policies where it is sought to consider the user impacts of these stimuli in terms of the user costs or user benefits (reductions in user costs). Then the report presents the various ways in which road users are classified currently and argues for the modification of this traditional vehicle classification scheme to include subclasses to reflect the vehicle emerging technologies. Further, the report identifies the various categories of road user costs in the ECAV era. Further, the report provides data on road user cost values (direct costs only) in the traditional and the emerging era of ECAV transportation, to serve as inputs to such appraisals and evaluations. The use of reliable road-user cost data in stimulus-impact analysis facilitates the Infrastructure Owner and/or Operator (IOO)'s assessment of the systemwide benefits and costs incurred by all road-use stakeholders of the stimulus. In addition, such analysis helps the road users, including the ECAV fleet owner and the individual traveler, to measure the costs and benefits associated with their ECAV ownership and operations compared to other modes.

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AAA	American Automobile Association
APA	American Planning Association
ASA	AV Staging Area
AV	Autonomous Vehicle
CAV	Connected and Automated Vehicle
CPI	Consumer Price Index
DSRC	Dedicated Short Range Communications
ECAV	Electric Connected and Automated Vehicle
EV	Electric Vehicle
FHWA	Federal Highway Administration
HDV	Human-driven Vehicle
ICEV	Internal Combustion Engine Vehicle
IOO	Infrastructure Owner and/or Operator
OEM	Original Equipment Manufacturer
PAYG	Pay As You Go
PCE	Passenger Car Equivalent
PUDO	Pick-Up Drop-Off (area or facility)
RCP	Revenue Contribution Percentage
V2I	Vehicle to Infrastructure
V2X	Vehicle to Other (pedestrian, cloud, etc.) communication protocol
V2V	Vehicle to Vehicle
VMT	Vehicle Miles Traveled
SAE	Society of Automotive Engineers
SAVs	Shared Autonomous Vehicles
TaaS	Transportation as a Service

CHAPTER 1. INTRODUCTION

1.1 Study Background

A transportation stimulus can be defined as any project, policy, program, device, material, or infrastructure that changes the way engineers design, construct, and operate transportation infrastructure. If the change is profound, then the stimulus could be described as transformative or disruptive. For any stimulus, it is useful to assess the impacts (benefits and costs) to provide information to support the analysis of the stimulus' overall feasibility (in the case of ex ante assessments) or validate its overall cost-effectiveness (in the case of ex poste assessments). In some cases, the need for such assessment is driven by legislative or regulatory requirements (e.g., some are required by law to ensure compliance with government regulations); or in the private sector, as part of a business case development related to the stimulus (Sinha and Labi, 2007).

In assessing prospective transportation stimuli for purposes of business case development or to fulfill a legal mandate, the following are often considered: Which impact types to assess, what is the nature of the impacts, and who are the stakeholders? In these respects, the present report addresses the following: impacts – costs and benefits (i.e., cost reduction); impact types – direct and indirect, tangible and intangible, in the context of electric, connected, and/or automated vehicles (ECAV); stakeholder – the road user.

Arguably, road users constitute the most important of all transportation stakeholders because transportation systems intended to serve them specifically. As such, their perspectives of the impacts are critical in evaluating past or future transportation stimuli. A comprehensive impact (costs and benefits) analysis can be beneficial to IOOs. As we discuss in the report, there are several categories of road user costs that could be impacted by the advent of vehicle automation and connectivity, depending on whether the cost is AV-related, CV-related, direct, tangible, and so on. This report generates information and data that could be helpful in the user cost aspects of ECAV-related stimuli evaluations.

1.2 Study Motivation, Objectives and Scope

It is widely anticipated that vehicle automation, connectivity, and electric propulsion will become widespread and will ultimately dominate the highway transportation landscape. Also, it is expected that the adoption of these technologies will influence (and will be influenced by) the costs and benefits that will be borne by road users. This study seeks to throw more light on road user cost issues and to develop user cost values that are helpful in evaluating stimuli intended to benefit the road users.

1.3 Organization of this Report

The remainder of this report is organized as follows: Chapter 2 presents the principles of evaluation as they relate to ECAV systems with emphasis on the impacts to the system users. Chapter 3 presents the various classifications of road users that may be affected by ECAV technologies, and Chapter 4 discusses the various classes of road user costs. Chapter 5 presents some detailed user cost estimates associated with specific components and outcomes related to ECAV, and discusses issues related to the derivation and implementation of some of these cost estimates. In Chapter 6, the report concludes the study. Chapter 7 presents a synopsis of USDOT performance indicators, and Chapter 8 lists the study outcomes and outputs (conference papers and presentations, publications), wider impacts of the study outcomes, challenges encountered, and lessons learned.

CHAPTER 2. THE BASIC PRINCIPLES OF ECAV STIMULUS APPRAISAL CONSIDERING ECAV USER COSTS

2.1 Introduction

A transportation stimulus is often intended and beneficial but there exist examples of stimuli that were unintended or non-beneficial, or both. Intended and beneficial stimuli include policy changes or new designs and often lead to increased positive outcomes and/or decreased negative outcomes to the stakeholders of the system. Examples of these outcomes include: for the road users (including vehicle purchase cost, ride comfort, convenience, safety, access), the road agency (including construction cost, maintenance cost, public relations, reduced exposure to tort, etc.), and so on), and the community (e.g., air quality, noise, privacy, economic development, etc.).

Regarding transportation systems, the landscape of history is punctuated with stimuli that have profoundly impacted the way humankind travels and have generated outcomes that represent the good (economic productivity, mobility, accessibility, safety), the bad (emissions, congestion), and the ugly (increased amounts of travel with the accompanying environmental damage and climate change). In transportation, stimuli include the invention of the airplane, asphalt, the automobile, and the construction of interstate highways. At the current time, human society is on the cusp of vehicle automation, connectivity, and electrification. ECAV is probably the most impactful stimulus in the history of transportation, as it is expected to profoundly influence the direct outcomes of transportation in terms of travel time, safety, mobility, and productivity.

It is useful to assess the effect (or effectiveness) of a transportation stimulus in order to provide information to support the analysis of the stimulus's feasibility (in the case of ex ante assessments) or its cost-effectiveness (in the case of ex poste assessments). In other cases, the need to assess the costs and benefits of the stimulus is driven by legislative or regulatory requirements (impact assessments are often required by law to ensure compliance with government regulations and policies); or in the private sector, as part of a business case development prior to adoption of the intended stimulus.

2.2 Considerations

In assessing prospective transportation stimuli for purposes of business case development or to fulfill a legal mandate (Figure 2.1), the following considerations are made:

- **Which types of impacts are we assessing**? These are the various things that the stimuli could affect beneficially or adversely. For example, the comfort of the drivers and passengers, physical condition of durability of the road infrastructure, economic productivity of local businesses that depend on an efficient roadway system, road safety, traffic congestion, and so on.
- **What is the nature of the impacts?**
    - Monetary vs. non-monetary
    - Direct vs. indirect
    - Tangible vs. intangible

- **Who are the stakeholders**? These are the entities that are affected by the stimulus: the owner or operator of the transportation system (IOO); the government, the road users; the environmental groups, and the general public.

In respect to the above, the present report addresses the following:

1. *Stimulus type*: the 3 collective pillars of next generation transportation: electric, connected, and automated vehicles, or ECAV. This is discussed in Section (b) below.
2. *Stakeholder*: the road user.
3. *Stimulus outcome type*: Costs and benefits, direct and indirect, tangible and intangible. However, the report places emphasis on the direct user costs. This is discussed in Section (c) below.

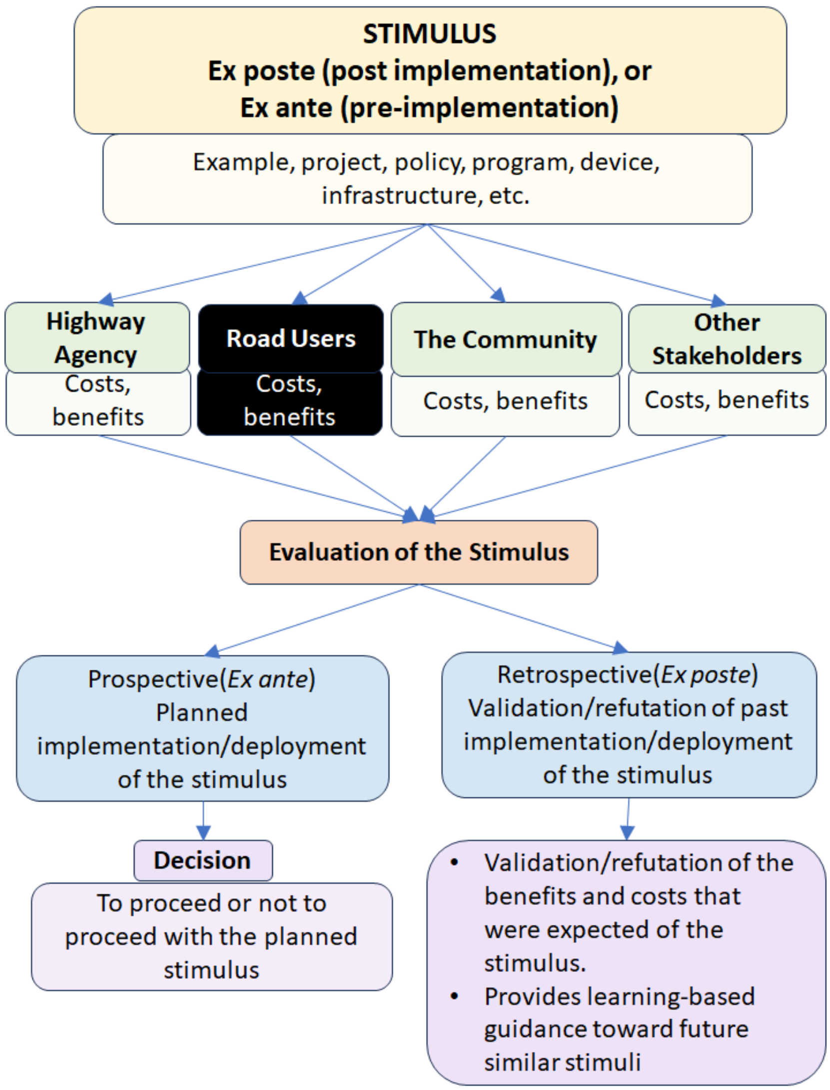

Figure 2.1 Overall evaluation framework for ECAV stimuli and role of ECAV-related user costs (highlighted black)

