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External Economic Costs of Intelligent Urban Transportation Systems: A Method to Evaluate the Externalities of Comparative Technology Adoption Pathways in the Urban Mobility Service sector

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EXTERNAL ECONOMIC COSTS OF INTELLIGENT URBAN TRANSPORTATION SYSTEMS: A METHOD TO EVALUATE THE EXTERNALITIES OF COMPARATIVE TECHNOLOGY ADOPTION PATHWAYS IN THE URBAN MOBILITY SERVICE SECTOR

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by
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ABSTRACT

By 2050, urban mobility demands will increase to 2.6 times the current level, even faster than the urban population growth. Current urban transportation plans fail to address these rapidly increasing urban mobility demands. Inefficient urban transportation generates great economic losses in traffic congestion, air pollution and climate change.

The current urban transportation pressure and emerging technology-driven trends have revolutionized how industry players respond to changing consumer behavior, develop partnerships, and drive transformational changes. A transition (P2S) from current product-based competition to a marketplace focused on mobility services is expected. Electric vehicles, automated driving systems and mobility-sharing platforms are introduced to provide mobility services by market-agents in the P2S transition.

The adoption of these technologies has proven to be beneficial in simulations. In reality, externalities occur when introducing disruptive technologies into a marketplace with the absence of instrumental institutions (non-market agents). However, all agents fail to evaluate the economic impacts of different technology adoption pathways at the mass-adoption scale.

The method proposed in this research contains: (1) a resource-demand view framework to capture multiple technology adoption pathways in the P2S transition (2) scenario designs that integrate electric vehicle technology, automated driving systems, and mobility sharing platforms in one or several combinations (3) a set of economic externality models to evaluate the costs of traffic congestion, human health impact, and climate change resulting from each variation.

This dissertation is an informative comparative study that demonstrates the externalities (social economic impacts) of different sets of technology adoptions in urban mobility. Regulators can utilize the method while funding research and designing regulations for disruptive automotive technologies. The method also provides a platform for market-agents to quantify the economic impact of new product designs in the mobility marketplace.

DEDICATION

This work is the result of the collaboration of a group of wonderful people who must be given credit.

First of all, I want to thank my committee members who have coached me step by step throughout my doctoral program. Dr. Bodde, who recruited me from Business School. His experience and passion encouraged me to keep discovering new knowledge and his support and patience reminded me of the importance of my work. He lead me on a fun and satisfying doctoral journey. If I were the happy warrior, Dr. Bodde is the best mentor I could possibly ask for. Together, we fight the good fight.

Dr. Mears, for always providing challenges and logical guidance to keep me moving forward; Dr. Taiber for bringing a variety of opportunities to work with industrial partners; Dr. Brooks for honest and insightful feedback; Dr. Jia for introducing advanced knowledge and new research perspectives.

Next I would like to thank Even Skjervold for being my life partner. Even helped me build new research ideas; proofread my dissertation word for word; cooked me meals so I did not have to live on baby carrots and coffee cheered me up through the times I thought I would never become a doctor.

Lastly I want to thank my friends for supporting my dream; my parents for setting high standards and telling me that I can always achieve more. Their faith and trust helped me become a curious, decisive and brave young lady.

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1. INTRODUCTION TO URBAN MOBILITY CHALLENGES

1.1 An introduction describing the background of the problem

1.1.1 The consequences of rapidly increasing mobility demand in urban metro areas

The first area to face the rapidly increasing mobility demands due to high population density is the urban metro areas. The United Nations reported that by the year 2050, 70% of people will live in urban metro areas [1]. ADL Future Lab reported that the urban mobility demands will increase to 2.6 times the current level, even faster than the growth rate of urban population [2]. Current urban transportation plans fail to address the rapidly increasing urban mobility demands.

Some consequences of inefficient urban transportation are listed:

- In 2014, congestion caused urban Americans to travel 6.9 billion hours additional, and to purchase and extra 3.1 billion gallon of fuel. The national congestion cost was $160 billion [3].
- Urban air pollution is connected to 1 million premature deaths each year. Urban air pollution is estimated to cost approximately 2% of GDP in developed countries and 5% in developing countries. Over 90% of air pollution in cities is attributed to vehicle emissions [4].
- Heat island describes built up areas that are hotter than nearby rural areas. The annual mean air temperature of a city with 1 million people or more can be 1.8 – 5.4°F warmer than its surroundings [5]. The replacement of internal-

combustion engine (ICE) vehicles by electric vehicles can reduce heat emissions in urban area [6].

1.2 Transformation of the automotive industry and the Product-to-Service Transition

The automotive industry is a wide range of companies and organizations involved in the design, development, manufacturing, marketing, and selling of motor vehicles. The current urban transportation pressure and emerging technology-driven trends will revolutionize how industry players respond to changing consumer behavior, develop partnerships, and drive transformational change [7].

The transition (P2S) from current product-based competition to a marketplace focused on mobility services is unclear. The social economic benefits of adopting different sets of technologies in the transition have not been measured.

The three major leading indicators of the transformation in the transition in the automotive industry are technology push, consumer pull and regulation.

A. Innovation inputs: Technology push in the transition

Traditional technical innovations in the automotive industry tend to focus on optimizing the performance of a vehicle as a product. The innovative parties are primarily tiered suppliers and original equipment manufacturers (OEM). The P2S transition in the automotive industry challenges the traditional innovation process due to technology complexity and new perspectives from nontraditional participants.

The following innovation activities have been observed in the P2S transition:

- Participants from the technology industry are focusing on mobility service related user behavior learning, and software system integration. These participants help improve user experience in mobility services, and assign travel tasks based on user preferences.
- OEMs and tiered suppliers develop and implement alternative fuel technologies and partially automated driving technology (level 1-2 by NHTSA standards). The technologies improve travel efficiency of individual vehicles, but do not address traffic efficiency at a system level.

B. Technology adoption key factors: Market pull and consumer preferences

a. Mobility sharing trend in Generation Y

Gen Y (those born from 1977 to 1994) is emerging as the largest segment influencing the automotive industry. Gen Y has grown up in a connected world that has changed how they interact with friends, family and the world around them. The needs to complete tasks that require access to a vehicle are being met by emerging transportation models such as car-and-ride-sharing, and improved public transportation. These multimodal systems are shifting preferences to vehicle access in contrast to vehicle ownership. As a result, the basic concept of mobility is being redefined for this group. Vehicle sharing is becoming an increasingly large component of this redefinition [8]. In the mobility-sharing trend, consumer preferences (such as price, travel time, environmental consciousness, etc.) will lead to different mobility sharing solutions.

b. Hidden problems in mobility sharing

Shared mobility is defined as the shared use of a vehicle, bicycle or other mode of transportation. It is an innovative transportation strategy that enables users to gain short-term access to transportation modes on an “as-needed” basis [9]. A number of environmental, social, and transportation-related benefits have been reported due to the use of various shared mobility modes. However, the benefits have not been quantified in economic models to demonstrate social economic benefits. Another concern is that market participants only consider the personal benefits and costs in making their decisions; market outcomes (the aggregate of individual decisions) will not be socially optimal. This is the classic example of the tragedy of the commons.

C. Regulation and policy: The mobility service adoption catalyst

Regulation is a rule of order having the force of law, prescribed by a superior or competent authority, relating to the actions of those under the authority’s control. Regulations can encourage or discourage innovation and technology adoption in the marketplace. In mobility service sector, regulations are observed at different levels:

- In the automotive industry, regulations directly affect the way cars look, how their components are designed, the safety features that are included and the overall performance of any given vehicle. For example, the Corporate Average Fuel Economy is a set of nationalized standards for automotive fuel efficiency that require substantial investment from automotive companies to ensure new car models are fuel-efficient and safe [10].
- In mobility service marketplace, especially new forms of mobility service,

regulations directly affect the operational activities and geography of service providers. For example, Uber and Lyft are not allowed to operate in Austin, TX without a fingerprint security check system due to local regulation [11]. Another example would be DriveNow, who has been successful in Europe, but stumbled in the San Francisco market due to parking and car-sharing regulations [12].

1.3 Problem statement

Oblivious to the social economic impacts that are brought by adopting different technologies in urban mobility service sector can cause further economic loss and exacerbate urban transportation related consequences. Previous research has illustrated how transportation externalities can be quantified in different transportation scenarios and used as a determinant in the regulatory process. However, it has not been shown that externalities can be used as a leading indicator for future technology adoption scenarios when multiple pathways are available.

This study will address this gap in the existing literature. The research problem is therefore to investigate whether the external cost of new technology adoption pathways can be quantified before implementation and used as a leading indicator to assist governments in making informed and socially efficient regulations.

1.4 Purpose of the study

The urban mobility demand is increasing rapidly. Researchers have proposed different set of solutions that integrate alternative fuel technologies, self-driving technologies and sharing models to address the challenge. The simulation results are promising. At the same time, industrial partners from diverse background are pushing for technical and business innovations to capture the mobility services marketplace. The social economic benefits that are brought by implementing new technologies or sets of technologies have not been quantified.

The purpose of the study is to revise the externality models of transportation economics to evaluate the social economic impact of different possible technology adoption pathways in the transition in urban mobility service sector before implementation. The quantified economic impacts in the parametric study can assist governments in making informed and socially efficient regulations for the P2S transition.

1.5 Significance of the Study

Social impact: This study will quantify the economic impacts of multiple technology adoption pathways on a societal level. This information may help governments form more informed and socially aware regulations.

Academic impact: By creating mathematical models for externalities related to transportation economics, new technologies can be evaluated for social benefit prior to implementation.

1.6 Conducting the study

The study cannot be contained in one academic field alone. The research requires knowledge of business, micro- and macroeconomics as well as automotive engineering. Detailed research design will be introduced in Chapter 3 and Chapter 4.

1. Business: Understanding general industry developments and innovation models help build a framework for the research.
2. Automotive: Understanding selected disruptive technologies inside the automotive industry helps demonstrate the most likely pathways in the transition.
3. Economics: Quantifying externality models in the transportation sector helps evaluate potential outcomes or impacts when adopting a certain technical pathway.

1.7 Thesis structure

This thesis will build models to calculate the externalities of prospective technology adoption pathways in the P2S transition. The results help OEMs, researchers, and governments understand the P2S transition from a quantified cost-benefit perspective.

The thesis is structured as follows:

- Chapter 1 presents the background of the problem, and introduces the overview of the thesis study.
- Chapter 2 presents previous research related to the P2S transition in the automotive industry. It introduces a range of literature from the fields of business innovation, automotive engineering, and transport economics to gain an in-depth understanding of the P2S transition.
- Chapter 3 formulates an innovation framework that can help industry partners and researchers understand prospective technology adoption

pathways in the P2S transition. The chapter follows the design process of eight scenarios based on a resource-demand view of the framework. This enables further research on the externalities in the transition.

- Chapter 4 reviews externality models for traffic congestion, human health, and climate change. The chapter also revises externality cost models based on open transport data in urban areas of the U.S. in 2013.
- Chapter 5 evaluates and analyzes externalities in mobility sharing with ICE vehicles and mobility sharing with EVs scenarios.
- Chapter 6 evaluates and analyzes externalities in automated driving with ICE vehicles and automated driving with EVs scenarios
- Chapter 7 evaluates and analyzes externalities in the visionary scenario where urban mobility services are offered by electric, automated driving and shared systems.
- Chapter 8 summarizes and compares the modeled results of all scenarios.

CHAPTER TWO

2. LITERATURE REVIEW

The goal of calculating the externalities of each technology adoption pathway is to quantify and understand the benefits of each alternative pathway. There are multiple requirements for a viable model for externalities as related to technology adoption. In order to fully identify a scenario, the following questions must be addressed.

- What are the internal changes and external pressures that lead to the Product-to-Service Transition in the automotive industry?
- What technologies can be implemented to improve the current situation?
- How will the technologies be delivered to the consumers?
- What are the socioeconomic impacts of each technology adoption pathway?

The research topic is plagued with uncertainty and the burden of continuously changing technologies and innovation systems. As a result, researchers are forced to establish boundary conditions and adopt models and frameworks from multiple academic fields that allow them to account for the necessary factors and answer research questions despite these uncertainties.

The literature review section is structured as follows:

1. The general introduction of consequences in urban metro areas.
2. Automotive engineering – the technical specifications of disruptive technologies that are being developed, and benefits of integrated solutions as simulated by researchers.

3. Business innovation – frameworks and theories that can capture and illustrate possible technology adoption pathways in the transition.
4. Economics – social cost models that have been developed to quantify external cost in transportation sector.
5. Review of existing external cost models and categories. The requirements for moving forward will be presented.

2.1 The consequences of increasing mobility demands in urban cities

Increasing population and urban mobility demands in urban metro areas challenge current mobility service systems. As of 2015, there are 37 megacities in existence, and 50% of the world's population lives in cities. United Nation reported that this figure is projected to increase to 70% by 2020 [1]. By the year 2050, people live in urban metro are projected to travel 67.1 trillion passenger-kilometers [2]. Current mobility systems cannot match the rapidly increasing mobility demands. The major consequences of rapidly increasing urban mobility demands are observed as follows:

2.1.1 Time and financial loss from traffic congestion

In 2014 traffic congestion caused urban Americans to travel 5.5 billion hours more than necessary and to purchase an extra 2.9 billion gallons of fuel. The total congestion costs amounted to $121 billion. Table 1 shows the congestion cost in 2014 in detail, and projection in year 2020 [3].

Table 1: United States national congestion cost in 2014

	2014	2020
National congestion cost	$160 billion	$192 billion
Delay hours	6.9 billion	83 billion
CO_2 produced during congestion	59 billion lbs.	-
Wasted fuel	3.1 billion gallons	3.8 billion gallon
Average commute per year	42 hours; $960	45hours; $1,010

2.1.2 Urban air pollution

Urban air pollution is linked to 1 million premature deaths each year. Urban air pollution is estimated to cost approximately 2% of GDP in developed countries and 5% of GDP in developing countries. Over 90% of air pollution in cities is attributed to vehicle emissions [4].

2.1.3 Urban island heat effect

The annual mean air temperature of a city with 1 million people or more can be 1.8 – 5.4° F warmer than its surroundings. In the evening, the difference can be as high as 32° F. The Urban Heat Island effect can affect communities by increasing summertime peak energy demand, air conditioning costs, air pollution and greenhouse gas emissions, heat-related illness and mortality, and water quality [5].

The reports and studies mentioned above found that the urban mobility demand is increasing rapidly while the current urban transportation system is not able to address the challenge sufficiently. Both the individual transportation user and society are bearing huge financial losses, and environmental issues. The consequences of urban transportation urge technical innovations and business model innovation to deliver new forms of urban transportation services.

2.2 Disruptive technologies and integrated mobility services

This section will consolidate the main technical findings from research and present them as individual technologies that can be adopted in the mobility service sector, followed by integrated solutions in simulations and the social benefits of each.

2.2.1 Disruptive technologies in the product-to-service transition

A disruptive innovation is an innovation that creates a new market and value network. It will eventually disrupt an existing market and value network, displacing established market leading firms, products and alliances [13].

Technology-driven trends will revolutionize how industry players respond to changing consumer behaviors. Industry players will develop partnerships and drive transformational change [7]. Digitization, increasing automation, and new business models have revolutionized the automotive industry. These forces are giving rise to disruptive technology-driven trends in the automotive industry: diverse mobility, autonomous driving, electrification, and connectivity. These technologies improve vehicle fuel efficiency, reduce well-to-wheel emission, and can be used to increase traffic efficiency at a system level. The next section will review studies in these technical areas and introduce the benefits of each.

A. Electric vehicles

Electric vehicles (EV) are propelled by one or more electric motors powered by rechargeable battery packs. EVs themselves emit no tailpipe emissions[14]. Some social impacts from shifting to electric vehicles are [15]:

- Increased urban air quality due to alternative fuel
- Decreased carbon emissions due to energy efficiency
- Decreased urban noise
- Decreased urban heat island effect

The decreased urban heat effect is worth a special mention. An internal-combustion engine does not convert all the chemical energy of gasoline into propulsion. Some of the energy is lost to heat as well. Compared to conventional gasoline vehicles, electric vehicles convert a higher percentage of the expended energy into motion. Therefore, EVs release less heat into the surrounding area. A 2012 study showed that replacing conventional vehicles with electric vehicles can reduce heat emissions in an urban area. For Beijing, switching would lower heat island effect by 0.94 degrees Celsius (33.7° F). This in turn would reduce the amount of energy spent to air condition buildings by 14.44 million kilowatt hours and reduce daily CO_2 emissions by 10,686 tons [6].