In addition to the framework presented above, there exists a number of frameworks that exist for evaluating transportation projects, policies, and programs that could be used to appraise ECAV-related policies, programs and infrastructure projects. These frameworks can be found in Sinha and Labi (2008), Berechman (2009), and several appraisal guidelines provided by the World Bank, African Development Bank, Asian Development Bank, USAID, and other development organizations and institutions. Also, the American Association of State Highway and Transportation Officials (AASHTO)'s Red Book, titled "User and Non-user Benefit Analysis for Highways" published in 2010, helps transportation planning authorities at all governmental levels evaluate the road users' economic costs and benefits of their highway improvements and policies. ECAV related road investments are expected to directly impact the road users in terms of travel time, safety, and economic productivity. Therefore, the red book can be used to calculate the user benefits of ECAV-related infrastructure investments, using some of the user cost types and rates provided in this report.

(b) The Three Pillars of Next-generation Transportation

Vehicle automation. An autonomous vehicle (AV) characterizes and navigates the roadway environment (the guideway, obstacles, traffic signs and signals, neighboring vehicles, and lane markings,) using sensors (LIDAR, radar, and camera, for example). The AV's computer possesses algorithms fuse sensor information with connectivity data and use them for path navigation and for controlling the pedals and steer, with minimal human input. AVs have connectivity capabilities and thus integrate sensed information with connectivity-generated information.

Vehicle connectivity. Connectivity helps the vehicle to be aware of happenings in a specified radius from them, helps the AV to exchange information and data to enhance efficient and safe driving enabling; communicate with pedestrians, data centers, nearby vehicles, etc., be cognizant of other road users and their intentions and carry out crash-avoidance maneuvers. Connectivity is facilitates using radio, GPS, DSRC, Wi-Fi, and cellular. Connectivity technology and legislation continue to evolve and are expected to influence OEM costs and road users' indirect or intangible costs.

Electric vehicles (EVs). EVs use electric motors for propulsion and the power source for the electric motor may be from an external source, such as guideway chargers, in-pavement chargers, pantographs (overhead charging wires or arms) or a power source that is internal (battery) which requires recharging or swapping).

Other Pillars. The ECAV revolution is occurring in sync with other emerging transformational transportation developments: shared transportation (which has already taken root) and airborne personal transportation (which is still in a prototype phase and not yet deployed).

(c) The monetary costs and benefits associated with ECAV-related stimuli

A candid and comprehensive assessment of a prospective stimulus such as ECAVs or ECAV-related systems and infrastructure, is feasible only after due consideration of not only the benefits but also each stakeholder's costs of each alternative option. A comprehensive impact (cost and benefit) analysis can help the IOO to assess the system benefits and costs to the road users. Such evaluation is often carried out relative to a base case scenario (which, often, is the do-nothing alternative). As we discuss in the report, there are several categories of road user costs that could be impacted by the advent of vehicle automation and connectivity, depending on whether the cost is AV-related, CV-related, direct, tangible, and so on. In a later chapter of this report, road user cost information (and the relevant sources in the literature) are provided to facilitate the assessment of the monetary costs and benefits associated with ECAV-related stimuli.

CHAPTER 3. CLASSIFICATIONS OF ROAD USERS

3.1 Introduction

The impacts of ECAV on road users will be different for each type of road user. Therefore, it is important to identify the various ways of classifying road users and levels under each classification scheme.

3.2 Classification based on Vehicle Size and Axle Configuration

3.2.1 Traditional Classification

At the current time where vehicles are mostly traditional, highway users are represented by the size of their vehicles, and to some extent, the number of axles. There exist thirteen (13) classes established by the Federal Highway Administration (FHWA) (Table 3.1 and Figure 3.1).

Table 3.1 FHWA Vehicle Classes (FHWA, 2014)

Vehicle Class	Main Description	Detailed Description
1	Motorcycles	"All two or three-wheeled motorized vehicles. Typical vehicles in this category have saddle type seats and are steered by handlebars rather than steering wheels. This category includes motorcycles, motor scooters, mopeds, motor-powered bicycles, and three-wheel motorcycles."
2	Passenger cars	"All sedans, coupes, and station wagons manufactured primarily for the purpose of carrying passengers and including those passenger cars pulling recreational or other light trailers."
3	Other 2-Axle, 4-tire single-unit vehicles other than passenger cars	"Pickups, panels, vans, and other vehicles such as campers, motor homes, ambulances, hearses, carryalls, and minibuses. Other two-axle, four-tire single-unit vehicles pulling recreational or other light trailers are included in this classification. Because automatic vehicle classifiers have difficulty distinguishing class 3 from class 2, these two classes may be combined into class 2."
4	Buses	"Vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. This category includes only traditional buses functioning as passenger-carrying vehicles."
5	2-axle, 6-tire, single-unit trucks	"Vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with two axles and dual rear wheels."
6	3-axle single-unit trucks	"Vehicles on a single frame including trucks, camping and recreational vehicles, motor homes, etc., with three axles."
7	4 or more axle single-unit trucks	"Trucks on a single frame with four or more axles."
8	4 or fewer axle single-trailer trucks	"Vehicles with four or fewer axles consisting of two units, one of which is a "tractor or straight truck power unit."
9	5-axle single-trailer trucks	"Five-axle vehicles consisting of two units, one of which is a tractor or straight truck power unit."
10	6 or more axle single-trailer trucks	"Vehicles with six or more axles consisting of two units, one of which is a tractor or straight truck power unit."
11	5 or fewer axle multi-trailer trucks	"Vehicles with five or fewer axles consisting of three or more units, one of which is a tractor or straight truck power unit."
12	6-Axle Multi-Trailer Trucks	"Six-axle vehicles consisting of three or more units, one of which is a tractor or straight truck power unit. "
13	7 or more axle multi-trailer trucks	"Vehicles with seven or more axles consisting of three or more units, one of which is a tractor or straight truck power unit."

In addition, the FHWA (2014) provided the following guidance on truck classification: "(a) Truck tractor units traveling without a trailer will be considered single-unit trucks; (b) A truck tractor unit pulling other such units in a saddle mount configuration is considered one single-unit truck and will be defined only by the axles on the pulling unit; (c) Vehicles are defined by the number of axles in contact with the road. Therefore, floating axles are counted only when in the down position; and (d) The term "trailer" includes both semi- and full trailers."

This road user classification scheme has long and adequately served highway agencies. The scheme served as the basis for vehicle counts, and thus, traffic volume (which is a critical data type for several agency functions including):

- Assessing the level of travel (road usage)
- Measuring traffic loading on infrastructure
- Infrastructure design (structural and functional capacity)
- Allocating costs of road provision and upkeep, to road users

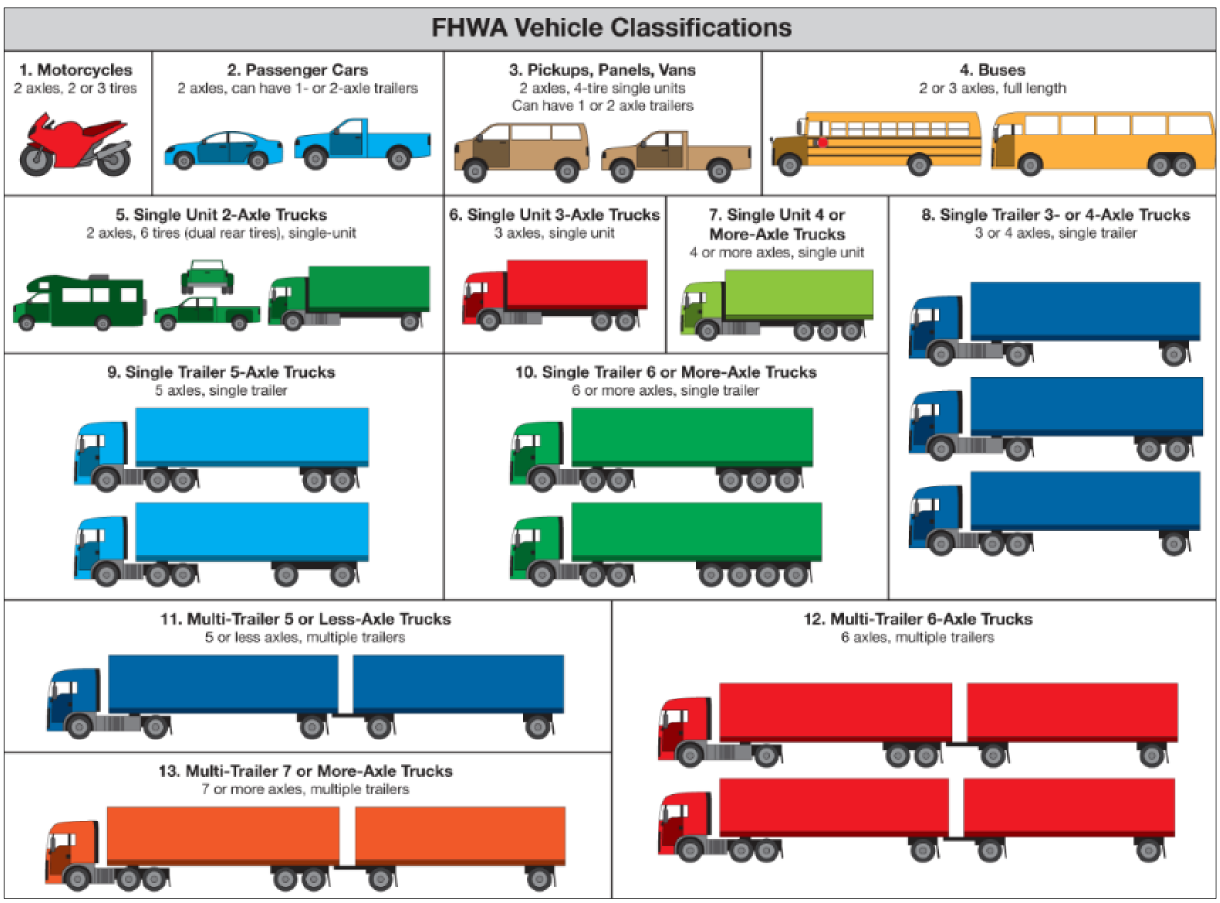

Figure 3.1: FHWA Vehicle classification (FHWA, 2014)

3.2.2 Proposed Classification

In the prospective era of ECAVs, there could exist, for each of the 13 vehicle classes class, new vehicle classes that reflect the emerging technologies, as alluded to by Mwamba (2022). The proposed new classes are presented in Table 3.2. Such revisions in the traditional (FHWA vehicle classification) scheme can be considered imperative because these new subclasses are expected to grow to the point where their numbers will exceed the non-ECAVs, and (b) with the passage of time, the following attributes will be expected to differ significantly across the new sub-classes of vehicles in each class:

- the level of travel (road usage) which is a function of the market penetration of the new technologies,
- the traffic loading on infrastructure and effect on pavement and bridge infrastructure design (structural capacity),
- the requisite lateral road space and the effect on road geometric design (functional capacity),
- Revenues contributed to the highway fund.

Figure 3.2. shows the proposed revision of FHWA classes using class 2 as an illustration.

Table 3.2 Proposed Classification of Vehicles in the ECAV Era

Main Description	**Traditional (FHWA Class)**	**Hybrid electric**	**Electric**	**Autonomous & connected, gasoline/diesel**	**Autonomous & connected, electric**
Motorcycles	1	1H	1E	1A	1AE
Passenger cars	2	2H	2E	2A	2AE
Other 2-Axle, 4-tire single-unit vehicles other than passenger cars	3	3H	3E	3A	3AE
Buses	4	4H	4E	4A	4AE
2-axle, 6-tire, single-unit trucks	5	5H	5E	5A	5AE
3-axle single-unit trucks	6	6H	6E	6A	6AE
4 or more axle single-unit trucks	7	7H	7E	7A	7AE
4 or fewer axle single-trailer trucks	8	8H	8E	8A	8AE
5-axle single-trailer trucks	9	9H	9E	9A	9AE
6 or more axle single-trailer trucks	10	10H	10E	10A	10AE
5 or fewer axle multi-trailer trucks	11	11H	11E	11A	11AE
6-Axle Multi-Trailer Trucks	12	12H	12E	12A	12AE
7 or more axle multi-trailer trucks	13	13H	13E	13A	13AE

Notes: It is assumed here that autonomous vehicles will be (a) connected, (b) either fossil-fueled or electric, not hybrid.

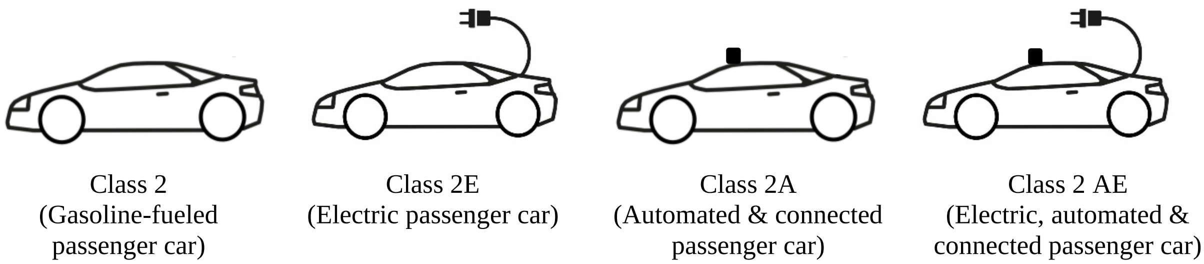

Figure 3.2. Proposed Revision of FHWA Classes (Using Class 2 as Illustration)

3.3 Classification based on ECAV Ownership or Operating Status (OOS)

ECAVs could be classified based on any one of the following user ownership or operating status (OOS) models, as listed below:

a) OOS Class 1: Personal car owner, self-use only: ECAV owner uses his/her ECAV for personal travel only); does not make it available for public use.
b) OOS Class 2: Personal car owner/renter (ECAV owner uses their ECAV for essential trips and rents it for public use when they are not using the vehicle.
c) OOS Class 3: Car fleet owner who only rents the vehicle for public use by individuals or groups of individuals. For example, a car rental company such as Hertz, Enterprise, and Avis. The renter drives the vehicle and is responsible for the vehicle operations, insurance, fuel, and so on.
d) OOS Class 4: User of an OOS class 3 vehicle.
e) OOS Class 5: Ride-hailing company (fleet) car owner who provides the vehicle as and when needed for use by individuals or groups of individuals. This is done through a mobile device-installed user app. For example, a ride hailing company such as User, Lyft, and Zipcar. The hailer is only a passenger and is not responsible for any aspect of the car's operations and does not drive the vehicle.
f) OOS Class 6: User of an OOS class 5 vehicle.
g) OOS Class 7: Driver of an OOS class 5 vehicle.
h) OOS Class 8: Car sharing company, program, or platform where there exists a fleet of cars shared among various patrons, like a car rental service but difference in the sense that rental periods can be much shorter, for example, by the hour.
i) OOS Class 9: Driver of an OOS class 8 vehicle.

The term "Private ECAVs" refer to (a) only, while "shared ECAVs" refer to (b)–(e). Table 3.3 presents use cases corresponding to the OOS classification described above. The table also presents approximate amounts representing the road user under each OOS. These amounts are for illustration only and vary widely depending on some or all the following factors: type of car, age of car, location, and so on. Also, it is worth noting that the OOS classification and Table 3.3 are presented in the context of passenger vehicles only. The discussion could be made to apply also to the users of other vehicle classes.

Table 3.3 Use cases corresponding to the OOS classification

OOS Class	**Use case**
Class 1	Tom owns a saloon vehicle that is electric, connected, and autonomous. He bought the car at $100,000 and paid a $5,000 vehicle title. He commutes to and from work using the car and uses it for post-work and weekend errands and recreational trips. He pays for the annual vehicle registration ($1,000), driver's license every 5 years ($200), pays $500 for the annual vehicle registration, and buys fuel ($1,500). He spends an annualized amount of $5,000 dollars on vehicle maintenance over the life of the car.
Class 2	Kelly owns an SUV that is electric, connected, and autonomous. She bought the SUV at $120,000 and paid a $6,000 vehicle title. Like Tom, Kelly commutes to and from work using the car, but uses it for essential trips only. She pays for the annual vehicle registration ($1,000), driver's license every 5 years ($200), $500 for the annual vehicle registration, and electric charging fees ($1,500). She spends an annualized amount of $6,000 dollars on maintaining the SUV over the life of the car.
Class 3	Perpetual Taxi Services, Inc., is the owner of a fleet of taxis that rents vehicles for public use by individuals or groups of individuals. The company bought the car at $100,000 and paid a $5,000 vehicle title. PTS pays for the annual vehicle registration ($1,000), $500 for the annual vehicle registration, are responsible for fuel ($1,500), and an annualized amount of $5,000 dollars on vehicle maintenance over the life of the car.
Class 4	Jane uses a taxi and pays on average of $2.4 per mile. She is not responsible for any other cost related to the vehicle.
Class 5	Zapp, Inc. is a ride hailing company. The company does not own any vehicles but matches passengers with drivers of vehicles for hire. The costs of the company include technological and administrative maintenance of the service. There are no direct vehicle related costs.
Class 6	Manny owns a vehicle for hire, available to customers of a ride hailing company. He bought the car at $70,000 and paid a $3,500 vehicle title. He uses the vehicle solely for work. He pays for the annual vehicle registration ($600), driver's license every 5 years ($200), pays $300 for the annual vehicle registration, and buys fuel ($1,200). He spends an annualized amount of $5,500 dollars on vehicle maintenance over the life of the car.
Class 7	Jenny uses her phone to hail a vehicle from a ride-hailing company and pays an average of $17 for a 6-mile trip to a gym club. She is not responsible for any other cost related to the vehicle.
Class 8	Moove, Inc. is a car sharing company that owns vehicles and has patron subscriptions with annual fees and reduced rental rates. Cars parked at various points in the city can be rented via the company's mobile app and possessed by the renter using an entry code. Moove also makes its car available for use by non-patrons at a higher fee. Costs are similar to those of Class 3.
Class 9	Kofi uses his phone to hail a vehicle from a car sharing company and pays an average of $2.5 per mile for a 16-mile trip to a recreational club. He is responsible for only gas, mileage and insurance. The vehicle may be manual (in which case the renter drives it) or autonomous.

CHAPTER 4. CATEGORIES OF ROAD USER COSTS

4.1 Cost Categories

Road user costs may be categorized in several ways as discussed in the sections that follow. For a given stimulus appraisal exercise, the consideration of each cost category in the analysis will depend on the type of stimulus, the context of the problem, and type of emerging technology in question, the evaluation spatial and temporal scope, and the evaluation tool (for example, economic efficiency analysis, multi-criteria analysis, real options, and so on).

4.1.1 Direct vs. Indirect Costs

There exists two directs of costs:

(a) the road system causes costs to the road users (for example, road tolls, delay costs caused by congestion, vehicle operating costs caused by rough pavement surfaces, and so on). Some of these costs are out-of-pocket and may be tangible or intangible.