B. Automated driving technology

The National Highway Traffic Safety Administration (NHTSA) defines automated vehicles as those in which operations occur without human drivers' direct input. NHTSA also classified automation into 5 levels, from level-0 (no automation) to level-4 (fully self-driving vehicles) [16].

Currently commercial offerings of partially automated vehicles are level-2 automation. For example vehicles with adaptive cruise control functions. Google's autonomous vehicles are level-3 automation because they do not conduct trips without human drivers who are prepared to take over control. Below are the impacts from using automated vehicles in urban area [17]:

- Increased safety
- Increased convenience
- Increased productivity
- Increased traffic efficiency and lower congestion
- Enabling technology for widespread car sharing

The cost of an automated vehicle could be a potential concern to both consumers and original equipment manufacturers (OEMs). Figure 1. Illustrates additional costs of an automated vehicle over a conventional vehicle. GPS and Lidar are the two most expensive technologies. To bring entire suite of automated-driving vehicles (AV) features to market, OEMs and suppliers will have to make substantial R&D investments over the next decade for further developments. The price will drop with the further R&D activities [18].

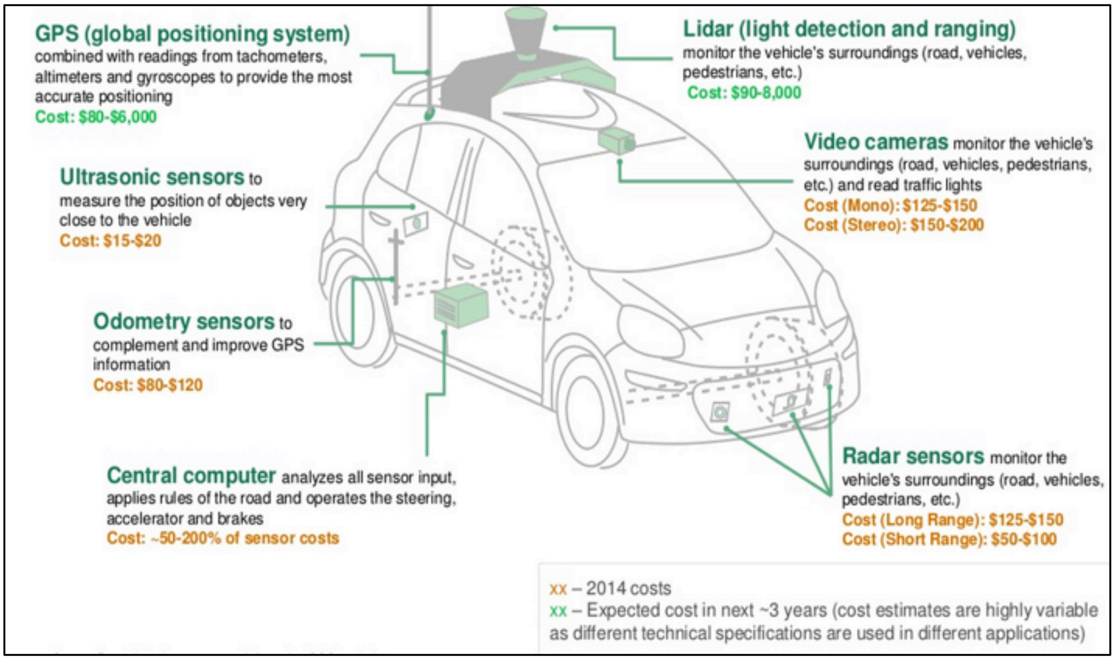


Figure 1: Hardware of automated driving technology

IHS Automotive forecasts that the price for self-driving technology will add between $7,000 and $10,000 to a car's sticker price in 2025, a figure that will drop around $5,000 in 2030 and about $3,000 in 2035. In 2035 the report believes that most self-driving vehicles will be operated completely independently from a human occupant's control [19].

In order to decrease costs and facilitate mass adoption it is necessary to form R&D partnerships and collaborations across industries.

C. The use of big data – optimized system

In the envisioned urban mobility service, the technologies cannot stand alone to achieve the electric, automated driving and shared mobility service. All the technologies are linked to the system or infrastructure to optimize the system's performance. In this context a data exchange would facilitate communication between transport operators, transport providers, transport users, and third party applications.

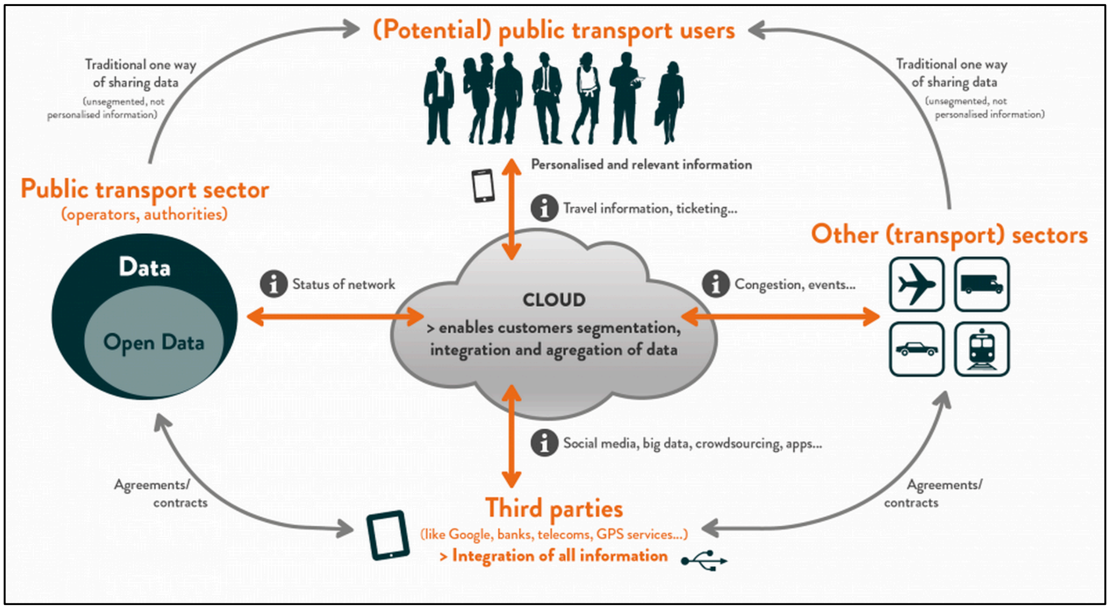


Figure 2: Open data exchange opportunities in transport sector

Such data exchange activities could provide insights on customer behaviors and utility usage to maximize the capacity of the infrastructure. Combine the linked technologies with insights from big data to enable widespread car sharing, and establish a intelligent and sufficient transportation system [20].

Figure 2. Illustrates the data exchange activates in the transportations sector. The transport users experience better service and save money by getting accurate transportation related data. The transport providers increase the number of customers and decreases the infrastructural cost by maximizing the capacity of mobility service. The data exchange activities also generate entrepreneurial opportunities.

McKinsey Global Institute also published a study to predict the value generated by the use of open data in the transport sector. Based on their analysis the global potential economic value that could be unlocked through the use of open data in the transportation sector is about $720 billion to $920 billion per year.

Optimized fleet operations could enable as much as $370 billion a year. Improved infrastructure planning and management and improved consumer decision making can each lead to value of as much as $280 billion per year [21].

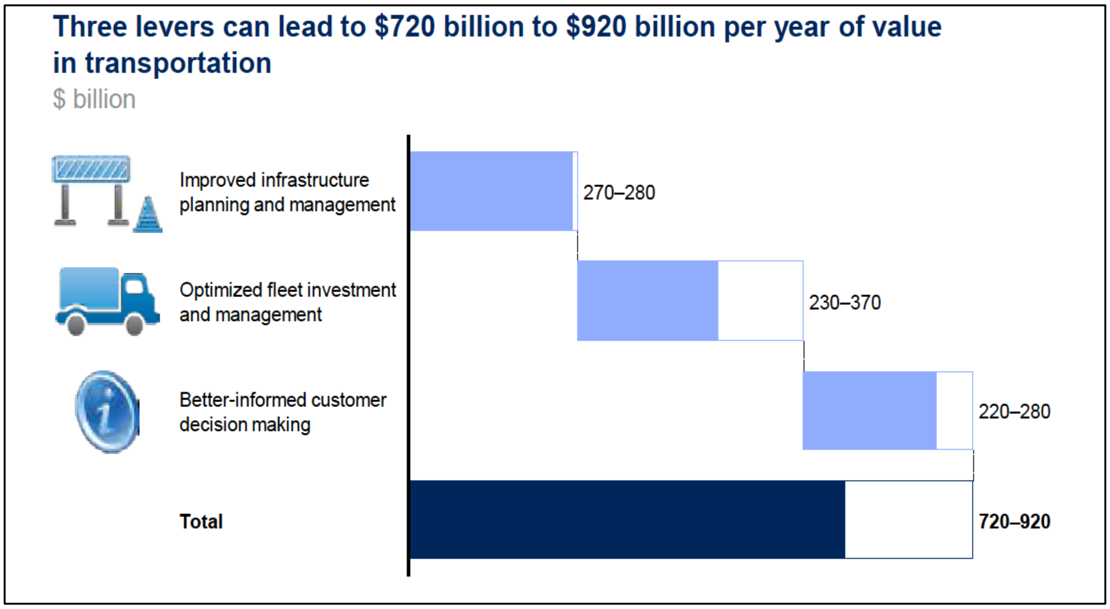


Figure 3: Overview of open data related market

2.2.2 Integrated mobility service solutions

This section is going to introduce simulations proposed in various research papers to emphasize the benefits of disruptive technology adoption in the Product-to-Service Transition.

Literature in the field proposes an optimized urban mobility system as electrified, automated, connected and shared mobility-sharing service. The researcher reviewed a list of literature that illustrates the impacts of an optimized mobility service from different perspectives.

- Boston Consulting Group used the automated driving and shared taxi as an example to emphasize the significantly lower cost of this mobility service compared to conventional taxi services.
- A Singapore study simulated the result of the reduced national fleet size to 1/3 of registered number if all individual owned conventional vehicles are replaced with shared automated vehicles.
- A Lisbon study evaluated the impacts on traffic flow rate in scenarios. In the study, automated driving and shared vehicle service adoption with or without integration with existing public transportation services are both considered.

The detailed results are described as follow:

A. Singapore study

The study in Singapore used the Mobility-on-Demand system. The Mobility-on-Demand (MoD) system considers arrival rate, average O-D distance, mobility demand distribution, earthmover's distance, and average velocity to calculate the minimum fleet size needed in real traffic to meet mobility demands. The Singapore traffic data is from The House Hold Interview Travel Survey, Singapore Taxi Data, and Singapore Road Network.

In a real MoD system, passengers would typically wait for the next available vehicle rather than leave the system immediately if no vehicles are available upon booking, the waiting time will not beyond 3 minutes. As a result, the MoD suggests a shared-vehicle mobility solution can meet the personal mobility needs of the entire population in Singapore with a fleet size is approximately 1/3 of the total number of passenger vehicles currently in operation [22].

B. Lisbon study

The study developed a new agent-based model to simulate the behavior of all players in this system: First, the travelers, as potential users of the shared mobility system. Second, the cars, which are dynamically routed on the road network to pick-up and drop-off clients, or to move to, from and between stations. Third, a dispatcher system tasked with efficiently assigning cars to clients while respecting the defined service quality standards. The study is based on a real urban content, the city of Lisbon, Portugal [23].

The result shows that:

- With a fleet of 100% shared self-driving vehicles, a ride sharing model could reduce the fleet size to 10.4% - 12.8% of current size based on the public transportation capacity
- With a fleet of 100% shared self-driving vehicles, a car sharing model could reduce fleet size to 16.8% - 22.8% of current size based on the public transportation capacity
- In a scenario where 50% of private cars are used for motorized trips, both ride sharing and car sharing models would most likely reduce the fleet by an insignificant number or increase the fleet size

The Lisbon study pointed out that transition from current fleet operational behavior to a future sharing economy is challenging and important for the impact of automated sharing service.

These two studies look into sharing models from a perspective of reducing fleet size, as a smaller fleet could lead to less congestion and relieved air pollution.

Boston Consulting Group generated a study to illustrate the low cost per passenger mile shared automated taxi service in New York City area.

C. New York City study

In this scenario, the Robo-Taxi would offer commuters door-to-door service, enabling them to work or be entertained during the trip and allowing them to share the ride and cost with other commuters. The shared automated taxis would be owned and operated by mobility providers – taxi service operators, ride sharing services, new entrants from the technology sector and OEMs – and rented to consumers by the minute or the mile.

Figure 4. Shows the cost per passenger mile of the Robo-Taxi service. The cost of conveying one passenger one mile by Robo-Taxi would be 35% less than doing so by conventional taxis at the average taxi occupancy rate of 1.2 passengers. From a provider's perspective – and factoring in the full cost of public transit, including government subsidies – Robo-Taxis would become competitive with mass transit at an average occupancy rate of 2 passengers [18].

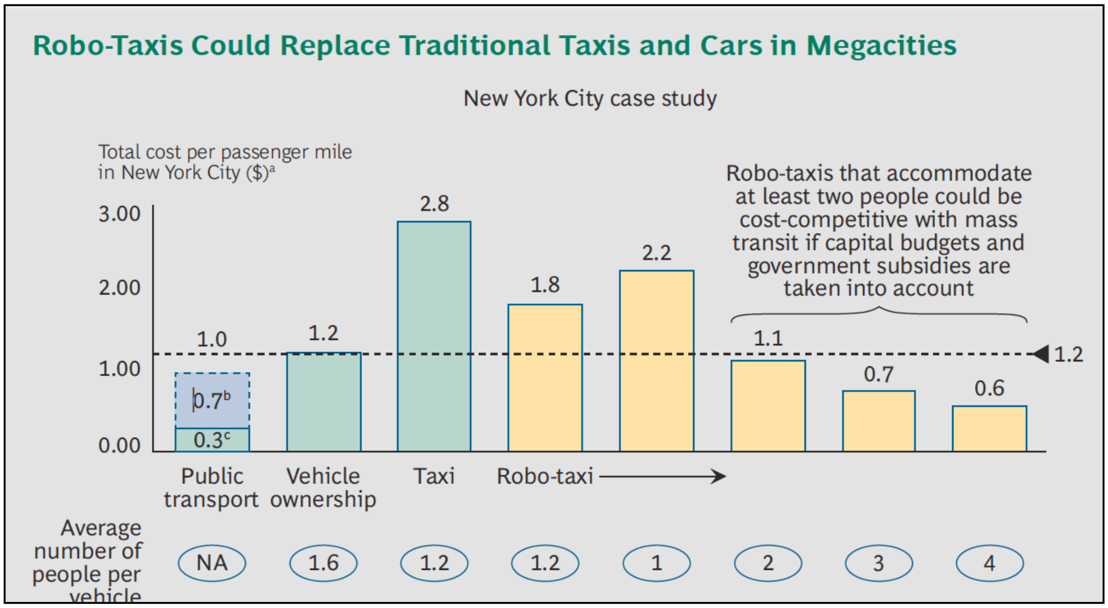


Figure 4:Robo-Taxi service in New York City

Overall, the simulation results of optimized, shared and automated driving mobility services can reduce traffic flow and fleet size at an affordable level. However, the implementation of such services remains challenging.

2.3 Business innovation framework and path dependence theory in industrial transition

Section 2.2 looked at research papers contributing to the current state of knowledge about disruptive technologies that can be implemented in the Product-to-Service Transition. Section 2.3 will focus on reviewing theories and innovation frameworks that can promote implementation processes for technologies that were introduced in section 2.2.

The Product-to-Service Transition is a transformational change that is driven by external social pressures, technical innovations and consumer behaviors in the automotive industry. Industrial transitions share similar characteristics but follow different pathways. People can learn from past but not copy one the same exact process. Every transition has its own pathway that leads to a unique revolutionized marketplace.

2.3.1 Path dependency theory

Path dependency occurs in an economic system when a "sequence of economic changes is one of which important influences upon the eventual outcome can be exerted by temporally remote events, including happenings dominated by chance elements rather that systematic forces. A key characteristic of path dependencies is that history is important in the actual development of their economics [24].

In the Product-to-Service Transition, technology adoption pathways are illustrated to help identify the leading indicators and capture possibilities, but not to predict the future.

Path dependent processes occur because of the network effect - when the benefit of consuming a good or adopting a technology varies directly with the number of others who consume the good or adopt the technology [25]. Consumer preferences are also a factor that could influence the pathway by adopting different technologies at varying rates.

The customary interpretation of path dependencies resulting from network effects is that they pose externalities that result in a lock-in of inferior technologies, which prevents market-based economies from evolving toward the most efficient technologies.

There are three degrees of path dependence:

- First degree path dependence is a simple assentation of an intertemporal relationship, with no implied claim of inefficiency
- Second-degree path dependence stipulates that intertemporal effects propagate error
- Third-degree path dependence requires not only that the intertemporal effects propagate error, but also that the error was avoidable

Path dependence theory does not offer methods to predict the future, but indicates that different pathway adoptions lead to different market results. Therefore, capturing the trends of possible adoption pathways and evaluating the economic benefits of each pathway help understand the transition from a quantitative perspective.

2.3.2 Complex adaptive system

A complex adaptive system is a collection of individual agents who have the freedom to act in ways that are not completely predictable, and whose actions are interconnected such that one agent's actions change the context for other agents [26].

An innovation ecosystem is understood as a smart system that is explained by the characteristics of complex adaptive systems [27]. Many researchers struggle to bridge the gap between a conceptual understanding of the innovation process, and informed debates and investments in policy and implementation arenas [28]. Nevertheless, the topic of complex systems, with all its seductive traps for conceptual musing, still needs to rise to the challenge of demonstrating what practical value it can bring to mainstream development policy and practice. For the

P2S transition, policy needs to engage with complexity. It needs to focus on strengthening capacities and processes in order to better cope with unforeseen change and innovation capacity. The understanding of complex adaptive systems at a conceptual level helps understand the regulation-making process for identified technologies in the P2S transition.

The essence of systems thinking can be summarized in the following way:

1. A system is defined as an entity made up of interconnected elements, and has a boundary, which separates the inside from the environment.
2. Complex adaptive systems' behaviors cannot be understood solely by formal analysis of the constituent parts. Instead they have to be understood as whole entities with their own idiosyncratic properties.
3. Complex adaptive systems are evolutionary. They should be seen as a series of unpredictable responses to events where a critical role is played by feedback mechanisms.

Complex adaptive systems help understand the P2S transition at an intuitive and conceptual level. Surprising and innovative ideas can emerge from unpredictable corners of a complex system that fosters diverse relationships among the parties within the system.

2.3.3 Innovation framework and systems

Literature in the previous section showed that the importance of the technology adoption pathway taken in the Product-to-Service Transition. This section will introduce different forms of innovation frameworks that are being used in the automotive industry to help identify possible technology pathways.

Innovations are defined as new ideas, improvements or solutions that are implemented and transferred into useful outcomes. Not all creative ideas become innovations - only if they are implemented and adopted in a beneficial way. The innovation process to enhance technical innovations and implement solutions in reality is the key to transfer an idea into products. Singular innovations alone cannot unlock the full power of advanced technologies. In addition, large-scale, timely innovation will require platforms to compete effectively with the incumbent business models and technologies. The most effective innovation systems will find ways to include entrepreneurs in a predictable, systematic manner [29].

A. Traditional Innovation Processes

Current innovation processes are able to optimize a single system and reduce the cost of goods sold at the product level. The closed innovation framework lacks the scope to integrate products and services on multiple levels into one coherent solution.

The traditional innovation processes that are adopted currently:

- R&D investment partnerships
- Corporate venture capital
- Research and commercialization alliances

B. Platform Innovation Ecosystem

The innovation ecosystem is able to address the scope of the envisioned urban mobility service by definition. As innovation ecosystem can be defined as collaborative arrangements through which firms combine their individual offerings into a coherent customer-facing solution [30].

An innovation ecosystem consists of economic agents and economic relations as well as the non-economic parts such as technology, institutions, sociological interactions and culture [31]. An innovation ecosystem is a hybrid of different networks or systems. The collaborative arrangements might be based on local concentration of industrial specifications, such as Porter's clusters, but the ecosystem model has expanded the idea of local clustering to encompass a global, networked economy and various interdependent actors. Innovation ecosystem expands the innovation process from internal R&D activities to numerous co-creators and co-innovators.

The literature has identified competitive advantages and risks of forming an innovation ecosystem; a good example to illustrate the process would be Apple's platform innovation ecosystem.

Figure 5. Shows that Apple offers a variety of products from software to hardware. 80% of Apple's revenue comes from hardware sales; however, the 20% that comes from selling software helps drive future hardware sales as customer lock into this platform. Apple engages entrepreneurs during the software creation stage to provide diverse and interesting content to attract users.

Figure 5: Overview of Apple's innovation ecosystem [32]

Literature on innovation systems and frameworks is not well structured in academia due to the difficulties of evaluating returns on investment and the efficiency of such a network. However, the innovation ecosystem theory has proved to work well in complex transitions like the Product-to-Service Transition. The important gains in the innovation framework literature review chapter are listed:

- Innovation ecosystem, especially platform innovation framework captures a complex marketplace that can engage a variety of industrial partners and entrepreneurs.
- Formulating a theoretical innovation framework for the Product-to-Service Transition at the resource level can illustrate possible technology adoption pathways in the transition.
- Both collaboration and competition will be observed in every innovation framework, and among parallel frameworks. Parallel frameworks in this

scenario are defined as those innovation frameworks that are trying to achieve and deliver optimized mobility service at a system level.

2.4 Social costs models that have been developed in transportation sector

In previous literature reviews we have learned how to illustrate a new marketplace and capture possible pathways by forming the innovation ecosystem from a resource-based view. The literature review in this section will focus on quantifying economic models that can evaluate social impact in transportation scenarios.

2.4.1 External cost of urban transportation - key concepts

A. The concept of externalities

In economics, an externality is the cost or benefit that affects a party who did not choose to incur that cost or benefit [33]. Road transport imposes negative externalities on society, including congestion related costs, environmental and road damage, accident costs, and oil independence.

An efficient equilibrium is defined as a situation in which marginal social costs are equal to marginal social benefits. Externalities are a form of market failure, which means that the market is incapable of reaching an efficient equilibrium [34].

An efficient urban mobility system must take into account the true cost of transportation. A novel method to calculate urban mobility service externalities would help quantify and understand the social impacts of new technology adoption in advance. A resource-linkage based innovation framework is also needed to illustrate the market tendency under natural technical push and consumer pull, and to advise policy makers to internalize the external social costs.

B. Scope and categories of social cost

The external costs of transportation are neither paid by producers nor users, and hence are not taken into account when the participants in transportation system make decisions. Internalization of external costs through the use of market-based instruments is generally regarded as an efficient way to limit the negative side effects of transportation [35].

In order to define external costs properly, it is important to distinguish among:

- Internal costs – Directly imposed by the transportation user, such as wear and tear on the vehicle, the energy cost of use, own time costs, transportation fares and transportation taxes and charges.
- External costs – Costs that are borne by other decision makers.
- Social costs – All costs occurring due to the provision and use of transport infrastructure, such as wear and tear on infrastructure, capital costs, congestion costs, accident costs, and environmental costs [36].

Economic assessments of externalities from road travel are defined in Table 2.

Table 2: Internal and external costs in transport sector

Cost Component	**Internal Cost**	**External Cost**
Congestion Cost	All cost for traffic users (time, reliability, operational cost, missed economic actives) caused by high traffic density	The extra costs imposed on other users and society

Accident Cost	All cost of an accident (medical cost, material cost, operational cost, production losses)	Cost of the increased accident risk, and direct economic costs associated with average accident risk
Air Pollution Cost	-	Damage to the rest of the society which is not paid by anyone (producer, or user)
Climate Change Cost	-	Damage to the rest of the society and damage to the opportunity of future generations
Noise	Cost of the vehicle users	Costs imposed on other users in the traffic and in neighborhood

2.4.2 Practice methodologies

A. Valuation approaches

Individual preferences are important indicators to appraise costs imposed on society. The preferred solution is to estimate costs. Three factors are relevant:

- Willingness to Pay (WTP) – The maximum amount an individual is willing to sacrifice to procure a good or avoid something undesirable.
- Willingness to Accept (WTA) – The minimum amount of money that a person is willing to accept to abandon a good or to put up with something negative, such as pollution [37].
- Impact Pathway Approach (IPA) – The approach follows the dose-response function considering several impact patterns on human health and nature, especially useful in evaluating environmental related externalities.

Table 3: Best practice approaches for important cost components

Cost Component	Best practice approach

Costs of scarce infrastructure	WTP* for the estimation of the value of time (based on stated preference approaches). Alternatively: WTA* WTP for scarce access slots (based on SP* with real or artificial approaches). Alternatively: WTA
Accident costs	Resource costs for valuation of injuries. WTP for the estimation of the value of statistical life based in SP fir the reduction of traffic risks. Alternatively: WTA
Air pollution costs and human health	Impact pathway approach using resource cost and WTP for human life (life years lost). Alternatively: WTA
Air pollution and building/material damages	Impact pathway approach using repair costs
Noise	Annoyance costs: WTP approach based on hedonic pricing (loss of rents-this reflects WTA) or SP for noise reduction. Health cost: impact pathway approach for human health using WTP
Climate change	Avoidance cost approach based on reduction scenarios of GHG-emissions; alternatively, damage cost approach; shadow prices of an emission trading system
Nature and landscape	Compensation cost approach (based on virtual repair costs)

*WTP – Willingness to pay; WTA – Willingness to accept; SP – Stated preference approach

B. Procedures – Top down and bottom up approach

Top down approaches use average national data to illustrate the average cost. Such approaches are more representative on a general level, allowing comparisons between modes. Bottom up approaches consider specific traffic conditions and refer to individual case studies. The results are more precise and accurate, but the estimation approaches are costly and difficult to aggregate.

The author is going to use top-down approaches in the dissertation. The top down approach will be developed based on average U.S. urban transport data to demonstrate the social impacts in different technology adoption scenarios. Table X shows the difference between marginal cost (bottom-up) and average cost (top-down).

Table 4: Relation between marginal and average costs

Cost Component	Difference between marginal and average cost
Costs of scarce infrastructure	In congested areas, marginal costs are above average costs. The difference is relevant to define external costs.
Accident costs	Marginal costs differ individually (for non-scheduled traffic). Clustering or infrastructure users according to accident risk are possible (and typically applied by insurance companies). Thus, average and marginal costs can be assumed to be similar in each cluster.
Air pollution costs and human health	Linear dose-response function: Marginal costs are similar to average costs.
Air pollution and building/material damages	Linear dose-response function: Marginal costs are similar to average costs.
Noise	Decreasing impact of an additional vehicle with increasing background noise due too logarithmic scale. Marginal costs below average costs.

Climate change	Complex cost function. As a simplification: Marginal damage costs similar to average costs (if no major risks include). For avoidance costs, marginal costs are higher than average costs.
Nature and landscape	Marginal costs are significantly lower than average costs.

Many researches have been done in transportation externality area at both micro-level and macro-level. Macro-level studies focus on formulating cost models to calculate the externality of certain transportation scenario and inform policy makers with findings. Micro-level studies focus on methods to calculate unit cost of variables in transportation externalities. Policy makers have been using externality as an indicator of regulation making process for existing technologies. However, no studies have focused on integration of externality cost and future technology adoption scenarios, especially in urban mobility service sector. There is a need for using externality concept to quantify future technology adoption pathways in mobility service sector.

2.5 Conclusions

Previous studies that could be used to understand the P2S transition have not been carried out into quantifying solutions. The studies have illustrated technology adoption trends, but pathways taken to the future are uncertain. In particular, the socioeconomic impact made by adopting a certain pathway is not quantified.

Important findings from the literature review:

- The consequences of increasing urban mobility demands include environmental damage and financial loss to both individual users and society. The current mobility system and physical resources are not able to address future mobility demands sufficiently
- Industry partners are working on alternative fuels, automated driving and mobility sharing technologies while researches have simulated the impacts of integrated mobility services at the system level
- Path dependency theory introduces the importance of the pathway taken, and market lock-in effect in industry transitions like the P2S transition. Building an Innovation Ecosystem at the resource level provides a framework to capture possible pathways in a descriptive way.
- Externalities in the transportation sector quantify social external costs in certain transportation scenarios. The quantified externalities assist the regulatory process for new technologies. The concept has not been applied on the P2S transition in urban mobility service sector previously.
- Externalities in traffic congestion, human health impact and global warming categories are suitable to capture social impacts by adopting different technology pathways in the P2S transition on multiple levels.

The next chapter will focus on developing the innovation framework, technology adoption pathways, and scenarios along different pathways.

CHAPTER THREE

3. FRAMEWORK AND SCENARIO DESIGN

Previous research indicates the possibility of positive social impact when implementing electric vehicles, automated driving and shared urban mobility services. However, none have quantified economic results. In the short term, industry partners encourage consumers to adopt innovations that can optimize performance of individual owned vehicle in an incoherent way. In the long-term mathematical models that can evaluate technology adoption pathways in mobility service sector will be critical in maximizing the potential social improvement of technology adoption. The innovation framework at a resource-based view level helps capture possible technology pathways.

The structure of this chapter is as follows:

- Section 3.1 describes the requirements for framework based on evidence collected in Chapter 2.
- Section 3.2 proposes an innovation platform at a system level and a framework that captures the innovation tendencies in the P2S transition.
- Section 3.3 demonstrates quantifiable scenarios within the framework.

3.1 Requirements and goals for Framework

There are a variety of possible technology adoption pathways in the P2S transition due to changing dynamics in both technology and the marketplace. The framework serves to capture the tendencies of pathways for further quantifying studies.

The goals of the framework:

- To illustrate a resource-based framework to capture urban mobility market trends
- To demonstrate technical innovations, and consumer demand shifts in the transition
- To describe a system-level solution that integrates a set of innovations, and the ability to adopt continuous innovation

3.2 A framework for the P2S transition

In this chapter we will propose a framework, which enables analysis of the pathways needed to integrate technical innovations (electrical propulsion technology, automated driving technology) and consumer behavior (mobility sharing) into one coherent system-level solution. The framework suggests partners and governments with future market directions, and identifies technology adoption pathways.

3.2.1 Resource-Demand view of mobility market and the framework for P2S transition

This section will introduce a view of the mobility market from a resource-demand perspective. This view helps understand the mobility marketplace better due to the capability of recombining resources to offer different forms of services.

The original concept is Resource-based View. Resource-based view (RBV) as a basis for the competitive advantage of a firm lies primarily in the application of a bundle of valuable tangible or intangible resources at the firm's disposal [38].

In the P2S transition, innovative technologies are resources. Consumer demand (purchasing preferences) is another important factor when designing a framework for the mobility service marketplace. Therefore, a resource-demand view of urban mobility service marketplace is described as follows:

Table 5 and Figure 6: Resource-Demand View Framework of the P2S Transition in Urban Mobility Service Marketplace.