(b) the road users cause costs to the transportation system simply by being a part of the traffic stream (such as congestion, and poor road conditions, and safety), which, ironically, comes back to cause higher operations costs for the users, as indirect costs. For example, an ECAV that enters road traffic causes the following costs:

- Increased traffic congestion, and incurring indirect cost of added travel time to reach its destination,
- Increased pavement damage due to loading, and incurring the indirect cost of pavement damage including tire wear, mechanical failures, and so on, and
- Increased crash exposure to other road users and incurring the indirect cost of higher probability of a crash, time lost due to a crash, and legal liability for at-fault crashes.
  Ultimately, besides suffering these indirect costs, the road user is made to pay, through license fees or overweight permit fees, to generate revenue that is used to improve road capacity, pavement structure, and safety.

4.1.2 Monetary vs. Non-monetary Costs

A monetary cost is one that is expressed in dollar values; otherwise, it is considered a non-monetary cost. The most common examples of monetary costs are those of vehicle purchase, maintenance, insurance, interest payments on loans, and fuel costs. A few non-monetary road user cost types are associated with road systems construction, maintenance work zones, or operations, for example, the road user incurs the non-monetary costs of discomfort and inconvenience in such conditions. Non-monetary costs are incurred not only by the road user but also by the other stakeholders namely, the agency (public relations issues) the community (social disruption when road systems fail physically). Certain non-monetary costs are termed *intrinsically monetary* if they can be converted into dollar values. In addition, the road user's non-monetary costs may be tangible or intangible.

4.1.3 Tangible vs. Intangible Costs

The tangible costs associated with road systems are those costs that can be measured; these costs may be monetary or non-monetary. Intangible costs are those that are difficult to quantify or measure, and they often represent a variety of adverse impacts borne by the road system's ECAV user, road agency, or the community, such as losses in ECAV fleet owner's productivity or customer goodwill. Another example is the privacy that is often lost when the road user is personally identified by the road agency for any reason, for example, government surveillance, traffic conditions monitoring, tracking of vehicle miles of travel for purposes of congestion pricing or EV charging, and so on.

4.1.4 Internal vs. External Costs

Closely related to the concepts of monetization, directness, and tangibility of costs is the cost externality. The *externality* (also often referred to as a *transaction spillover*) of a stimulus is a benefit (positive externality) or cost (negative externality) that is transmitted not through price and is incurred by a stakeholder that did not necessarily agree to the stimulus (Leal et al., 2017; Labi, 2014). A market-driven approach to mitigate negative externalities is to "internalize" them, in other words, quantifying them, attaching a cost value to them, and including them in the stimulus appraisal. Governments often lower negative externalities using a variety of initiatives including environmental legislation (laws on emissions standards, for example); passing civil tort legislation (to prevent/mitigate injuries in the community that arise from the stimulus); providing services or infrastructure that mitigate the adversity; and imposing Pigovian penalties (taxes) or rewards (subsidies) to motivate behavior that mitigates the adversity. A Pigovian tax is a special fee that is imposed on organizations and industries that, through their operations, inadvertently cause negative externalities to the society, such as emissions.

4.1.5 Recurring vs. Nonrecurring Costs

A *recurring* cost is one that is repetitive and thus occurs continuously over the vehicle life cycle while a *nonrecurring* cost occurs only once or a few times within a given time horizon. If the time horizon is one life cycle of the vehicle, then the purchase cost is considered to be non-recurring while the vehicle operations cost (fuel, tolls, etc.) and maintenance cost are considered to be recurring. If the time horizon is infinity, then the purchase costs are also considered to recur because vehicles do not last forever while their services are needed by society perpetually and thus, vehicles are generally replaced upon reaching their end of life.

4.1.6 Fixed vs. Variable Costs

Some costs remain unchanged irrespective of the level of activity or output. These are referred to as *fixed* costs, for example, car insurance and taxes for a specific car, and license and registration fees). *Variable* costs, on the other hand, change in proportion with the level of activity or the amount of output. For a specific cost category, the ratio of variable costs to fixed costs is an important number because it influences the nature and extent of cost economies of scale associated with (a) the volume of vehicle purchases (for the ECAV fleet owner), and (b) the extent of vehicle operations (both ECAV fleet owner and individual ECAV owner).

4.1.7 Initial, Rest-of-Life, and Life Cycle Costs
Initial costs refer to the costs incurred before the ECAV individual owner or fleet owner starts operating the vehicle after purchasing it. Often, this is meant to consist only of ECAV purchase cost and vehicle title cost but may also be extended to include other initial one-time costs associated with the ECAV vehicle. Rest-of-life costs refer to the costs of the vehicle operations, maintenance, insurance, and in some cases, disposal or resale costs. These costs are incurred between the inception of the vehicle use and vehicle resale or end of life The life cycle cost is the arithmetic sum of initial and rest of life costs.

4.1.8 Sunk Costs vs. Working Costs
In the context of evaluating alternative courses of action (for example, using an HDV vs. ECAV; ECAV ownership vs. ECAV sharing, and so on) one often encounters costs that have occurred in the past and are common to all alternatives under consideration, and therefore do not influence the estimation of future costs and benefits of the alternatives. Such costs, known as sunk costs, play no role in the evaluation of alternative actions.

4.1.9 Ownership Cost vs. Societal Cost
The ownership cost is the sum of all costs related to the ECAV. For example, title fee, license, registration, and insurance. This also includes the cost of operations. The societal cost, which is generally not only indirect but also intangible, is the costs borne by society due to the use of the vehicle, for example, noise, emissions, pollution, congestion, and pedestrian safety.

4.2 Car Ownership versus Car sharing/Ride-hailing – Direct, Indirect and Intangible Costs

Car sharing is a broad term that has been defined in different ways across the literature. In this report, we define it to consist only of vehicles that are owned by a fleet owner and the car (and in certain cases), tips, are shared by various users at different times of day. This definition excludes carpooling of commutes.

As Table 3.3 in Chapter 3 suggests, the cost associated with the use of an AV will depend on whether the vehicle is owned by the driver. There exist several reasons why a road user or traveler would prefer to own an autonomous or gasoline car rather than use a taxi or ride hailing one. Pixwell (2023), Ablison (2023), and Litman (2023) offered insightful causes for this. The sections presented below are based on the findings and opinions of these researchers as well as the thoughts of other pundits and web bloggers.

4.2.1 Advantages of car ownership over ride-hailing/car-sharing
The several advantages of car ownership over sharing (ride-hailing/car-sharing) have been discussed in the literature (Ablison, 2023; Litman (2023). These advantages are related to some type of costs associated with each of the two options: some are direct costs, and some are indirect costs, but most are intangible costs. Some of these are identified and discussed below:

<u>(a) Direct Costs</u>
Lifetime cost:
This could also be referred to as the life cycle cost of the car. Some road users consider having a car to be less costly, over the life of the car, compared to constantly using taxis or ride-hailing

services. This is generally true when the car is low cost and highly durable, not always heavily loaded, driven carefully, and is used in an environment or climate that does not cause undue deterioration of the car's components.

(b) Indirect Costs

Time-efficiency and emergency situations:
In areas where there is limited public transportation service, a car owner does not need to wait for buses or trains, or for a taxi or rail hailing service, thereby avoiding time lost in waiting for these modes. Also, regarding buses and trains, the car-owning road user avoids riding in buses and trains that have circuitous routes relative to their destination. Litman (2023) noted road users receive quick response (arrival) to taxis and ride hailing services, but noted that the response time could be longer in situations such as: busy periods (where there is high demand), nighttime (when supply is low), or special transport services such as wheelchair (where time is needed to secure the passenger), and at remote areas. In such cases, it is advantageous to own the vehicle.

Employment opportunities:
Certain jobs or business opportunities require the employee or business associate to own a car. Jobs that require this are typically those where adherence to the work schedule is imperative and punctuality is required strictly.

(c) Intangible Costs

Trip schedule flexibility and travel freedom:
Owning a car gives the road user great flexibility in planning their trips. There is no need to stick to a schedule, and the road user can commence their trip when they prefer or change their start and end times depending on unexpected situations, without depending on mass transit and other modes. The car-owning road user is able to undertake trips spontaneously or change travel or route plans at the last minute or may even choose to deviate off the usual route for an errand or exigency.

Convenience:
The road user that owns a car is afforded a very high level of convenience compared to other modes of transportation. typically keeps personal items in the car that may be needed during the trip. For example, personal sanitation supplies, car seats, and so on. Owning a car provides the freedom to load any needed materials or to transport dependents.

Versatility:
Besides the convenience it offers, a personally owned car could be used for a wide variety of purposes beyond just personal transport. For example, it could be used as a space for storage, a mobile office, or a sleeping place (Ablison, 2023). Also, a personal vehicle can be used to transport heavy or bulky items. These activities are generally only possible when the vehicle is owned, and not one being used for a shared ride.

Emergencies:
In cases of medical or disaster emergencies, and other time-sensitive trips, having a car readily nearby could be beneficial, because it allows the user to be able to respond more quickly. This is particularly the case when the emergency happens at a time or location where there are limited travel options.

Comfort and privacy:
According to Ablison (2023), a personal car could be considered "an extension of one personal own space" where one could adjust the windows, temperature, music sound level, fan; listen to one's preferred kind of music, carry additional pillows, adjust the seat recline and height, and so on. Such level of comfort is possible only when the user owns the vehicle.

Personal security and safety:
Using one's personal car removes the need to walk longer distances or from the transit station and reduces exposure to natural and man-made threats. While public transport is generally safe, having a car can sometimes offer additional security. At late nights, for example, driving home is generally preferable to waiting at a bus stop or train station.