Table 5: Resource-Demand view of the P2S transition

	Current demand (Individual ownerships of vehicles)	**Changing demand (Shared mobility)**
Current technical resource	Traditional product offered	Shared mobility with current technologies
Increasing technical resource (Electric vehicle, automated driving)	Technical innovations with individual owned vehicle	Mobility sharing with technical innovations

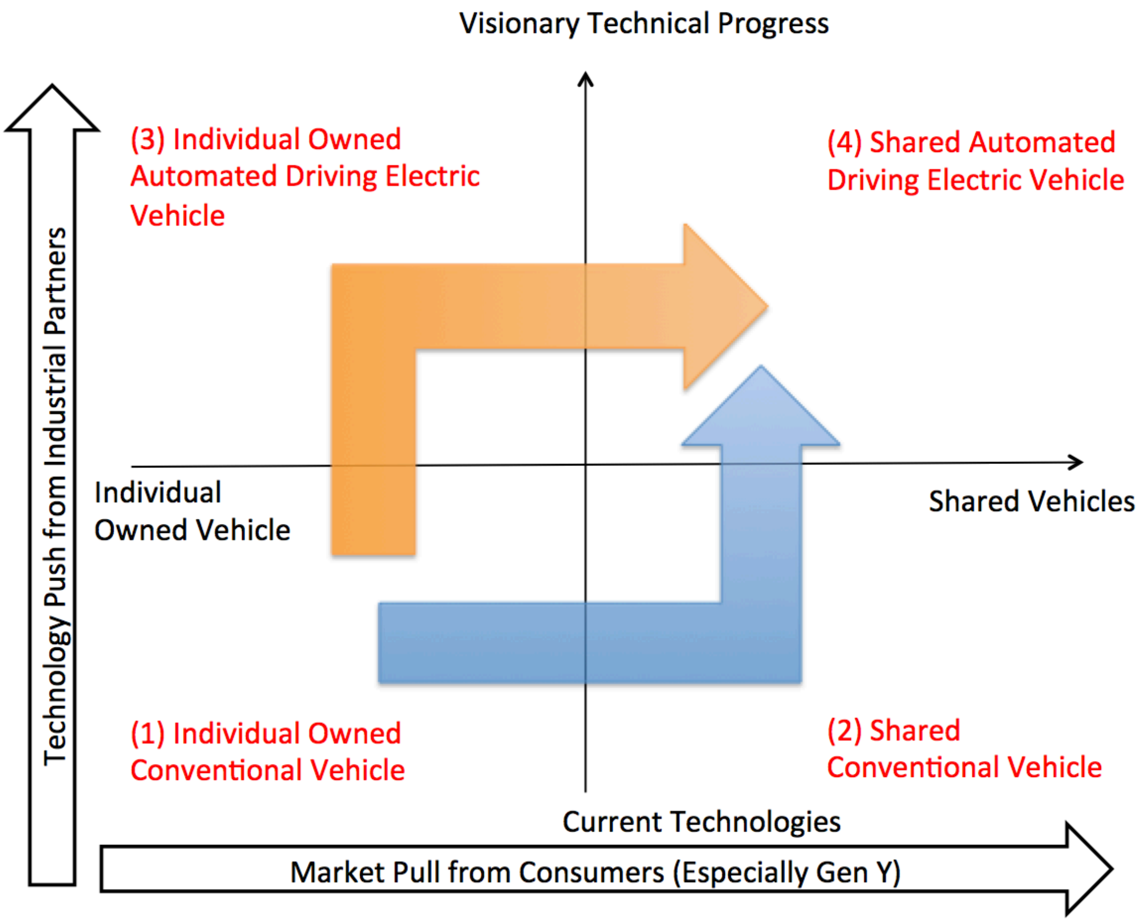


Figure 6: Resource-Demand View Framework of the P2S transition

3.3 Scenario Design

The scenario design serves the purpose of quantifying externalities in adoption pathways in mobility service transition.

Table 6: Designed scenarios in the P2S transition

Urban mobility scenarios design				
	ICE vehicles	**Electric vehicles**	**Automated driving vehicles**	**Automated driving electric vehicles**
Individual owned fleet	Baseline Scenario	Individual Owned EV Scenario	Individual Owned AV Scenario	Individual Owned EV+AV Scenario
Shared fleet	Shared ICE Scenario	Shared EV Fleet Scenario	Shared AV Scenario	Shared EV+AV Scenario (Visionary Scenario)

*ICE – Internal combustion engine

3.4 Conclusion

This chapter outlined the requirements for the framework that helps capture technology adoption pathways in the mobility service sector. The chapter also introduced the logic behind the design of the framework and scenarios. The work presented here helps further the externality model design for the transportation sector in the next chapter.

CHAPTER FOUR

4. EXTERNALITIES IN MOBILITY SERVICE SECTOR

Externalities are costs or benefits arising from an economic activity that affect somebody other than the people engaged in the economic activity and are not reflected fully in prices. In Chapter 2, all categories of externalities were reviewed. The congestion, human health and environment impact related externalities are the ones will be considered due to attributes of considered technologies, and data availability.

The chapter follows the general structure:

- General literature review, procedure review and cost function review in selected externality categories
- Review, compare and select unit cost of variables in selected cost models
- Revise selected cost models based on open traffic data in urban areas in the United States
- Apply revised models into baseline scenario, and calculate externalities in traffic congestion, human health and climate change in 2013

4.1 Congestion externalities

Congestion externalities arise as a result of user effects on a road network. The user's decision to use the network to drive from a point A to point B impacts the utility of the same network capacity for all other users. The external costs include opportunities foregone due to travel delays, the discomfort of crowding, and the impact of travel-time uncertainty on the reliability of arrival and delivery times.

At the simplest level, congestion delay costs on the road are equal to hours of delay multiplied by the value of opportunities foregone during an hour of the day. Hours of delay are estimated on the basis of the difference between the average speed in a baseline travel situation and the average speed in a scenario with increased travel; this difference in turn is based on empirical relationships between average speed and travel volume, which in the case of road traffic can be fairly complex.

There is much confusion among practitioners as well as in some parts of the literature as to whether the external costs defined above can really be regarded as external. It is sometimes argued that road vehicle users only exert a negative effect on other road vehicle users. Hence, as road vehicle users do not affect the utility of no-road vehicle users, they should not pay for the negative effects just described. A market tends to overproduce when decision makers only care about own benefits.

This type of argument confuses the issues of fairness and efficiency. The impact that vehicle usage has on the speed of other vehicles leads to inefficiency in the use of scarce road capacity due to the tragedy of the commons. Therefore, any positive (very rare in transportation) or negative impacts on others that are not internalized or paid in equivalent monetary payments leads to an inefficient transport system due to the overconsumption of common resources.

4.1.1 Methods of estimations

The table below summarizes recent estimates of external congestion delay costs on road. Most authors focus on time-delay costs of road congestions.

Table 7. Estimates of congestion delay costs by mode (year-2006 cents) [39][40][41][42][43]:

Table 7: Congestion externality by mode

	Road ($, cents)
Gorman et al. (2008)	0.22 to 0.54/tm (freight) [a]
Lemp and Kockelman (2008) [b]	7.6 /vmt; 4.75/pmt
Parry et al. (2007) [c]	6.08/vmt; 3.80/pmt
Delucchi (2004a) [d]	3.09 to 11.94/vmt; 1.93 to 7.46/pmt
Levinson et al. (1998) [e]	1.41/vmt; 0.88/pmt

* tm = ton-mile; vmt = vehicle-mile of travel; pmt = passenger-mile of travel

a. Using forecasted year 2000 congestion costs due to trucks of $5.0 billion (year -1994$) and 198,789 million vehicle miles for trucks reported by FHWA assumes a 14.8-ton average payload and estimates $0.0022 per tm (year 2006$). However, Gorman's payload estimate implies an unrealistically high 2,942 billion ton-miles for trucks in 2000. Using an estimate of 1,203 billion ton-miles for all trucks (Dennis, 2004), Delucchi estimated $0.0054 per tm (year 2006$).

b. Lemp and Kockelman (2008) use a formula that predicts delay as a function of traffic volume, estimates of differences in delay caused by different vehicle types, and an assumption that travel time costs $8/vehicle-hour. The estimates appear to be in vehicle-miles of travel in year 2006 dollar. I converted to PMT, assuming 1.6 passengers per vehicle (U.S. DOT, 2008, Table 4-22)

c. Parry et al. (2007) report FHWA's (2000) estimate of the "weight-average" marginal external delay cost at 5 cents per passenger mile". According to Parry et al., FHWA estimated marginal external costs for representative urban and rural roads at different times of day, and then weighted each estimate by its share of total VMT. The estimate is in terms of cents per vehicle-mile, the conversion of passenger-mile of travel is also listed in the table, assuming 1.6 passengers per vehicle (U.S. DOT, 2008).

d. Delucchi estimates low and high external delay costs on the basis of low and high assumptions regarding the value of travel time by trip purpose, delay by trip purpose, and other factors.

e. The estimate from Levinson et al. (1998) appears to be in year 1995 dollar. Both pmt and vmt estimates are listed.

4.1.2 Externalities in traffic congestions for baseline scenario

Gorman's method to calculate the urban congestion related external cost of freight transportation, and Lemp's method to calculate urban congestion related external cost of light duty vehicles are adopted and revised in the research.

The previous studies did not distinguish the urban miles traveled by different type of vehicles, although different type vehicles generate different level of external costs in urban congestion.

A. Urban miles traveled by vehicle type

Two vehicle types are identified here due to availability of open traffic data, light-duty vehicle and heavy-duty trucks.

Federal Highway Administration reports that in year 2009, and year 2010, 7.06% and 7.44% of urban miles are generated by freight transportation [44]. The latest urban miles traveled update on United States Department of Transportation shows the urban miles traveled in 2013 [45]. Therefore, the urban miles traveled by light duty vehicles and heavy-duty trucks are listed in the table.

Table 8: Urban miles traveled by LDV and HDV

	Light-duty vehicles [Billion miles]		Heavy-duty vehicles [Billion miles]		Total urban VMT [Billion miles]
2006	1,900	96.12%	122	6.18%	1,977
2007	1,891	94.85%	129	6.47%	1,995
2008	1,856	93.60%	134	6.77%	1,983
2009	1,823	92.37%	139	7.09%	1,975
2010	1,807	91.15%	147	7.42%	1,982
2011	1,774	89.95%	153	7.76%	1,972
2012	1,768	88.76%	161	8.12%	1,992
2013	1,792	87.59%	174	8.50%	2,046

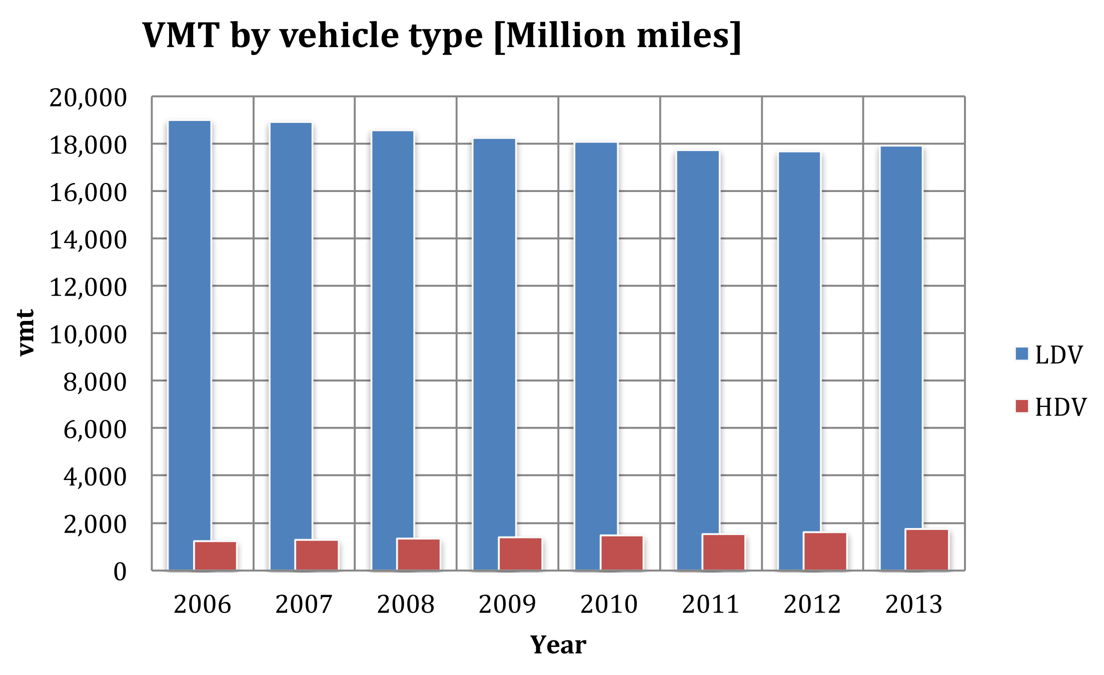


Figure 7: Urban miles traveled by vehicle type

B. Urban external congestion cost by HDV from 2006 - 2013

In Gorman's study, the external congestion cost of freight is $0.0022 per tm, and a 14.8-ton average payload. Heavy-duty truck (freight) cost $0.45 billion dollars in year 2013 in external congestion cost category.

$$Congestion\ externality_{HDV} = VMT_{HDV} \cdot unit\ cost_{HDV}$$

Equation 1: Congestion externality for HDV

Table 9: Congestion externality of HDVs in urban areas

Heavy-duty vehicles	External congestion cost [Dollars per VMT]	VMT [Million miles]	HDV external congestion cost [Million dollars]
2006	0.0022	122,270	3,981
2007	0.0023	129,078	4,394
2008	0.0024	134,298	4,770
2009	0.0023	139,931	4,763

2010	0.0024	147,005	5,222
2011	0.0025	153,035	5,662
2012	0.0025	161,772	5,986
2013	0.0025	173,891	6,434

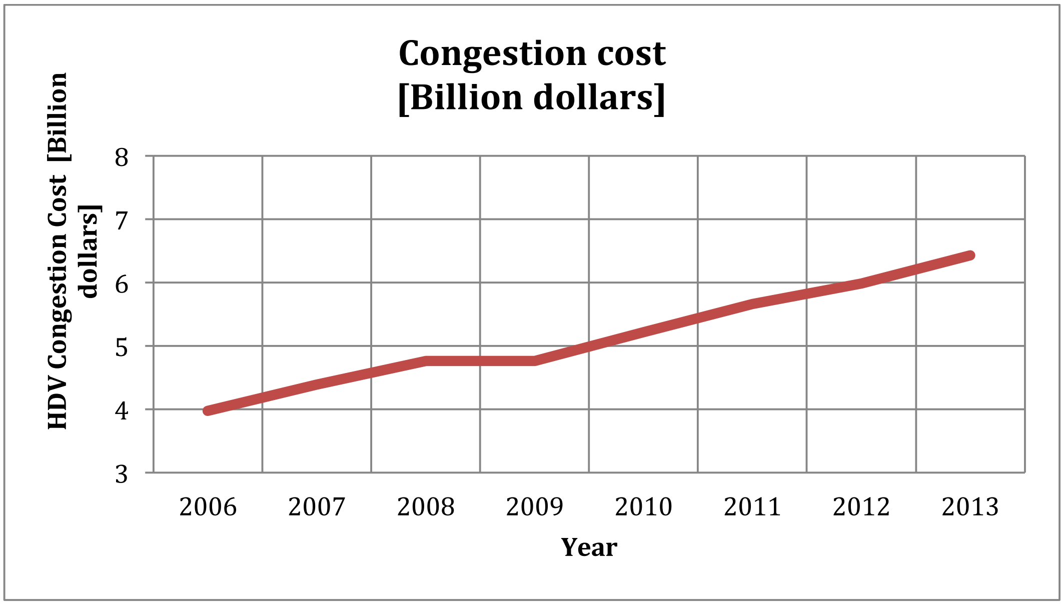


Figure 8: Congestion externality of HDVs in urban areas

4.1.3 Model redefine - Urban external congestion cost by LDV

A. Proposed model

Lemp and Kockelman used a formula that predicts delay as a function of traffic volume, estimates of differences in delay caused by different vehicle types, and estimate the delay cost by vehicle types. The formula is listed as follow:

$$CC = tf \cdot \alpha \cdot \left[\left(\frac{Vol + PCE}{Cap}\right)^{\beta} - \left(\frac{Vol}{Cap}\right)^{\beta}\right] \cdot Vol \cdot VOTT \cdot p$$

Equation 2: Unit congestion externality for LDV

Table 10: Variables in Lemp and Kockelman's model

Factors	Baseline scenario
t_f	Travel time at free-flow conditions per mile traveled
α, β	BPR-required parameters; 0.84 and 5.5 (fixed value)
Vol	Road capacity per hour per lane * travel demand
PCE	Passenger car equivalent
Cap	Road capacity
VOTT	Value of travel time
p	Congested conditions

Table 11: Define variables and constants in congestion unit cost

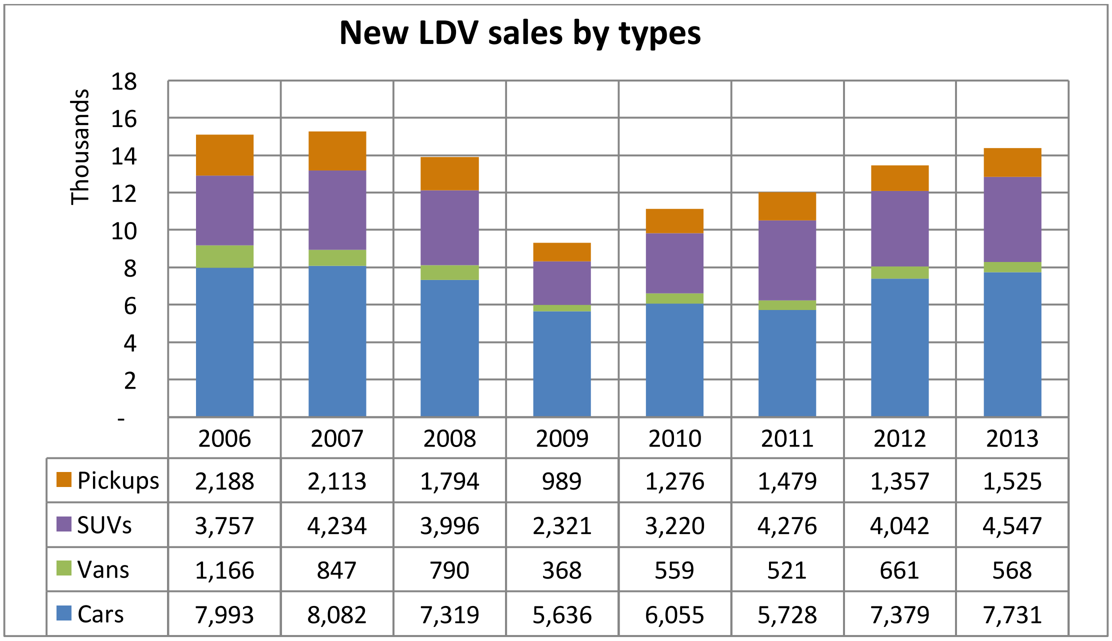
Factors	Definition
t_f	Travel time at free flow conditions. The average congested roadway was assumed to have a free-flow speed of 40 mph, corresponding to 1.5 minutes of travel time per mile traveled at free flow conditions.
α, β	BPR-required parameters; 0.84 and 5.5 (fixed value)
Vol	Road capacity is assumed to be 2000 vehicles per hour per lane (vphpl) and demand is assumed to be right at 95% of total available capacity in the baseline scenario. The capacity changes with penetration rate of autonomous vehicles as shown in Table 29.
PCE	PCE measures Passenger Car Equivalence. It is calculated based on sales volume of different vehicles in urban areas. PCE is considered constant at 1.104 for these scenarios.
Cap	Road capacity - Road capacity is assumed to be 2000 vehicles per

	hour per lane (vphpl)
VOTT	VOTT is a constant measurement of the Value of the Traveler's Time. The Victoria Transport Policy Institute estimates that the value of travel time for personal purposes is about 30% of household hourly income [46]. In 2006, the U.S. household hourly income was 16.83 dollars. After accounting for inflation, the VOTT is 6.04 dollars in 2013. Therefore, the VOTT here is estimated to be $5 per passenger hour, $8 per vehicle hours[47].
p	Congested conditions - The travel condition p is calculated from the travel time index found in Texas A&M's Urban Report 2013. In both baseline scenario and this scenario, p value is 0.1736.

B. Model redefine

The variables in the Lemp and Kockelman's model are designed for general traffic congestion scenarios, but not specifically for urban travel scenarios. Therefore, every variable in the formula will be reevaluated and redefined for urban traffic scenario in this section.

a. Calculation of average PCE based on vehicle sales



	2006	2007	2008	2009	2010	2011	2012	2013
🟧 Pickups	2,188	2,113	1,794	989	1,276	1,479	1,357	1,525
🟪 SUVs	3,757	4,234	3,996	2,321	3,220	4,276	4,042	4,547
🟩 Vans	1,166	847	790	368	559	521	661	568
🟦 Cars	7,993	8,082	7,319	5,636	6,055	5,728	7,379	7,731

Figure 9: New LDV sales by types [48]

Table 12: PCE based vehicle sales

Year	Cars	Vans	SUVs	Pickups	PCE
2006	52.92%	7.72%	24.88%	14.49%	1.106
2007	52.91%	5.55%	27.71%	13.83%	1.105
2008	52.66%	5.68%	28.75%	12.91%	1.106
2009	60.51%	3.95%	24.92%	10.62%	1.088
2010	54.50%	5.03%	28.99%	11.49%	1.103
2011	47.72%	4.34%	35.62%	12.32%	1.117
2012	54.91%	4.92%	30.08%	10.09%	1.103
2013	53.80%	3.95%	31.64%	10.62%	1.104

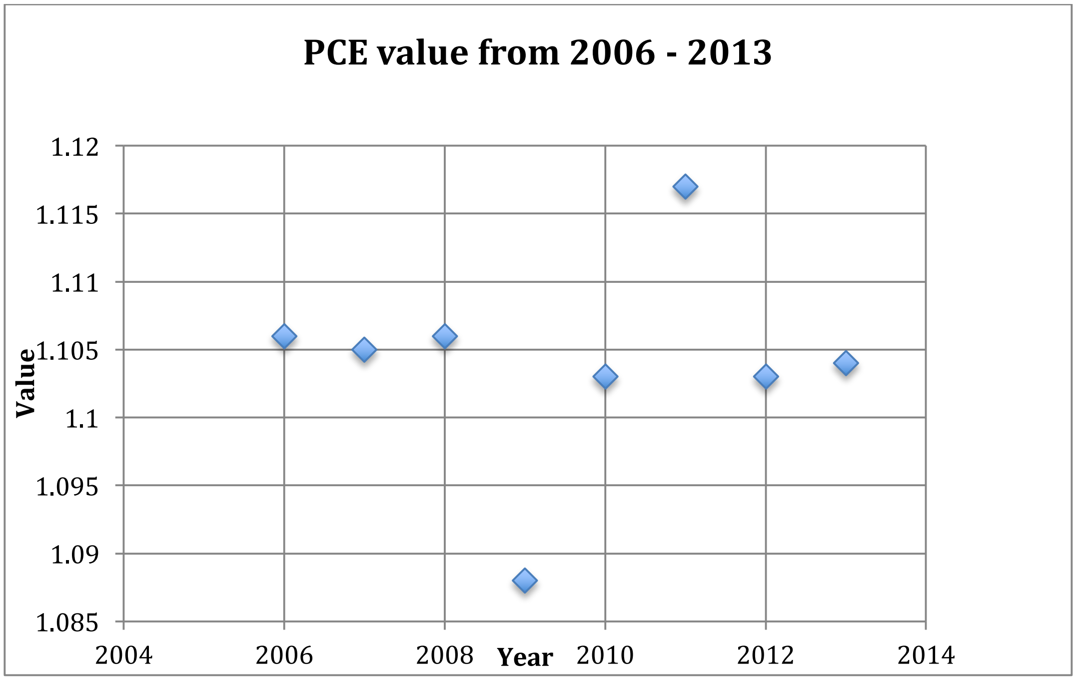
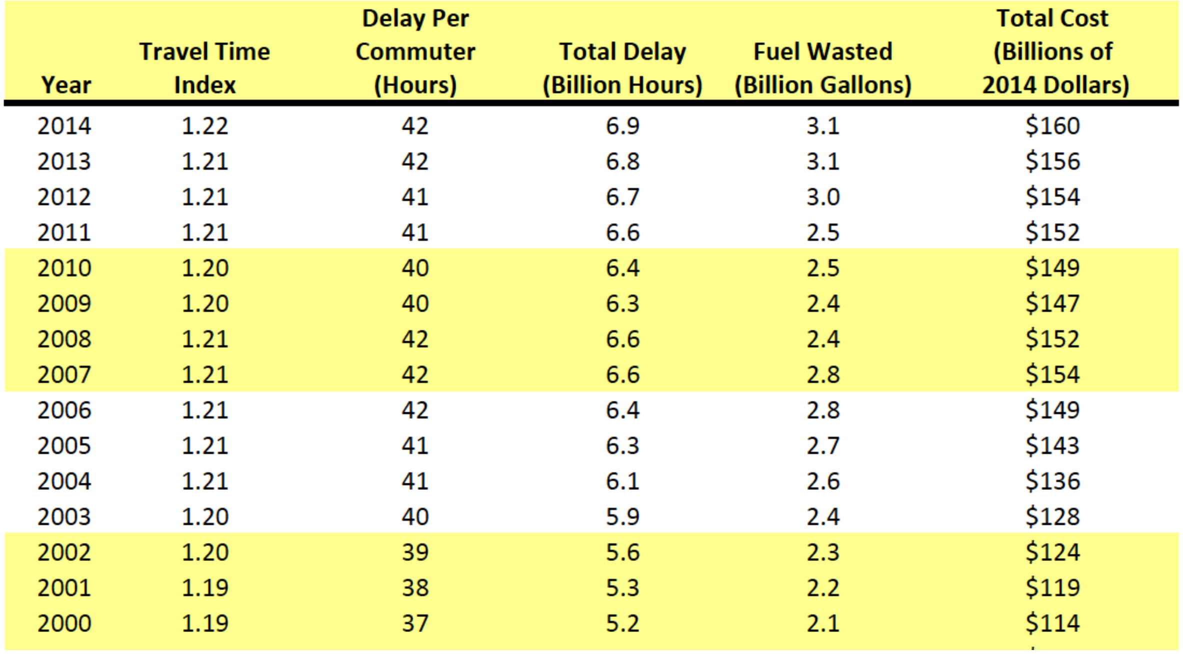


Figure 10: PCE value

b. Redefine congested level for urban area



Year	Travel Time Index	Delay Per Commuter (Hours)	Total Delay (Billion Hours)	Fuel Wasted (Billion Gallons)	Total Cost (Billions of 2014 Dollars)
2014	1.22	42	6.9	3.1	$160
2013	1.21	42	6.8	3.1	$156
2012	1.21	41	6.7	3.0	$154
2011	1.21	41	6.6	2.5	$152
2010	1.20	40	6.4	2.5	$149
2009	1.20	40	6.3	2.4	$147
2008	1.21	42	6.6	2.4	$152
2007	1.21	42	6.6	2.8	$154
2006	1.21	42	6.4	2.8	$149
2005	1.21	41	6.3	2.7	$143
2004	1.21	41	6.1	2.6	$136
2003	1.20	40	5.9	2.4	$128
2002	1.20	39	5.6	2.3	$124
2001	1.19	38	5.3	2.2	$119
2000	1.19	37	5.2	2.1	$114

Figure 11: National congestion measures[3]

In urban mobility report 2015, the data shows the congested level has been around 16.7 % for the past ten years [3].

$$Travel\ time\ index = \frac{Congested\ trave\ time}{Free\ tlow\ travel\ time}$$

Equation 3: Travel time index formula

$$p = 1 - \frac{1}{Travel\ Time\ Index}$$

Equation 4: Congested condition formula

Therefore, in year 2013

$$p = 1 - \frac{1}{1.21} = 0.1736$$

The average p value sine from year 2006 to 2013 is 0.1718

Table 13: Calculated P value in the U.S.

Year	Travel Time Index	P Value
2006	1.21	0.1736
2007	1.21	0.1736
2008	1.21	0.1736
2009	1.20	0.1667
2010	1.20	0.1667
2011	1.21	0.1736
2012	1.21	0.1736
2013	1.21	0.1736
Ave.	1.21	0.1718

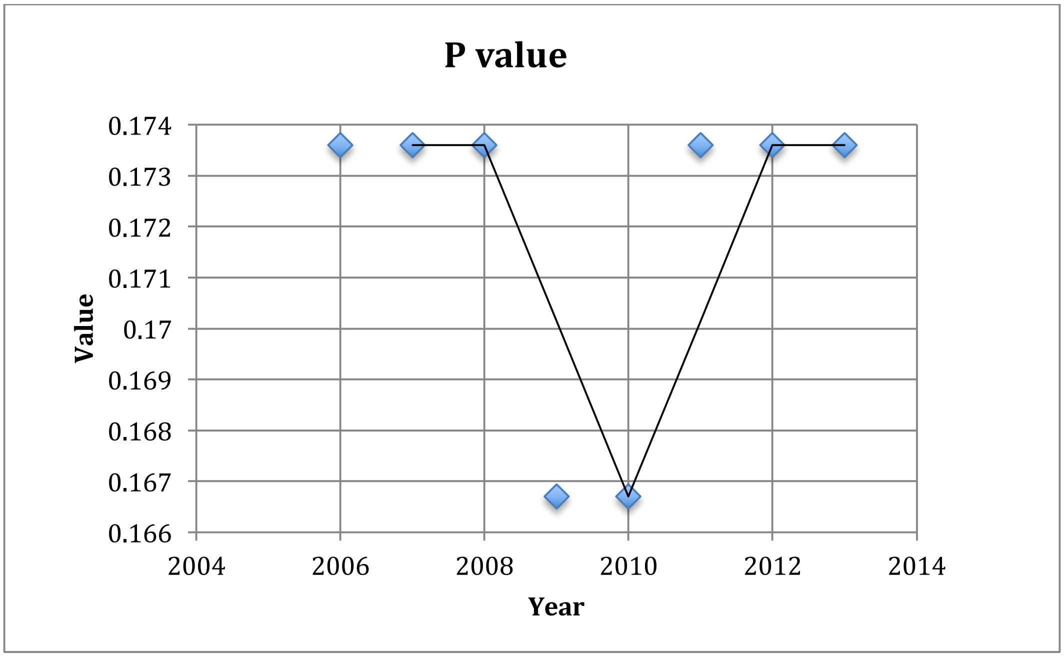


Figure 12: Converted P value

c. Redefine the VOTT from 2006 – 2013

Victoria Transportation Institute suggests that the value of travel time is about 30% of the average hourly income [46]. Therefore, the VOTT from year 2006 to 2013 is listed:

Table 14: Average hourly income and value of travel time [47]

	Average wage [Dollars per hour	VOTT [Dollars]
2006	16.72	5.02
2007	17.41	5.22
2008	18.04	5.41
2009	18.56	5.57
2010	19.03	5.71
2011	19.42	5.83
2012	19.72	5.92
2013	20.13	6.04

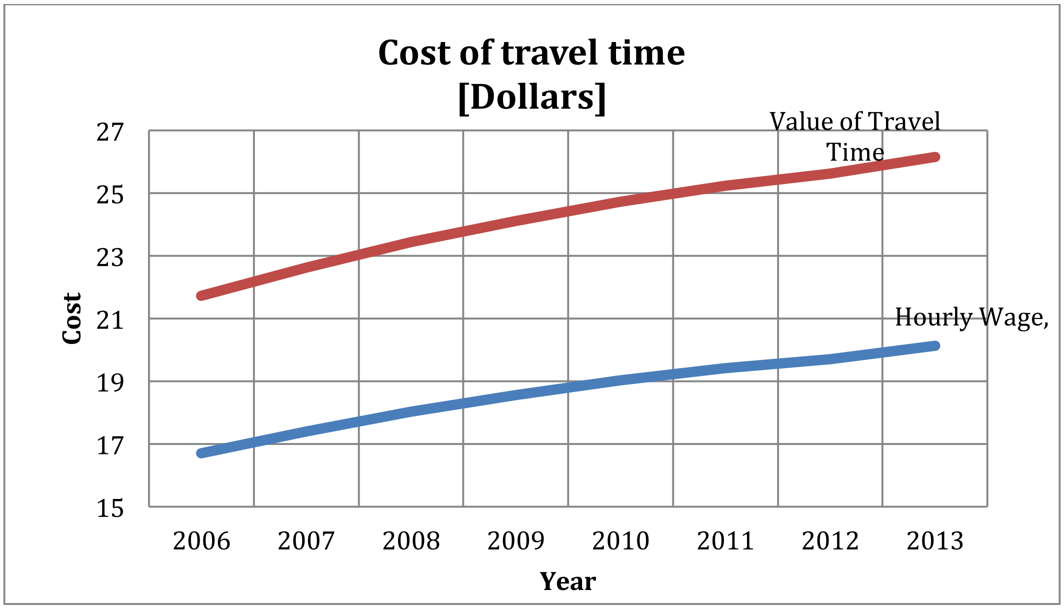


Figure 13: Cost of travel time in the U.S.

d. Redefine the model for LDV related to congestion externality in urban area

The original formula proposed is:

$$CC = tf \cdot \alpha \cdot \ [(\frac{Vol + PCE}{Cap})^{\beta} - (\frac{Vol}{Cap})^{\beta}\ ] \cdot Vol \cdot VOTT \cdot p$$