Other reasons why car ownership may be preferable to other modes, include the road user's propensity for self-control of a vehicle, driving as an activity one prides in, or the use of the vehicle for driving as a sport or entertainment. Others include the needed flexibility of movements when one has a young family of children with afterschool programs including gym, soccer, or other appointments. Car owners enjoy travel mode reliability in the sense that they need not worry about missing a train or bus or about having a lengthy wait for a taxi. The high predictability of ownership cost compared to ride hailing cost has been offered in the literature as a reason why ownership is often preferable to sharing.

4.2.2 Advantages of ride hailing over ownership
The several advantages of car sharing over car ownership have been discussed in the literature (Ablison, 2023; Litman (2023). Similar to the previous section, these advantages are related to some type of costs associated with each of the two options: some are direct costs and some are indirect costs, but most are intangible costs. Some of these are identified and discussed below:

<u>(a) Direct Costs</u>

Registration and purchase taxes:
Purchasing a car (considered a personal property in certain jurisdictions) involves a tax. Also, owning a car comes with the responsibility of paying vehicle registration fees. These taxes and fees are gradated based on the vehicle size (and in some cases, gross weight). In some jurisdictions, owners of electric vehicles are made to pay registration fees higher than what is typically paid by gasoline fuel vehicles.

Vehicle insurance costs:
According to legislation, car owners are required to possess some minimal level of insurance on their vehicles. If the car is a finance vehicle, the owner is required to possess an expanded list of

insurance coverage. Insurance costs are a regularly recurring expense at regular intervals, and the insurance costs vary widely, depending on host of factors including vehicle class and type, vehicle age, driver's age and driving history.

Vehicle fuel expenditures:
This is one of the primary costs of vehicle ownership. However, the unit fuel cost and the amount of fuel consumed can be highly variable, not only across different vehicle sizes, brands, and fuel types, but also, for a specific vehicle, across time and location. Electric vehicles and AVs (which are expected to be electric) do not consume fuel and will avoid such costs.

Vehicle repair and maintenance costs:
To keep their vehicle in a state of good repair, car owners bear the cost of carrying out regular scheduled (preventive and periodic) maintenance of their vehicle. These costs are important but not mandated by law. The cost items include replacement of wiper blades and brake pads, tires, light bulbs; fluid top-ups and oil changes. Maintenance expenditures also includes the costs of car cleaning (interior and exterior) and repairs to crashes. Electric vehicles have fewer moving parts compared to ICEVs and generally require less maintenance. However, the EV battery will need regular (albeit, indifferent) inspections and maintenance. Connected and autonomous vehicles are expected to have higher maintenance needs and costs due to regular inspection and testing of the sensors and connectivity devices.

(b) Indirect Costs

Vehicle depreciation:
Car owners incur the cost of their vehicle depreciation which means the resale value of their vehicle decreases over time. This is an indirect cost that is not incurred out of pocket by the vehicle owner. The pattern of depreciation may be one of several shapes: linear, concave, S-shaped, and so on. Road users that use taxis and ride hailing do not need to contend with the depreciation of the vehicles that they use.

Crash risk costs:
Generally, unlike the average car-owning driver, drivers of car-shared vehicles (taxis and ride hails) are more experienced and less likely to get into a crash. Car crashes lead to property damage or injuries, increased levels (and costs) of insurance premiums, and costly bills of repairing the damaged property or medical treatments.

(c) Intangible costs

Environmental impact:
Ride hailing helps reduce the number of cars on the road, thereby reducing (compared to car ownership) the costs associated with greenhouse gas emissions, pollution, traffic congestion, crashes, noise, and other ills associated with higher traffic volumes. These costs are borne not only by the road user but by society in general.

Parking costs:
A car owner driving into a downtown area will incur indirect cost (time looking for parking), intangible cost (the stress of securing a parking spot and towing risk), and direct cost (paying for parking). In such situations, owning a car could be "an inconvenience rather than a convenience" (Ablison, 2023). Users of taxis or ride hailing vehicles do not incur these costs as they simply "get off" at their destinations without worrying about where to store the car.

Ownership stress:
In dense congested traffic corridors or zones, on urban roads having deficient designs, and at areas with multiple types of vulnerable road users (VRUs) sharing the roadway space, road users that drive their vehicles need to contend with the stress of traffic navigation. Alerting or avoiding VRUs and dealing with aggressive drivers could exacerbate such stress. Also, car owners often worry about damage from the elements (wind, flood, hail), vandalism, or car theft. Also, car owners are unable to use their cars when there are periods when they cannot drive (medication, injury, etc.) or when the car is in the maintenance shop. Ride hailing road users do not typically encounter these costs.

4.2.3 Discussion

Overall, the choice between car ownership and ride hailing depends on the characteristics of the road user (age, occupation, etc.), location and road class of typical use, and the vehicle (class, size, and type). For a given road user type, vehicle class, and area of operations, the choice will also depend on the factors discussed above. Liman (2022) observed that, typically, ride hailing could be considered a superior choice for road users whose trips involve less than 6,000 annual miles, whereas for those living in areas of suburban or rural nature or lack public transportation options, typically commute by car, or drive high annual miles, car ownership is probably a superior option. Heineke et al. (2021) stated that convenience is the primary reason for using ride hailing, while safety, price, and reliability are its most important features.

Haustein (2021) stated that private cars exacerbate noise, GHG emissions, and air pollution, and occupy parking space that could have been used for other purposes including active transportation and green space. The author also noted that with current high car dependence, it is difficult to reduce vehicle ownership rates. It has been argued that the societal costs of car ownership are often underestimated and that if individuals were made aware of the full costs of car ownership, they would be more willing to choose other modes. On the other hand, Moody et al. (2012), in their Nature Sustainability article, argued that people tend to place a higher weight on car ownership compared to ownership costs, and they suggest that car ownership reduction is stalled by the high appreciation of automobiles much beyond their "pure functionality, rather than by underestimated costs". Bösch et al. (2018) agreed such prognostications, stating that "private vehicle ownership will likely endure the rise of such new technologies".

According to Morris (2021), it is unlikely that car ownership will die out as travelers' global addiction to personal vehicular transportation will take ages to change, but the need to own one all the time is diminishing. The author notes that autonomous taxis are already in commercial use at several cities and facilitate ride hailing, and that subscribing to an EV program and summoning an

EV when one needs it, or "hailing a self-driving EV for occasional journeys, could soon be the new normal".

A similar sentiment was echoed by Automoblog (2023) (which compared car ownership and ride-sharing) that car ownership has its merits, but the increasing costs associated with car ownership (depreciation, maintenance costs, and fuel prices) is leading to a situation where car sharing is becoming a superior option in terms of affordability. Due to these cost increases, novel business models (where high cost items such as maintenance and depreciation are avoided) are being proposed for personal mobility. The author makes a distinction between ride-hailing and car-sharing services and argues that the latter is a superior and cost-effective alternative to car ownership.

Birr and Stocker (2016) discussed a future blockchain-enabled mobility ecosystem (Figure 4.1) where electric and shared AV fleets or FAVES could reduce on-the-road traffic by 90%. Where user costs including loan repayments and insurance disappear or shrink, and where, secure peer-to-peer (P2P) transactions minimize the need for centralized authorities including ride-sharing service companies. This would allow road users to directly rent or rent out their vehicles under conditions and terms they set themselves.

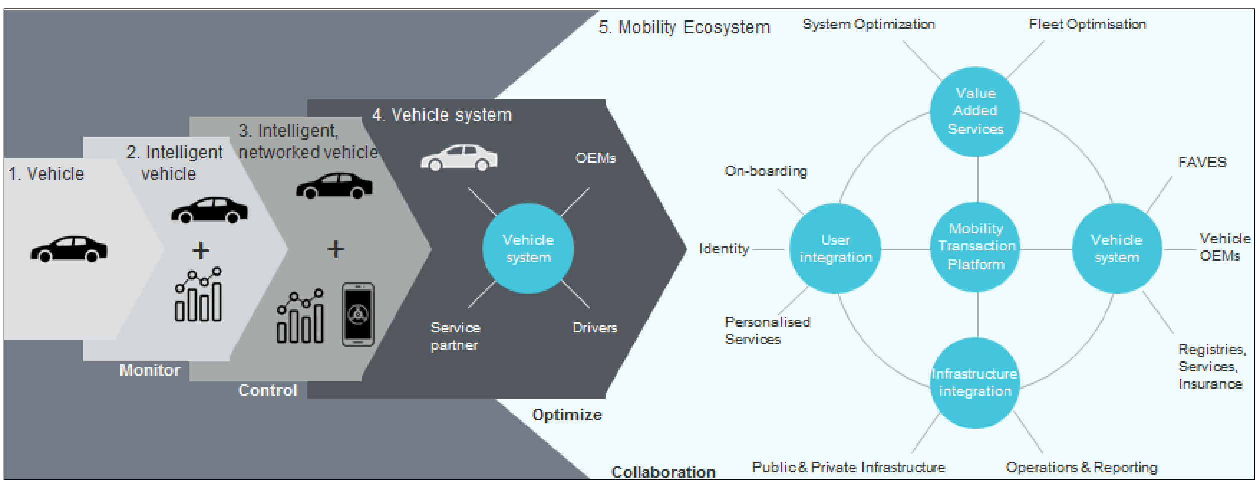

Figure 4.1: Mobility ecosystem innovation (Birr and Stocker., 2016)

CHAPTER 5. EXAMPLES OF DIRECT COSTS BORNE BY ECAV USERS

5.1 Prelude

Direct costs to the system user include fares, fees, and out-of-pocket costs associated with vehicle operations (fuel, tire maintenance, and so on). Indirect costs are those that are related to user safety, comfort, and convenience. From the societal perspective, indirect user costs may include noise, emissions, and air pollution. Out-of-pocket costs refer to the direct cash payments made by road users, for example, tolls, and parking fees. These out-of-pocket costs may be based on the extent to which the road user uses the roadway (e.g., hourly parking rates in a commercial parking garage. The former, which can be described as pay-as-you-go (PAYG) user costs, are more directly amenable to the price elasticities of supply and demand and therefore can be analyzed using the concepts of classic microeconomics.