Equation 5: Unit congestion cost of LDV

PCE value is defined based on the auto sales data in the United States from 2006 – 2013. The average PCE value is 1.1; average p value is 0.1718, t_f remains 1.5; α and β are assumed to be 0.84 and 5.5 respectively. Therefore, the formula is revised as:

$$CC = t_f \cdot \alpha \cdot \left[\left(\frac{Vol + 1.104}{Cap}\right)^{\beta} - \left(\frac{Vol}{Cap}\right)^{\beta}\right] \cdot Vol \cdot 6.04 \cdot 0.1718$$

Equation 6: Revised unit congestion cost of LDV based on 2013 urban traffic data

C. Congestion externality in baseline scenario

$$CC = 1.5 * 0.84 * \left[\left(\frac{1900 + 1.1}{2000}\right)^{\beta} - \left(\frac{1900}{2000}\right)^{\beta}\right] * 1900 * 6.04 * 0.1718 * \frac{1}{60}$$

$$= 0.101\ dollars$$

Equation 7: The calculated unit congestion cost for baseline scenario

Table 15: Unit congestion externality cost in baseline scenario from 2006 - 2013

	PCE	**Average Wage [Dollars per hour]**	**VOTT**	**P**	**External Congestion Cost [Dollars per VMT]**
2006	1.106	16.72	5.016	0.1736	0.084
2007	1.105	17.41	5.223	0.1736	0.087
2008	1.106	18.04	5.412	0.1736	0.091
2009	1.088	18.56	5.568	0.1667	0.088
2010	1.103	19.03	5.709	0.1667	0.092
2011	1.117	19.42	5.826	0.1736	0.099
2012	1.103	19.72	5.916	0.1736	0.099
2013	1.104	20.13	6.039	0.1736	0.101

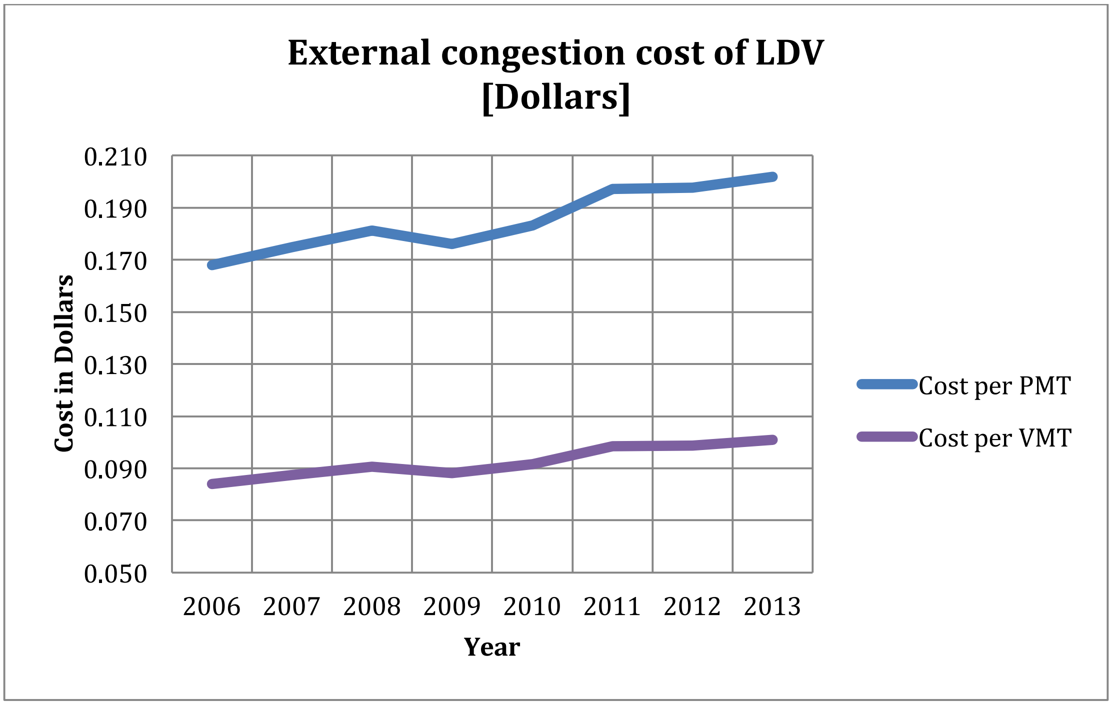


Figure 14: Unit congestion externality cost in the U.S.

4.1.4 Total urban congestion external cost from year 2006-2013

Table 16: Total congestion externality in the U.S.

	LDV External Congestion Cost (Billion dollars)	HDV External Congestion Cost (Billion dollars)	Total Cost (Billion dollars)
2006	160	4.0	164.0
2007	165	4.4	169.4
2008	169	4.8	173.8
2009	160	4.8	164.8
2010	166	5.2	171.2
2011	176	5.7	181.7
2012	175	6.0	181.0
2013	181	6.4	187.4

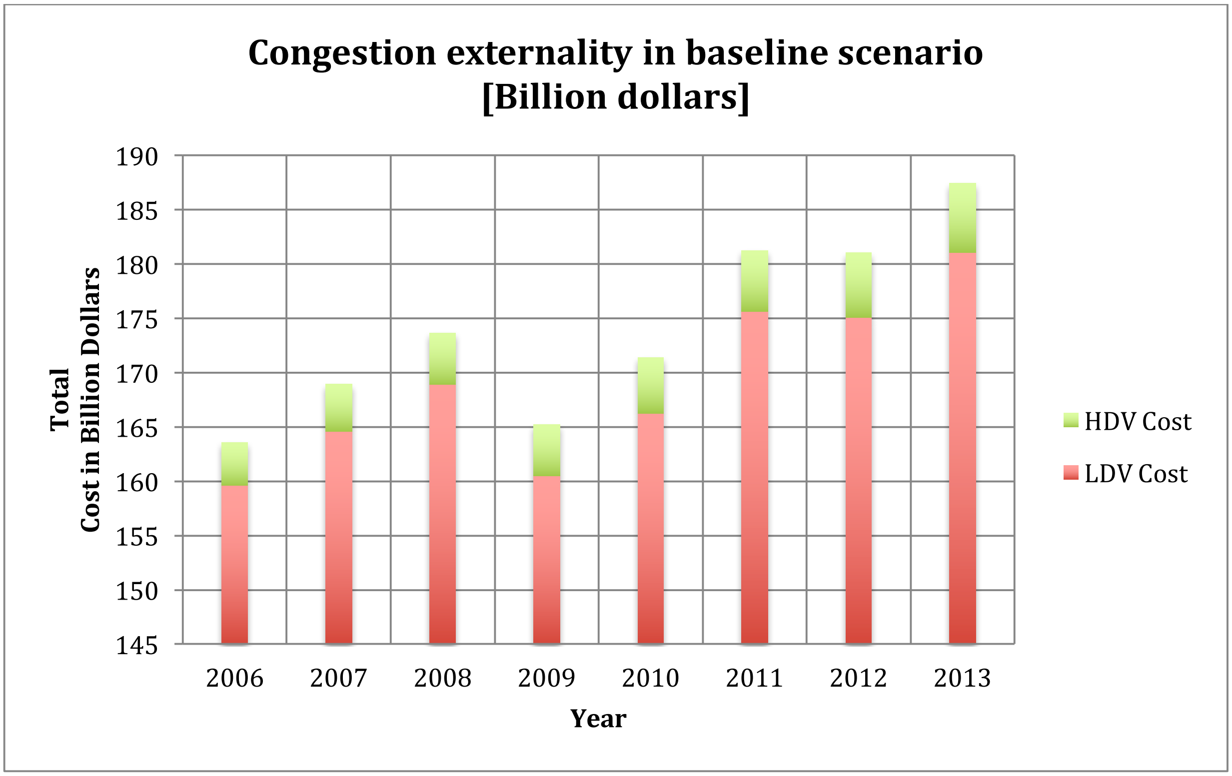


Figure 15: Total congestion externality in the U.S.

4.2 General Introduction of Health Impacts

All transportation modes emit significant qualities of air pollutants. Road transport is responsible for the emission of nitrogen oxides, sulphur dioxide, volatile organic compounds, carbon monoxide, lead and particulate matter with a diameter of less than 10 μm. The air pollutants affect human health in a variety of ways. The cost of these health effects is one of the largest external costs in transport sector. The effects of these pollutants form the subject of a large number of studies.

4.2.1 Approach proposed in European handbook 2014

The EU funded series of projects ExternE formalized the solution by using Impact Pathway Approach (IPA) [49]. The IPA follows a logical, stepwise progression from pollutant emissions to the determination of impacts and subsequently to the quantification of economic damage in monetary terms. The key steps are illustrated in the following figure:

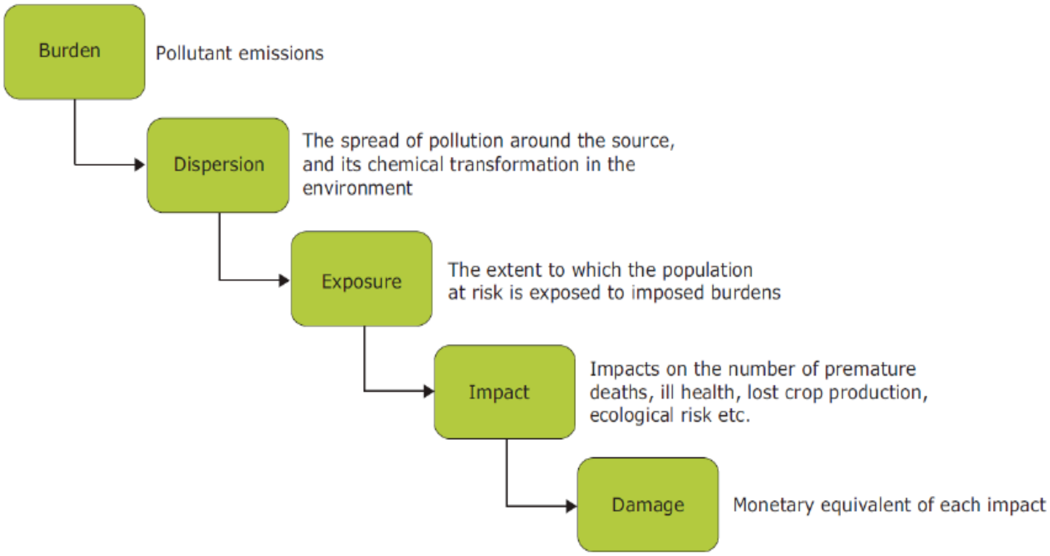


Figure 16: The impact pathway approach

- The first step quantifies the burden of pollutant emissions by using vehicle emission factors and the traffic data, e.g. vehicle-miles traveled in urban area.
- The dispersion of the pollutants around the source is modeled using atmospheric dispersion models, which are very complex and are not typically publicly available.
- The exposure assessment therefore relates to the population and the ecosystem being exposed to the air pollutant emissions. Spatially detailed information on population density must be available to allow proper assessment.
- The impacts of transport air pollutant emissions are highly location-specific and depend on many factors such as the local traffic conditions. The impacts

caused by the emissions are determined by applying so-called exposure response functions that relate changes in human health and other environmental damages to unit changed in ambient concentration of pollutants.

- The damage step is to evaluate the impacts of emissions on humans and ecosystem in monetary values. The step is based on valuation studies assessing the willingness to pay for reduced health risks.

The European Union approach requires massive complex data and models. The steps of IPA model demonstrates the clearly logic to evaluate the impacts of emission on human health. The approaches and unit cots of pollutants in the U.S. handbook will be reviewed in the following section.

4.2.2 Approach proposed in the U.S. handbook 2006

A. General procedures

To quantify the health impacts of air pollutants due to motor mobile emissions from transportation activities, researches have proposes the detailed procedure in four steps [50]:

1) Estimation the relationship between changes in transportation activity and changes in emissions of air pollution
2) Estimate the relationship between changes in emissions and changes in air quality; this can be done with sophisticated 3-dimensional atmospheric chemistry models, or, more crudely, with simple functions relating air quality to emissions

3) Estimate the relationship between changes in air pollution and changes in human exposure to air pollution; estimate the relationship between changes in exposure and changes in health impacts such as mortality, chronic illness, and asthma attacks. This step is often combined with previous step.
4) Estimate the relationship between changes in health impacts and changes in economic welfare. The objective is to estimate the dollar value of the physical health impacts.

B. Estimate of U.S. costs in urban transport sector

The table below summarizes recent estimates of air-pollution health costs by mode [40][41][42][43][50][51][52] [53][54]:

Table 17: Human health externality unit costs by mode

	Road [cents]
Delucchi estimates using COBRA	LDGV: 0.57/vmt; 0.91/pmt HDDV: 1.55/tm
Lemp and Kockelman (2008) [b]	0.07 – 0.96/vmt; 0.11 – 1.53/pmt
Parry et al. (2007) [c]	0.81/vmt; 1.29/pmt
Zhang et al. (2004) [d]	Car: 0.06/vmt; 0.09/pmt (intercity) Car: 0.54/vmt; 0.87/pmt (urban) Bus: 0.063/vmt; 0.10/pmt (intercity) Transit: 021/vmt; 0.34/pmt (urban) Truck:0.33/vmt; 0.52/tm (freight)
Forkenbrock (1998,2001) [e]	0.10/tm (freight truck)
McCubbin and Delucchi (1999) [f]	LDGV: 0.31- 0.41/vmt; 0.50 - 6.66/pmt HDDV: 0.64 – 12.1/vmt; 1.04 – 19.35/pmt

Levinson et al. (1998) [g]	0.44/vmt; 0.71/pmt
Small & Kazimi (1995) [h]	1977 car: 3.51/vmt; 5.61/pmt Tier II car: 0.15/vmt; 0.24/pmt ULEV: 0.13/vmt; 0.21/pmt 2000 HDDT: 8.08/tm

a. COBRA refers to the Co-benefits Risk Assessment (COBRA) Screening model (Abt Asssociates, 2006). COBRA estimates the value of health damages due to changes in fine particulate matter (PM) air quality due to changes in emission in PM precursors, including SO2, NO2, and NH3. “Built into COBRA are emission inventories, a simplified air quality model, health impact equations, and economic valuations ready for use, based on assumptions that EPA currently uses as reasonable best estimates” Estimates are in 2006 dollars.

b. Lemp and Kockleman multiply vehicle emission rates, which the authors get from U.S. EPA emission indices, by unit health damage costs from Ozbay and Berechman, for specific models of light-duty vehicles. The variation is due to different emission levels for different vehicles. Estimates appear to be in year 2006 dollars.

c. Parry reports the estimate in year 2005 dollars

d. Zhang calculated the increases in mortality and morbidity case due to the change in the concentration of each pollutant, and then estimated the monetary valuation of different impacts due to air pollution. The estimates are in 2002 Canadian dollars.

e. Forkenbrock’s estimates are based on the work of Haling and Cohen (1995), who use results of National economic research associates (NERA 1993) to assign costs of air pollution in 2233 rural US counties in various state. Estimates are in 1994 dollars.

f. McCubbin and Delucchi (1999, Table 4) use a detailed damage-function approach to estimate the health effects of air pollution from the on-road vehicle fleet in every county in the U.S. in 1990. Only emissions from motor vehicles themselves are included here; emission from petroleum refineries and emissions of road dust are reported in McCubbin and Delucchi (1999) but not included here. Estimates are in 1991 dollar/vmt.

g. Levinson synthesized earlier studies to develop cost estimates of air pollution caused by air travel, considering the health material, and vegetation from particulates, sulfur oxides, hydrocarbons, carbon monoxide and nitrogen oxides, plus the greenhouse damages due to carbon. Estimates are in 1995 dollars.

h. Small and Kazimi estimate air pollution costs by pollutant and vehicel type in Los Angeles. Their baseline results, which are presented here, use a $4.87 million value of life, the geometric average of the high and low particulate mortality coefficients, the geometric average of two ozone morbidity figures with the costs equally attributed to NO_x and VOC, and the only particulate morbidity figure. Estimates are in 1992 dollars.