Out-of-pocket user fees are often meant to generate funds for the upkeep of the roadways. The different road user groups cause different extents of damage to the road system and to its operational performance. As such, the direct user fees paid by each user group is intended to compensate or recoup the “damage” occasioned by that user class to the road system. As such, the road agency through a cost allocation study, typically sets a fee for each road user class based on the “damage” they cause. For each user class, the current fairness of the existing fee can be ascertained by comparing the existing fee paid by that class and their actual cost responsibility. If there is little or no difference between the two quantities, then the user fee structure is termed equitable. However, if some road user groups are seen to be paying significantly less or more than their occasioned damage, then the situation is described as inequitable, in other words, they are they are subsidizing or being subsidized by other road users.

5.2 Sample values of ownership costs

The American Automobile Association (AAA) has tracked the costs of vehicle ownership for decades. On their website, they provide average annual vehicle ownership costs based on a new car, a good driver, and an ownership period of 75,000 miles and 5 years. In 2016, the ownership and operating cost of an average gasoline sedan was determined as $8,558/year (that is, $713/month or 57 cents/mile). For gasoline minivans and sport utility vehicles (SUVs), the costs were $9,262 and $10,255, respectively. Table 5.1(a) and (b) present the breakdown for Class 2 gasoline vehicles.

Regarding the cost by vehicle type, Table 5.1(c) presents the average cost of ownership for each vehicle type ($/mile of driving). According to Betterton, AAA established these cost values by computing the costs associated with depreciation, fuel, financing, insurance, registration, licensing, taxes, repairs and tires, and maintenance, over 75,000 miles of travel and 5 years of ownership. These are averages only, with small sedans having the lowest cost and half-ton pickups having the highest costs. Other factors that affect the costs include the vehicle age, brand, and location of operations.

Table 5.1 Sample Ownership Costs (Betterton, 2023)

(a) Example shown for Class 2 vehicles

User cost item	Average annual amount
Depreciation	$3,759/yr ($313/month)
Insurance	$1,222/year ($102/month)
Maintenance	$792/yr ($66/month)
License/Registration/Taxes	$687/yr ($57/month)
Finance Charges	$683/yr ($57/month)
Tires	$150 per year ($13/month)

(b) Routine maintenance costs – Example shown for Class 2 vehicles

Maintenance	Frequency	Expected Cost
Oil change	5,000 – 7,500 miles	$20 – $75
Tire rotation	5,000 – 8,000 miles	$35 – $100
Basic inspection	5,000 miles	$150 – $250
Brake pad replacement	10,000 – 20,000 miles	$115 – $300 per axle
Air filter replacement	15, 000 – 30,000 (engine and cabin)	$35 – $80
Wiper replacement	Six months	$50 – $61
New tires	Six years or 25,000 – 80,000 miles	$45 – $250 each

(c) Average cost of ownership for each vehicle type Betterton (2023)

Type of Vehicle	Ownership Cost (cents/mile)
Electric	60.32
Small sedan	54.56
Subcompact SUV	61.64
Medium sedan	69.01
Medium SUV	75.37
Compact SUV	62.17
Half-ton pickup	86.21
Midsize pickup	70.25
Hybrid	64.61

5.3 AV Complete Vehicle Costs

- The lifetime costs of the vehicle (purchase, maintenance, and operations) for a new autonomous vehicle are: ($425,757, $288,479–$594,010 [95% CI]). Id higher than HDV costs over the same period, by 49% -- majority of the costs being part of the AV's initial cost. These costs, even when adjusted downward using 5-year Moore's Law forecast still exceed the costs for HDVs by 6% (Freedman et al., 2018).
- With future advancements, urban and autopilot will cause an additional $5,500 to the vehicle purchase price. It will cost $2,000 for self-parking module. Full autonomy may cost $10,000 in the first decade with the technologies on the market (Mosquest, 2015).
- The first generation of truly autonomous cars will likely cost $300K – $400K (Edelstein, 2020). Includes a central computer radar sensors, lidar SYstem, video cameras, GPS, and ultrasonic sensors.
- The Boston Consulting Group estimates that the costs of fully autonomous driving modules will drop significantly over time: for example, $10,000 per unit and $2,700 per unit in 2025 and 2035 respectively (Mosquest, 2015).
- It is projected that in the first 10 years of vehicle automation, there will be additional vehicle costs of $7K – $10K and about $3K in 2035 because of autonomous driving technology (Lim and Tawfik, 2018).

5.4 Costs of AV Units and Components

Figure 5.1 presents the costs of hardware in self-driving car in the year 2015 (Mosquet et al, 2015). The authors cautioned that there is wide variation in these unit costs, ranging as low as from "tens of dollars to multiple thousands" due to wide differences in scale of production, technical specifications, and prevailing maturity of the component. The costs at the time of reporting (2023) are even lower. Also, Table 5.2 presents examples of the costs of various AV components in a different study.

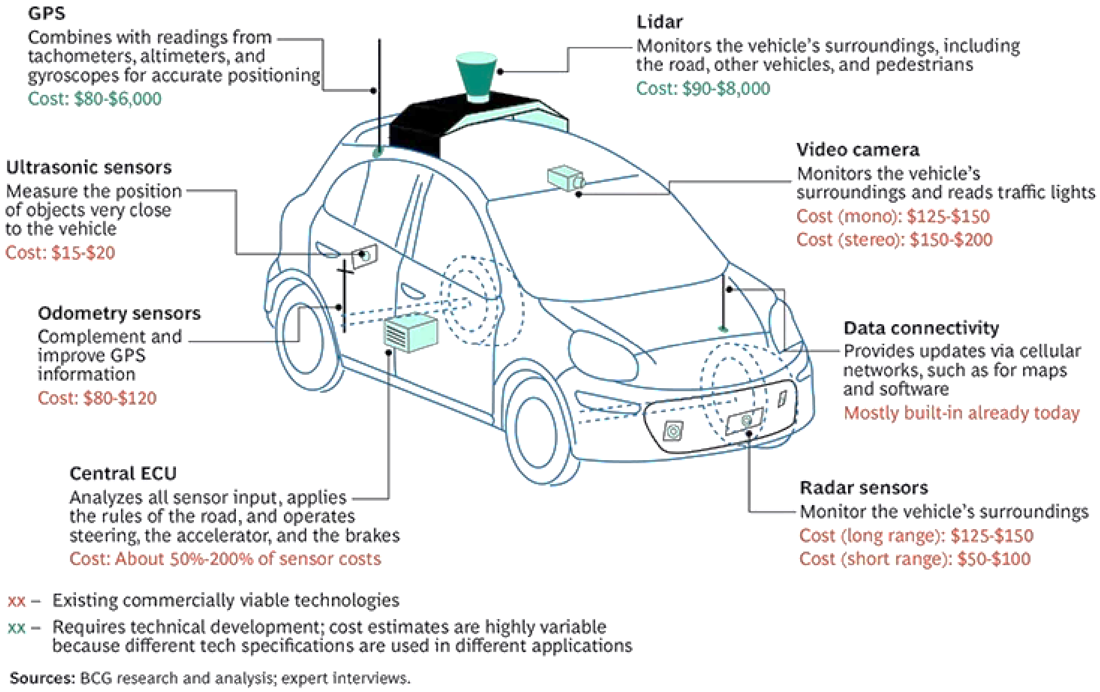

Figure 5.1 Costs of Hardware in Self-driving car as of 2015 (Mosquet et al., 2015)

Table 5.2 AV Component Costs shown in Figure 5.1 (from Mosquet et al., 2015)

Component	**Description**	**Cost**
GPS	Uses readings from instruments (tachometers, gyroscopes altimeters) to provide accurate positioning.	$80-$6,000
Odometry sensor	Compliment and improve information from the GPS.	$80-$120
Ultrasonic sensors	These measure the position and location of objects relatively close to the vehicle.	$15-$20
Central computer	Receives, and processes all sensor inputs, applies the traffic rules, and controls the steering and pedals (acceleration and brakes).	Up to 200% of total sensor costs
Lidar	Monitors vehicle's surroundings (roadway & natural environment, including road pavement, bridges, curbs, other vehicles, pedestrians) in various conditions (day, night, rain, snow).	$90-$8,000
Video cameras	Monitor the vehicle's surroundings and reads traffic signal lights.	Mono: $125-$150 Stereo: $150-$200
Radar sensors	Monitor surroundings of the vehicle (including the road, traffic vehicles, and natural environment).	Short Range: $50-$100 Long range: $120-$150

5.4.1 LIDAR Costs

Chuan et al. (2013) provided detailed cost trends and distributions of various LIDAR components. Due to advancements in technology, these costs have seen sharp declines in the last 10 years. The types of lidar are as follows:

- Microelectromechanical systems (MEMS), often used in LIDAR systems, continues to see decline in size and cost (to less than 2.3mm^2 and 10 cents, respectively (Chuan et al., 2013).
- Regarding conventional laser scanners:
    - Basis Software Surphaser cost is relatively high.
    - FARO Photon: cost is relatively high.
    - DI3D/DI4D: cost has a wide range from low to high.
    - Kreon Zephyr: cost is medium.
    - The Mantis Vision's F5: cost is low to medium.
- Velodyne Lidar: HDL-32E cost is medium.

5.4.2 Camera Costs

Chuan et al. (2013) also provided detailed cost trends of cameras used in AVs as follows:

- Image sensor wafer production capacity has increased over the past 2 decades, leading to lower cost in general. The cost per Mpixel has decreased sharpy over the years.
- Night Vision Systems are available in a few luxury cars. Audi A8L BMW 750i have passive thermal image sensors that detect warm objects, people, animals, and pedestrians at 500 ft. The also has a thermal image sensor (passive), and it costs $2600. Mercedes Benz CL55o's illuminator + Image Sensor (Active) is more costly than those stated above but had greater capabilities as of the Chuan et al. study.