4.2.3 Proposed procedure and externality cost models for human health

A. *General procedure*

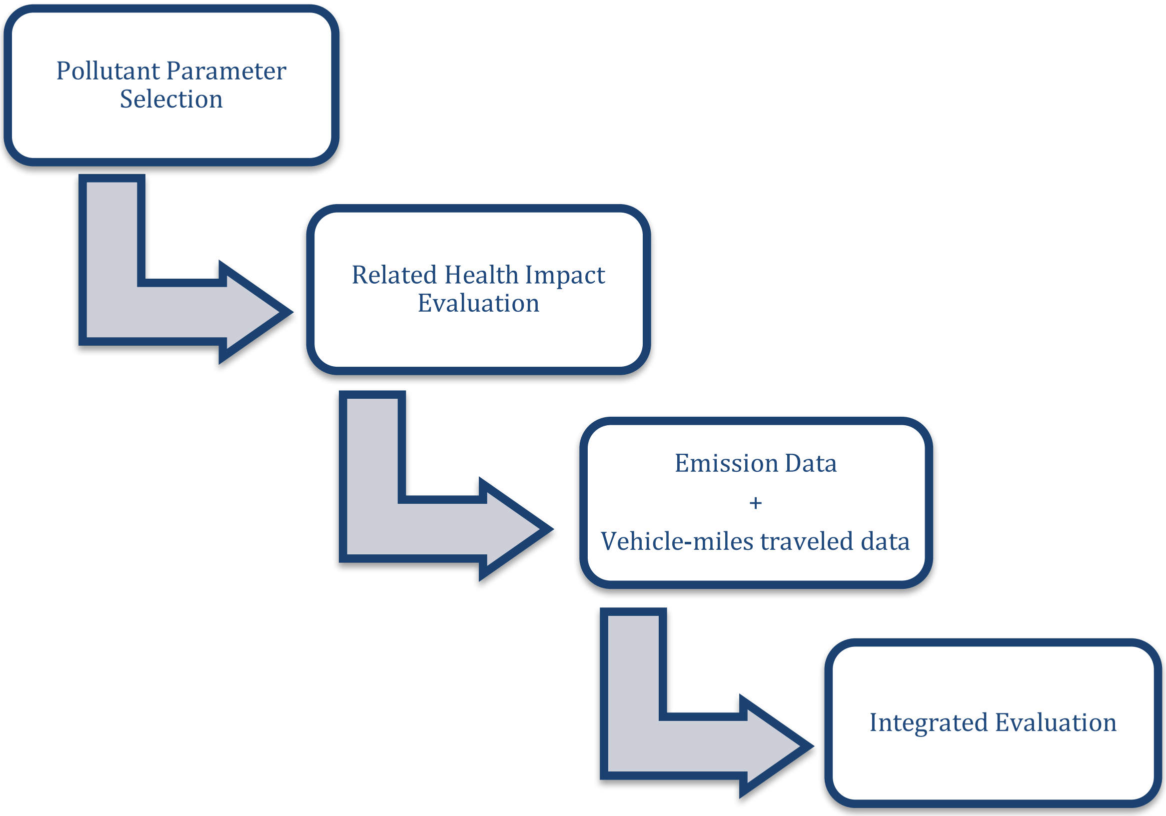


Figure 17: Designed human health externality evaluation procedure

B. *Pollutant parameter selection*

EPA defines the commonly found air pollutants in the United States "criteria pollutants". They are particle pollution (often referred as particulate matter), photochemical oxidants and ground-level ozone, carbon monoxide, nitrogen oxides, and lead. These pollutants can harm human health, environment and cause property damage [55].

a. Particulate Matter

Particulate matter (PM) is a heterogeneous mix of solid or liquid compounds, is regarded by some as the most damaging air pollutant to human health (McCubbin and Delucchi 1999). Studies have shown that the concentration of PM in the local atmosphere is positively correlated to mortality. The inhalation or particulate matter can cause respiratory problems.

In the literature PM is classified according to its size. The three most widely used are Total Suspended Particulate (TSP), PM2.5 and PM10. TSP includes air-borne particles (aerosols) of various dimensions (from hundreds of microns up to tens of microns) and weight; PM2.5 and PM10 include all particles with an aerodynamic diameter less than 2.5and 10 micrometers, respectively. McCubbin and Delucchi (1999) considered that particulates larger than 10 microns are generally not harmful to human health. Hence, this study will not use TSP as a measure of particulate matter.

b. Ozone

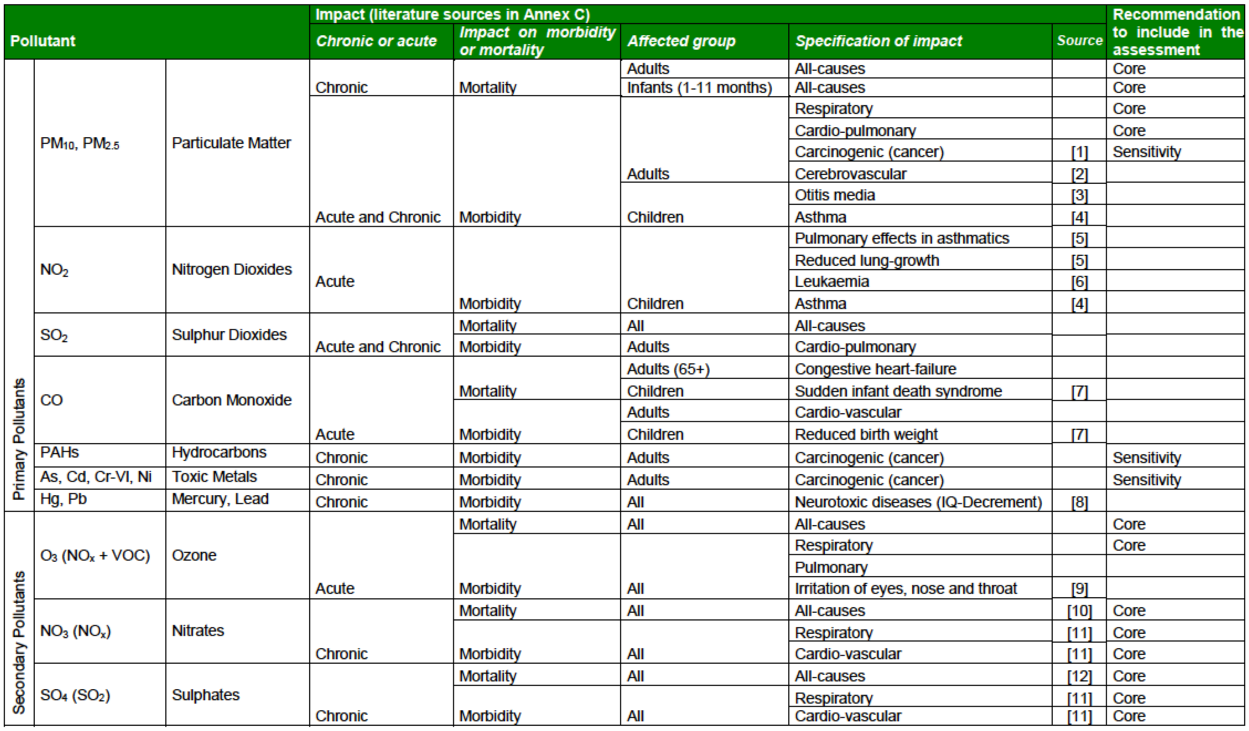
The damage caused by VOCs and Nitrogen Oxides is mainly evident through the formulation of Ozone. Ozone is not emitted by vehicles but is formed through chemical reaction among nitrous oxides (NO_x), VOCs and some other compounds in the atmosphere. Strong evidence shows that ozone is linked to several adverse morbidity effects. McCubbin and Delucchi cited epidemiological studies that the health effects include eye irritation, asthma stacks, and other acute lower ad upper respiratory symptoms.

c. Carbon Monoxide

Carbon monoxide (CO) binds with haemoglobin in the blood to form carboxyhaemoglobin, and reduces the oxygen carrying capacity of the blood and limits the release if oxygen from circulating haemoglobin (McCubbin and Delucchi 1999). Studies by Schewartz (1997) and Morris (1995) have shown that the concentration of CO is linked to cardiovascular problems. Schwartz and Morris and Burnett studies cardiac hospital admissions to provide quantitative evidence of relationship between day-to-day fluctuations in ambient outdoors CO concentrations and cardiac hospital admissions for the elderly [53].

Most studies have failed to find a significant link between mortality and SO2, independent or the effect of particulates. Therefore SO2 is not in the scope of the study.

Table 18: Air pollutants and their effects on human health



Pollutant			Impact (literature sources in Annex C)					Recommendation to include in the assessment
			Chronic or acute	Impact on morbidity or mortality	Affected group	Specification of impact	Source	
Primary Pollutants	PM$_{10}$, PM$_{2.5}$	Particulate Matter	Chronic	Mortality	Adults	All-causes		Core
					Infants (1-11 months)	All-causes		Core
			Acute and Chronic	Morbidity	Adults	Respiratory		Core
						Cardio-pulmonary		Core
						Carcinogenic (cancer)	[1]	Sensitivity
						Cerebrovascular	[2]	
					Children	Otitis media	[3]	
						Asthma	[4]	
	NO$_2$	Nitrogen Dioxides	Acute	Morbidity	Children	Pulmonary effects in asthmatics	[5]	
						Reduced lung-growth	[5]	
						Leukaemia	[6]	
						Asthma	[4]	
	SO$_2$	Sulphur Dioxides	Acute and Chronic	Mortality	All	All-causes		
				Morbidity	Adults	Cardio-pulmonary		
	CO	Carbon Monoxide	Acute	Mortality	Adults (65+)	Congestive heart-failure		
					Children	Sudden infant death syndrome	[7]	
				Morbidity	Adults	Cardio-vascular		
					Children	Reduced birth weight	[7]	
	PAHs	Hydrocarbons	Chronic	Morbidity	Adults	Carcinogenic (cancer)		Sensitivity
	As, Cd, Cr-VI, Ni	Toxic Metals	Chronic	Morbidity	Adults	Carcinogenic (cancer)		Sensitivity
	Hg, Pb	Mercury, Lead	Chronic	Morbidity	All	Neurotoxic diseases (IQ-Decrement)	[8]	
Secondary Pollutants	O$_3$ (NO$_x$ + VOC)	Ozone	Acute	Mortality	All	All-causes		Core
				Morbidity	All	Respiratory		Core
						Pulmonary		
						Irritation of eyes, nose and throat	[9]	
	NO$_3$ (NO$_x$)	Nitrates	Chronic	Mortality	All	All-causes	[10]	Core
				Morbidity	All	Respiratory	[11]	Core
						Cardio-vascular	[11]	Core
	SO$_4$ (SO$_2$)	Sulphates	Chronic	Mortality	All	All-causes	[12]	Core
				Morbidity	All	Respiratory	[11]	Core
						Cardio-vascular	[11]	Core

C. *Related health impact evaluation*

McCubbin and Delucchi's unit cost values of emission factors are adopted in the dissertation. The costs were in 1990 dollars, Table 19 listed unit costs in 2013 dollars as well.

Table 19: Unit cost value of emission factors in 2013

Emission	Ambient Pollutants	Vehicle emission cost in 1991 dollars [Dollars per kg]		Cost in 2013 inflation rate [Dollars per kg]	
		Low	High	Low	High
PM $_{2.5}$	PM $_{2.5}$	14.81	225.36	25.33	385.46
PM $_{2.5-10}$	PM $_{2.5-10}$	9.09	23.89	15.55	40.86
NO_x	Total	1.59	23.34	2.72	39.92
VOC	Organic PM_{10}	0.13	1.45	0.22	2.48
CO	CO	0.01	0.1	0.02	0.17

D. *Emission and Vehicle Travel data*

The urban miles traveled data has been reported in the previous chapter. The exception of BEV, HEV and PHEV is due to the low percentage among vehicles travel in urban areas.

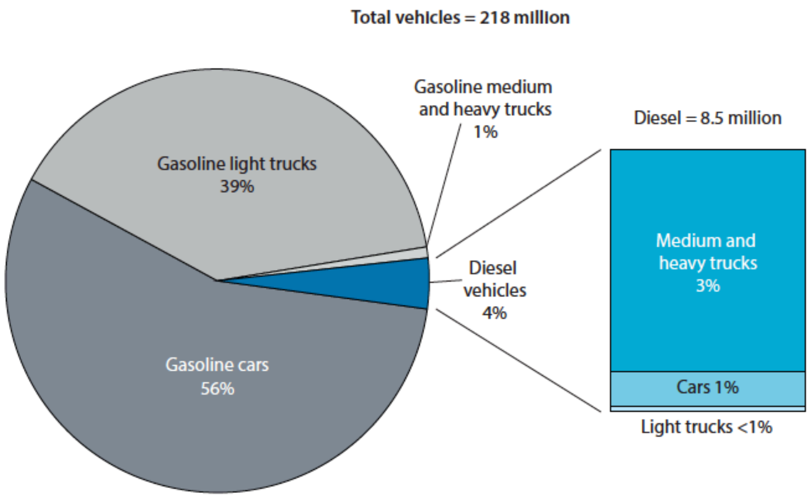


Figure 18: Composition of diesel and non-diesel fleet

4.2.4 Integrated environmental externality cost function

Cost function formula:

$$\begin{aligned} &\textit{Human health externality} \\ &= SUM\ (\textit{Unit cost of emission factor} \cdot \textit{Vehicle tailpipe emission}) \\ &\cdot \textit{Urban vehicle miles traveled} \end{aligned}$$

Table 20: Human health externalities in the baseline scenario

Emission	**Ambient pollutants**	**Average urban cost [Dollars per kg]**	**External Health Cost in Urban Area in the United States in 2013**			
			LDV Yearly Cost [Million Dollars]	HDGV Yearly Cost [Million Dollars]	HDDV Yearly Cost [Million Dollars]	Total Cost per Emission Factor
$PM_{2.5}$	**$PM_{2.5}$**	205.40	1,715.12	404.35	5,569.04	7,688.51
$PM_{2.5-10}$	**$PM_{2.5-10}$**	28.20	252.74	64.36	829.06	1,146.15
NO_x	**NO_x**	21.32	30,090.26	2,779.58	24,647.11	57,516.95

VOC	**Organic PM_{10}**	1.35	2,845.43	95.88	81.07	3,022.38
CO	**CO**	0.09	1,800.91	55.26	29.18	1,885.35
Total Cost [Billion Dollars]			36.70	3.40	31.16	71.26