5.4.3 Other Sibling Costs

Vehicle batteries currently cost 3-10¢ per vehicle mile (currently, must be replaced every 100,000 – 150,000 miles but this is expected to reduce with advancements in battery technology. EVs do not pay fuel tax but pay a registration surcharge at certain states so that agencies can recover the revenues lost by their use of an alternative source of propulsion energy. APA (2016) expects that such cost-recovery road-user fees would add $0.05-$0.10/vehicle-mile, thereby bringing EV operating costs to $0.10-$0.25/mile, almost at par with their ICEV counterparts.

5.5 AV Ownership Costs

- As of 2015, for a standard car, the operating costs (gas, maintenance, tires) is $0.21/mile, and the fixed costs (depreciation, insurance, finance, and registration-related costs) is $0.61/mile. This is compared to the operating cost is $0.17/mile and fixed cost of $0.26/mile for the "future mobility car (FMC)" (Albright et al., 2015). The FMC is considered to be a small sedan costing $25,000 with 3-year replacement intervals and no residual value, shared use, and 40,000 miles of operation annually.
- SAVs could bring in substantial benefits (profit) to shared vehicle fleet owners because the current system cost can be reduced by as much 50-80% depending on the driver wages in the area of interest. However, the absence of a driver to give rise to new indirect or intangible costs to the road user, for example, insanitary conditions, luggage lifting and

carrying to curb, and general guidance for travelers unfamiliar with their destination.

- Given the initially very high cost of ECAVs, it is generally expected that most travelers will experience driverless vehicles through ridesharing.
- The AAA (2020, 2021) reported average ownership costs among different cost areas (finance, depreciation, insurance, taxes, fuel, license, registration and general maintenance, and repair/tires).
  - From 2050 to 2060:
    - HDV costs = 54.56¢/mile (small sedan, 2022)
    - E-HDV = 57.58¢/mile (2022.
    - AV ownership cost = $1.01/mile
    - SAV use cost = $0.197/mile
  - From 2060 to 2070:
    - AV ownership cost = $0.35/mile
    - SAV use cost = $0.0034/mile
- "The average ownership costs per mile in 2022 for 20K miles/year is 70¢, an increase from 55¢ in 2021. The average ownership costs per mile for 10K miles decreased from 83¢ in 2021 to 76¢ in 2022."
- Levine (2017) stated that fully autonomous vehicles (FAVs) will have very high costs, "hundreds of thousands of dollars".

5.6 AV Operating Costs

- The individual vehicle or average cost and revenues per mile are key cost and revenue metrics of a specific road user: the TaaS fleet industry (Arbib and Seba, 2017) and owner (often, the driver) of a single vehicle being used as a SAV. In the case of the private ECAV owner, the key metric is the cost per mile, as benefits are nonmonetary and in some cases, intangible.
- Optimistic forecasts are that ECAVs will cost less than $0.05/mile to operate (APA, 2016).
- A private AV will have operating costs of $0.80-$1.20/mile which will be expected to fall to $0.60-$1.00/mile as AV technology becomes available in less expensive vehicle models and brands (APA, 2016).
- The cost of autonomous driving (and the reliability of such costs), which include additional hardware and software, vehicle and sensor maintenance, and mapping subscriptions, are expected to decrease with time: SAV (autonomous taxis) will likely cost $0.50/mile to $1.00/mile: this is lower compared to human-driven ICEV taxis but higher compared to a personal human-operated vehicle (APA, 2016).
- Transportation vehicle autonomy and electric propulsion will reduce fleet ownership costs drastically and will translate into vastly lower-cost transport alternatives for travelers who patronize TaaS – 4-10 times less costly ($/mile) compared to buying a new car and 2-4 times less costly compared to operating an existing vehicle (Arbib and Seba, 2021).
- SAVs may lead to consequences in inequity in transport access (Creger et al., 2019; Emory et al., 2022), road user equity an important intangible cost to this stakeholder.
- Currently, AV ownership and operating costs are $0.66–$1.00/mile in 2018, and in 2035, will cost $0.30–$0.50 cents/mile (Bosch, 2015).
- The total cost of owning an AV will be $0.58/mile in 2025 and $0.53/mile in 2030.

Regarding ride sharing in an AV, this cost will reduce to $0.35/mile in 2025 and 0.25/mile in 2035 (Insurance Journal (2018).

- SAVs will likely cost $0.50 – $1.00/mile. This is less costly compared to human-operated taxis ($1.50–$3.00/mile). (APA, 2016; Nunes & Hernandez, 2020; Litman, 2022).
- AVs will have lower costs of travel time and reduced energy costs (Gucwa, 2014) but SAVs could cause higher energy consumption and emissions overall due to higher usage levels (Zhong et al., 2023).
- Sivak and Schoettle (2018) discussed the relative costs of driving BEVs and ICEV vehicles in the individual states of the US, and found that the ratio of the average costs of driving an average ICEV and an average BEV is 2.3 in the US (highest is 3.6 in Washington and lowest is 1.4 in Hawaii)
- There may be little or negative energy cost savings with AVs compared to HDV because of larger sizes of AVs to serve as mobile offices (Litman, 2022). The interior setting of SAVs will likely be such that it may increase the need for office space, recreation, or comfort. This will require larger vehicles (Figure 5.2) that consume more fuel or require more electric power for propulsion.

Figure 5.2 SAV interior settings may increase space demands for comfort or work areas, leading to larger and heavier vehicles that consume more electricity thereby raising energy costs.

- Due to their higher initial costs, AVs may see significantly higher financing costs compared to ICEVs (Lim & Tawfik, 2018).
- Compared to SAV users, private AV users may incur generally higher costs of insurance because of their sole responsibility for that cost item.
- AV technology (such as the camera and LIDARs) is inherent suited for additional security and therefore provide vehicle surveillance with its sensors. That way, theft insurance would likely be lower compared to HDVs. Also, insurance for liability, injury, and vehicle damage associated with traffic crashes, is also likely to be lower for AVs, as indications

are that AVs may reduce accidents significantly (APA, 2016).However, the vulnerability to hacking and hence, theft or disablement, which are intangible user costs unique to automated driving systems, could increase the insurance costs.

- AVs and SAVs will likely be electric; The EV powertrain consists of far fewer parts than ICE, and this makes assembly repair easy and therefore generally less costly. As such, regarding vehicle maintenance/operations, on average, ICEV owners will spend more compared to AV owners.
- Connectivity-enabled platooning of trucks will reduce the energy costs of carriers (Hussein and Rakha, 2020).
- Hybrid electric vehicles is generally a suitable option to reduce the user costs of fleet owners, particularly for higher mileage vehicles (Lin, 2013).
- Regarding vehicle licensing, registration, and purchase taxes, driver licenses may become obsolete and vehicle registration fees will become more important. In some jurisdictions, driver license fees may be replaced by vehicle license fees (the permission to humans to drive on the roads (driver's license) may be replaced may by the permission to vehicles to drive on the roads.
- AV owners will incur vehicle ownership costs: title and registration, unlike SAV users.
- Regarding vehicle depreciation, due to higher levels of loading and frequency of internal use, (due to vehicle shared), there will likely be higher rates of wear and tear, and higher depreciation costs for SAVs compared to private AVs.
- Oh and Sinha (2008) developed VMT fee levels for various vehicle classes. VMT costs could be a convenient alternative to fuel taxes and EV fees. However, they may come at the added agency cost of vehicle tracking and the road users' intangible cost associated with privacy loss.
- AV users will likely incur platform fees or fees for using pick-up drop-off (PUDO) facilities or ASAs (AV staging areas). In some cases, however, this cost will be built to the travel service cost and will not be borne directly by the traveler.
- Road users travel time cost is a function of two variables: (a) amount of travel time (hrs) and (b) value of travel time ($/hr). Both the amount and the value of travel time are expected to change (albeit, in different directions) in the era of ECAVs (Zhong et al., 2020).
- Evidence from the price trends of vehicle innovations in the course of history (for example, automatic transmission) suggests that initially, AVs will be available only for higher end vehicle models and brands, and will likely take several years or decades to become standard features for lower end brands and models (Litman, 2023). This prognostication is already being manifest as AV capability and features are currently very common on high end vehicles and not so common for the lower end ones (Autobest, 2023).
- Road users' and shared vehicle fleet owners' vehicle insurance premiums will change (likely, a net reduction) to reflect the lower frequency but high severity of accidents (Albright et al., 2015)
- Over the foreseeable future, it can be expected that the cost of private AV will be $0.80-$1.20/mile on average but will subsequently fall to $0.60 to $1.00/mile as AV technology becomes more widely available (Litman, 2022).
- Kok et al. (2017) predicted that electric SAVs will cost less than $0.10/mile, and suggested that with such low cost, several trips could be funded through advertising, Litman (2022)

cautioned that such estimates may need to include other costs including vehicle cleaning (interior and exterior), vandalism repairs, profits, deadhead cruising (no-passenger travel) and so on.

- SAVs will likely be associated with user costs of inconvenience due to their possibly insanitary conditions (Broussard, 2018).
- SAVs will probably need to be cleaned every 5-15 trips, with some repairs occasionally to repair interior damage. This will lead to $0.33-2.00 cost increase per trip (assuming $5-10 cleaning cost per vehicle, plus travel time and costs for driving to and from cleaning locations (Litman, 2022).
- Bösch et al. (2018) stated that service costs will continue to be main cost factors that will drive the business models for SAVs.
- Autonomous vehicles are found to be more cost-effective when they are used as taxis (Freedman et al., 2018).
- Figures 5.3 and 5.4 compare user cost estimates. It was explained in the literature that the "average costs are what travelers consider when deciding whether to purchase a vehicle; operating (variable) costs are what vehicle owners consider when deciding how to make a particular trip" (Liman, 2022). Electric AVs may likely to be less costly compared to a majority of other modes. SAVs will be less costly than taxi and ride hailing services but more costly compared to the cost of private automobile operations. Further details of these user cost calculations are provided by Litman (2022).

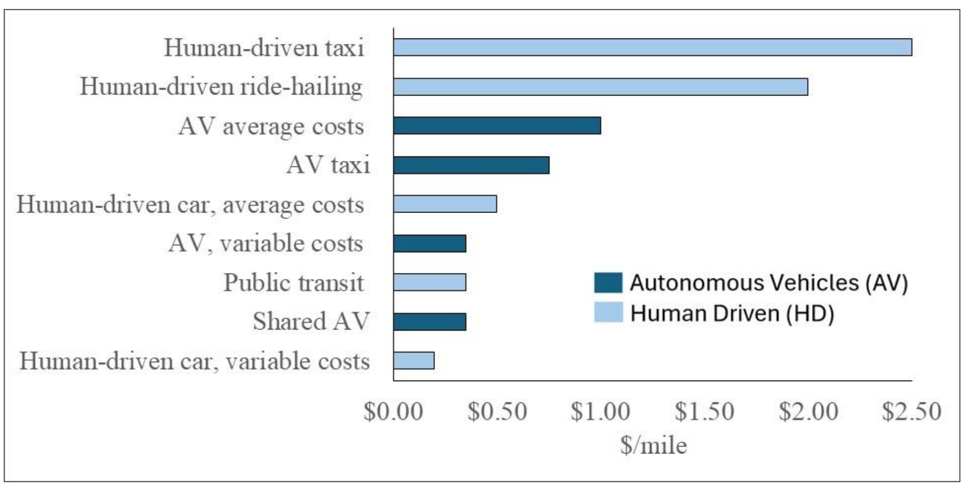

Figure 5.3: Total unit cost comparison across vehicle categories (adapted from Litman, 2022)

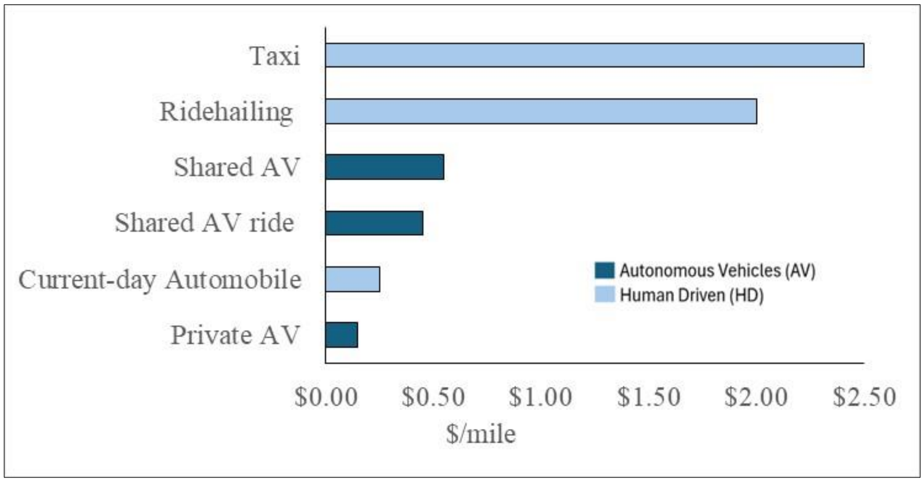

Figure 5.4: Cost comparison across vehicle categories and types (Litman, 2022)

5.7 User Benefits of Safety and Mobility regarding the ECA Technologies

Yue et al. (2018) evaluated safety benefits of vehicles' connectivity, advanced driver assistance, and low level automation systems, and found that these technologies generally exhibit higher safety benefits for heavy trucks compared to light vehicles. Albright et al. (2015) indicated that in the era of AVs, there will be fewer but more severe crashes. Thus, the frequency of insurance claims will decrease but the claim amounts will decrease.

5.8 EV Costs to the Road User: Discussion

In 2001, Delucci and Lipman argued that in order for EVs to be cost-competitive with gasoline ICEVs, the battery manufacturing cost must decrease sharply and should have a longer life. Several other studies have echoed this sentiment (Feng et al., 2012). In 2020, Ayodele et al. (2020) argued that EVs were not yet competitive with conventional ICEVs due to the high cost of batteries, and that advancements in battery technology is expected to reduce the cost of EV batteries, making EVs increasingly competitive.

EV fees generally have 3 mechanisms of payment: A flat periodic fee annually (this is often simply an add-on to vehicle registration and is independent of the extent of road use), a pay-as-you-go (PAYG) fee (4/KW-hr) imposed at the point of charging, and a VMT fee. For purposes of convenience, periodic fees other than annual (daily weekly, monthly) could be made automatically via deductions from a pre-established account or credit card. A flat annual EV fee may not be acceptable to road users due to the size of the fee when viewed from an annual perspective, thus, a VMT fee or pay-as-you-charge fee may be more equitable. Equity concerns may be assuaged further where the EV is gradated on a weight scale. VMT fees are convenient but require tracking of the vehicle and imposes additional (but intangible) user costs of privacy loss.

EV fee levels could be made to yield the same revenue as traditional fee structures. For example, Konstantinou et al. (2020) considered the most likely scenario of EV growth in Indiana from 2021 to 2035 and determined that the state will need to charge the following annual fees to recover the revenues that would be lost due to declining fuel tax receipts (Table 5.3).

Table 5.3: Annual fees to recover the loss of fuel tax revenue

Road-User Group (FHWA Vehicle Class)	**2021**	**2035**
motorcycles	$26	$35
Automobiles	$241	$342
Light trucks	$344	$435
Buses	$1,246	$1,488
Single-unit trucks	$969	$1,243
combination trucks	$6,192	$7,321

According to Konstantinou et al., (2022), potential obstacles to EV fee implementations include technological challenges, privacy concerns, administrative costs, and policy-related challenges (equity considerations, implementation process, and partnerships). The authors recommended that in establishing EV user fees, a critical initial step is to carry out pilot programs that not only gauge the road-users' perspectives and willingness-to-pay but also assess the revenue-generation potential of prospective fees and to gain public acceptance and support.

CHAPTER 6. CONCLUDING REMARKS

As governments and organizations continue to mull legislations, policies, programs, and infrastructure investment projects to support or facilitate the emerging transportation technologies (electric, connected, and/or automated vehicles (ECAV), they seek objective and rational frameworks that facilitate a candid and comprehensive appraisal of proposed stimuli related these technologies. Such appraisals are possible only when the appraisal takes into account not only the benefits but also costs of the proposed stimulus incurred by each of the key stakeholder. The road user who owns (and/or travels using any vehicle type including ECAV), is one of the key stakeholders of any transportation stimulus.

In this report, a general evaluation framework that considers road user perspectives as an input is presented first. Road agencies and development organizations may use the framework (or modify their existing frameworks in accommodate ECAV considerations) for ECAV-related appraisals of project investments, programs, and policies. This is particularly important where it is sought to consider the road user impacts of these stimuli in terms of the road user costs or user benefits (reductions in user costs). Then the report presents the various classes of road users, and argues for a new subclass of vehicles to complement the existing traditional (FHWA) classification. Then the report establishes the various ways by which ECAV-related user costs could be categorized. Further, the report provides data on road user cost values in the traditional and the emerging era of ECAV transportation, to serve as inputs to such appraisals and evaluations.

Comprehensive impact analysis with reliable data on road user costs could facilitate the Infrastructure Owner and/or Operator (IOO)'s assessment of the systemwide benefits and costs incurred by all road-use stakeholders of a prospective ECAV-related stimulus. In addition, such analysis helps the road users, including the ECAV fleet owner and the individual traveler, to measure the costs and benefits associated with ECAV travel compared to other modes.

CHAPTER 7. SYNOPSIS OF PERFORMANCE INDICATORS

7.1 USDOT Performance Indicators Part I

During the study period for this project, the PI taught 3 transportation-related courses and a study abroad course ("Automation & Connectivity for Sustainable Development of Resilient Infrastructure in Singapore", an undergraduate course worth 3 credit hours, with 16 students). Two undergraduate students participated in the research project during the study period, one funded by Central State University through a CCAT grant, and the other was unfunded.

7.2 USDOT Performance Indicators Part II

Research Performance Indicators:
As of the time of reporting, no journal article or conference presentation has yet been produced from this project. The preparation of two conference papers is currently in progress.

Leadership Development Performance Indicators:
This research project generated 3 academic engagements and 2 industry engagements. During the earlier half of the study period, the PI held positions in 2 national organizations that address issues related to this research project, including serving as chair of an ASCE national-level technical committee (ASCE Transportation & Development Institute's Committee for Economics and Finance) that is related to the subject of this study.

Education and Workforce Development Performance Indicators:
The data generated from this study is being incorporated into the syllabus for the various Fall and Spring 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). Regarding past offerings, the students in these classes will soon be entering the workforce. Thereby, the research helped (and is helping) 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.

The outputs, outcomes, and impacts are described in Chapter 8.

CHAPTER 8. STUDY OUTCOMES AND OUTPUTS

8.1. Outputs

No journal paper has been produced from this research. Two conference papers are under preparation.

Other products of this research are as follows:

- A CAV project evaluation framework and road-user cost data that was used in past course offerings (and will be used in future offerings, that is, Fall 2024, Spring 2025, and Fall 2025 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), an 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.

8.2 Outcomes

This project produced the following outcomes that could influence road transportation system evaluation in an era of CAVs:

- Increased understanding and awareness of the road user costs associated with CAVs in a privately owned and shared-use mode.
- Inclusion of more reliable estimates of road user costs for more robust long-term infrastructure investment appraisal (by road agencies) in a manner that accounts for the emergence of advanced technologies (vehicle electrification, automation, and connectivity, and shared transportation).

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