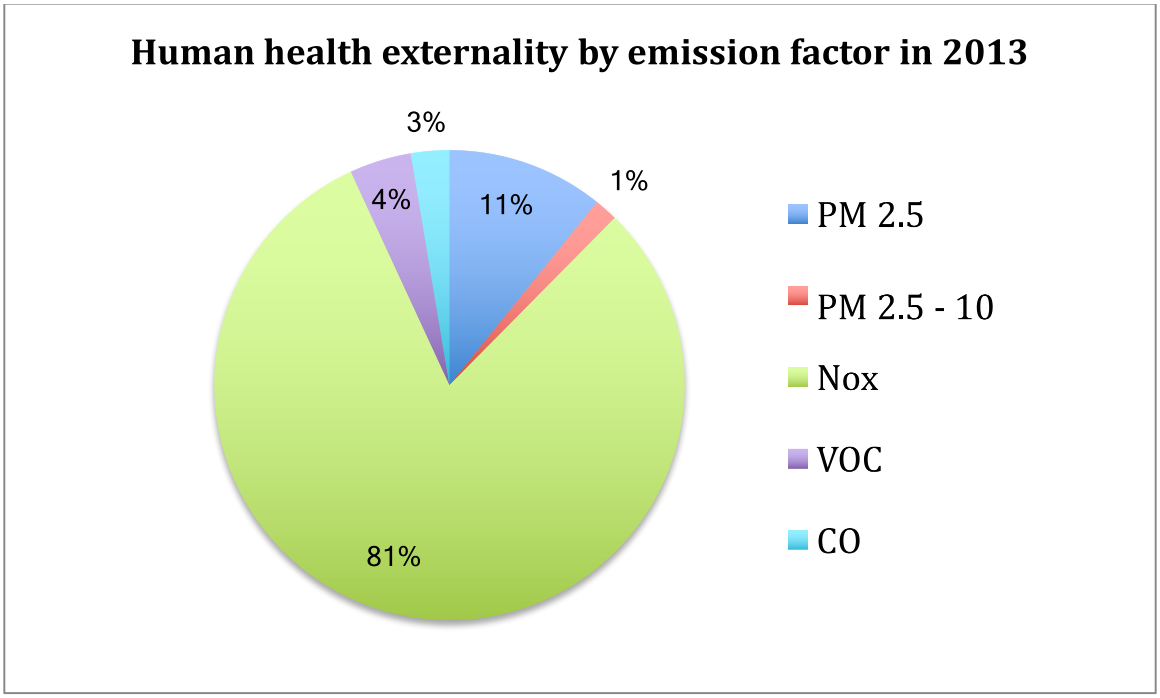


Figure 19: Human health externality costs by pollutants

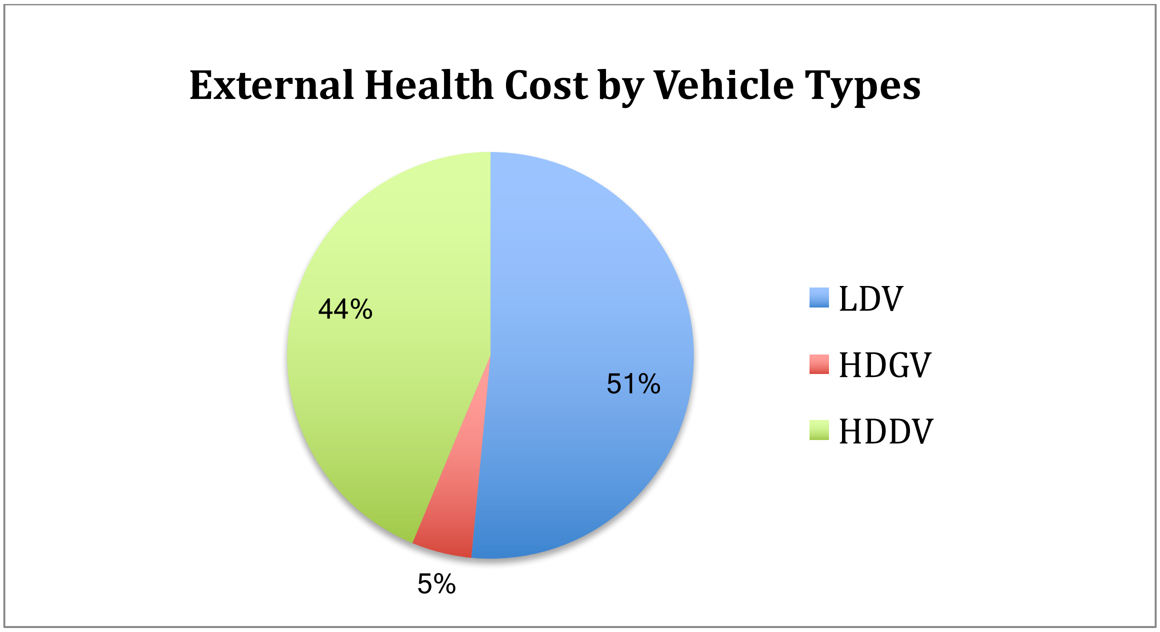


Figure 20: Human health externality by vehicle types

4.3 Climate changing externality in transport economics

Climate change induces by worldwide greenhouse gas (GHG) emission is currently one of the key topics of global research output. Light-duty vehicles account for a fifth of nationwide emissions of carbon dioxide, which is the leading greenhouse gas [56][57].

4.3.1 General introduction

Economists have attempted to estimate damages of global warming. Willian Nordhaus and Joseph Boyer put the (population-weighted) expected global costs of a 2.5 °C warming in 2100 at almost 2.0% of world GDP [58]. Half of this is from the risk of catastrophic or abrupt climate change, which they estimated based on subjective expert judgment about the likelihood of major disruptions to GDP. Another significant damage component is from the possible spread of tropical disease, especially in Africa, which is inferred from data on the incidence of various diseases across different climatic regions, and disability adjusted life years lost per disease.

All transportation modes emit pollutants that affect global climate. These climate-forcing pollutants are called greenhouse gas (GHG), includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), nitrogen oxides (NO_2), ammonia (NH_3), sulfur oxides (SO_2), volatile organic compounds (VOCs), chlorofluorocarbons (CFCs), and various forms of particulate matter (PM).

The climate change costs of transport can be estimated as the product of the two factors: CO_2 equivalent emissions of GHGs (in VMT), and the damage cost of a unit of GHG emission. The evaluation is to simplify the cost-evaluation process of a complex system.

In exaggerated population urban metro area, GHG emission causes the urban heat island effect. “Heat island” describes built up areas that are hotter than nearby rural areas. The annual mean air temperature of a city with 1 million people or more can be 1.8 – 5.4 °F warmer than its surroundings. In the evening, the difference can be as high as 22 °F. Heat island can affect communities by increasing summertime peak energy demand, air conditioning costs, air pollution and greenhouse gas emission, heat-related illness and mortality, and water quality [5].

4.3.2 Procedures and model review

A. General procedures

The unit cost estimation for different transport modes follows a procedure that is already familiar from the discussion of air pollution and noise costs. The general procedure follows the steps:

1) Quantification of GHG emission factors for different vehicles, expressed in ton CO2 equivalent per vkm
2) Valuation of climate change costs per ton of CO2 equivalent
3) Calculation of marginal climate change costs for different vehicle (and fuel) types

B. Review cost function models

Table 21: Climate-change externality cost by mode

	Road ($, cents)
Delucchi estimates[a]	LDGV: 0.038 – 2.99/vmt; 0.06 – 4.78/pmt HDDV: 0.03 – 2.74/tm
Lemp and Kockelman (2008) [b]	0.525 – 2.39/vmt; 0.84 – 3.82/pmt
Parry et al. (2007) [c]	0.19/pmt
Zhang et al. (2004) [d]	Car: 0.04/vmt; 0.06/pmt (intercity) Car: 0.075/vmt; 0.12/pmt (urban) Truck:0.04/vmt; 0.06/tm (freight)
Forkenbrock (1998,2001) [e]	0.19/tm (freight truck)

4.3.3 Proposed cost model

A. Data selection

Ideally, the CO_2 equivalent emissions are estimated for the entire lifecycle of a transportation mode. Lifecycle refers to all activities directly or indirectly involved in production, transportation, and waste disposal.

The CO_2 – equivalent greenhouse gases are described as follows:

- Carbon dioxide – released during the combustion of solid waste, wood and fossil fuels. 20% of total CO_2 emissions in the United States come from cars and light trucks
- Methane – emitted during the production and transport of coal, natural gas, and oil. Other sources may include the decomposition of organic wastes in landfills and raising of livestock
- Nitrous oxide – emitted during agricultural and industrial activities, as well as during the combustion of fossil fuels. Nitrous oxide plays a key role in the disruption of the ozone cycle, producing elevated level of ozone in the troposphere. [59]

In the dissertation research, I want to illustrate the social (external) cost of vehicle emission in urban metro area. Therefore, the research focuses on tailpipe emission of vehicle miles driven.

EPA regulate that carbon dioxide (CO_2), while not regulated as an air pollutant, is the transportation sector's primary contribution to climate change. Carbon dioxide emissions are essentially proportional to fuel consumption (and inversely proportional to fuel economy) – each 1% increase in fuel consumption results in a corresponding 1% increase in carbon dioxide emission. About 19.4 lb CO_2 is produced fro every gallon of gasoline combusted. Passenger cars and light-duty trucks also emit small amounts of other GHGs, but the difference could be tolerated.

Therefore, the cost function contains variables as follow:

- Amount of tailpipe emitted CO_2 per vehicle-miles driven based on vehicle types

- The damage cost per ton of carbon dioxide

B. Cost function

$$\begin{aligned} &Climate\ change\ externality \\ &\quad = Wheel2Wheel\ GHG\ emission\ \cdot VMT \cdot Cost\ of\ CO_2\ per\ ton \end{aligned}$$

Equation 8: Climate change externality cost function

C. Climate externality in baseline scenario

Table 22: Climate change cost of GHG

Climate change externality of carbon dioxide tailpipe emission - Light-duty vehicles						
Cost Per VMT	**In 2013 $ [Dollars per matric ton]**	**Unit emission [Kg per VMT]**	**Urban VMT [Billion miles]**	**PCE**	**Unit Cost [Dollars per VMT]**	**Total Cost [Billion dollars]**
5% Average	12.36	0.368	1844808	1.104	0.00455	9.26
3% Average	40.45	0.368	1844808	1.104	0.01489	30.32
2.5% Average	62.92	0.368	1844808	1.104	0.02315	47.16

4. 4 Total externalities in baseline scenario

In 2013, urban traffic generated 284.27 billion dollars in traffic congestion, human health impact, and climate change. Among all cost categories, traffic congestion was 64% of total cost, along with 13% human health cost, 13% of climate change cost, and 10% of urban island heat cost.

HDV generated 14% of total urban transport externality in 2013. The externalities generated by HDV have not been captured in previous studies. The author proposes to model externalities of HDV travel in future studies in the transport economic area. However, the externalities generated by HDV in urban area will not be considered in other scenarios in this research due to the unknown technology adoption trend among HDVs. The climate change cost will be simplified to the local climate impact – urban heat cost only.

Table 23: Externalities in baseline scenario

<table>
<tr><th colspan="5">Baseline scenario – externalities in 2013</th></tr>
<tr><th colspan="2">Cost in 2013 [Billion dollars]</th><th>Congestion cost</th><th>Human health impact</th><th>Climate change</th></tr>
<tr><td colspan="2">LDV</td><td>181.04</td><td>36.7</td><td>30.2</td></tr>
<tr><td rowspan="2">MDV; HDV</td><td>HDGV</td><td rowspan="2">6.43</td><td>3.4</td><td>-</td></tr>
<tr><td>HDDV</td><td>31.36</td><td>-</td></tr>
<tr><td colspan="2">Total cost</td><td>187.47</td><td>71.46</td><td>30.32</td></tr>
</table>

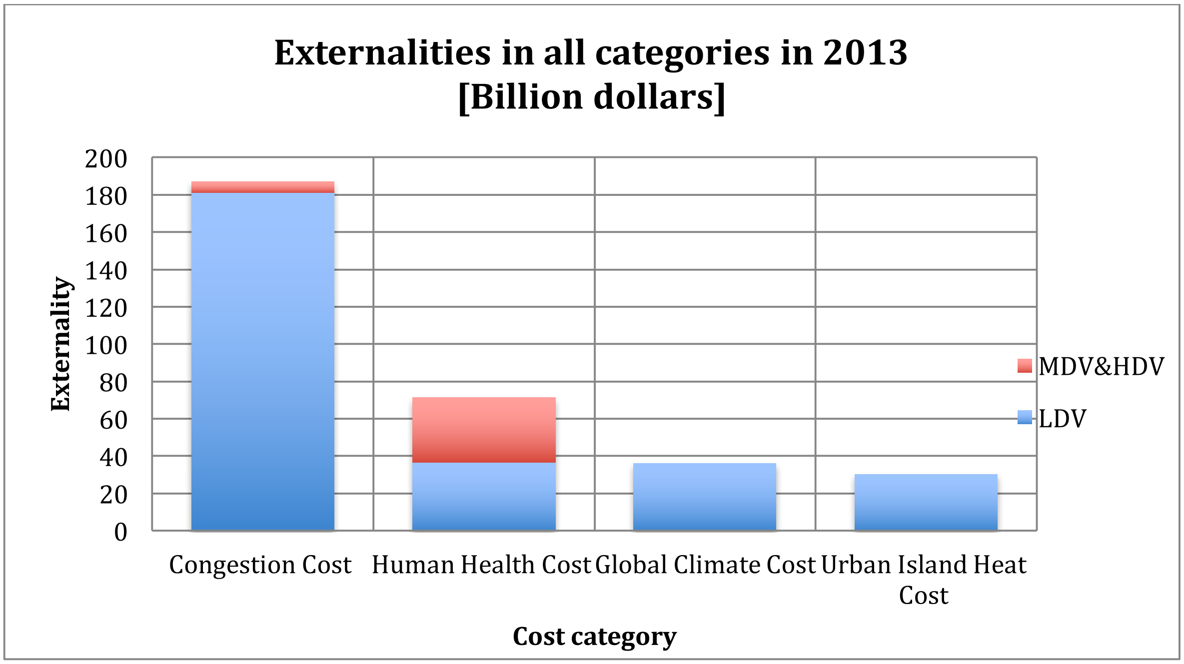


Figure 21: Total externalities in baseline scenario

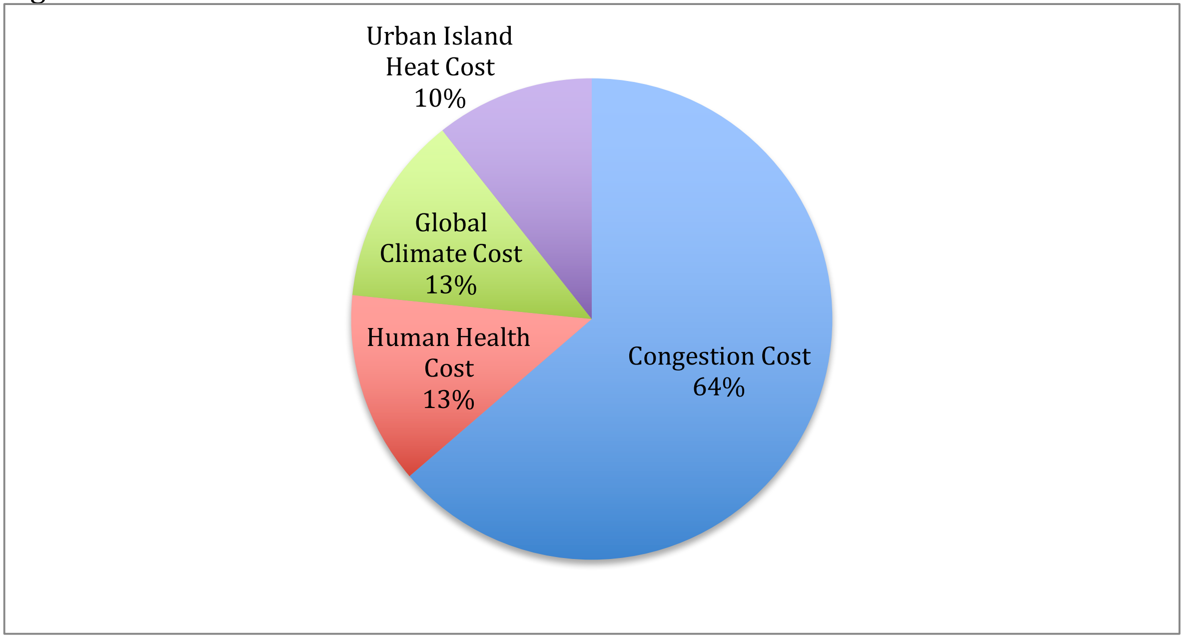


Figure 22: Distribution of cost categories

4.5 Conclusions when compare EV scenario to baseline scenario

The integration of electric vehicle technology at different penetration rates cause a decreased total external cost. The more electric vehicles in the traffic, the less total external cost. When 100% of vehicles in urban traffic are powered by electricity, the total external costs are reduced to 185.59 billion dollars - 73.47% of the baseline scenario.

The integration of EV at any penetration rate does not generate differences in in traffic congestion cost. However when the adoption at 100% rate, the external costs of the human health and climate change are eliminated due to zero tailpipe pollutions.

The adoption of electric vehicle technology effectively diminished the cost of health and environmental impacts, but does not affect congestion cost at all. The congestion cost is the largest cost among all current urban transport externalities. Therefore, the author suggests combining the adoption of EV technology with other technologies that are capable of improving traffic efficiency to release congesting cost.

Chapter 5

5. Mobility Sharing Scenarios

5.1 Introduction of mobility sharing

In this dissertation, mobility sharing is defined as an environmental and social boon rather than a business or financial service. The purpose of mobility sharing is to increase traffic efficiency and reduce unnecessary external costs. By 2013, the average vehicle occupancy had decreased to 1.5 persons per vehicle from 1.87 persons per vehicle in 1977[60][61]. Even at the 1977 level the average vehicle occupancy rates were below ideal.

5.1.1 Different definitions of mobility sharing

There are two general processes of mobility sharing, ride sharing and vehicle sharing. In the research, mobility sharing is for social and environmental purpose rather than business and financial service. Therefore the author will not define or analyze cases focused on specific companies. A brief summary of the marketplace will be presented at the end of this chapter to illustrate the market trends of mobility sharing.

A. Ride sharing

The Association for Commuter Transportation defines ride sharing as people pooling from a common origin, such as a residence or park-and-ride lot, to a common destination, such as a place of employment or businesspark. In some cases, an arrangement is made that allows carpool or vanpool drivers to recuperate the cost of the commute or receive some minimal compensation[62].

Ride sharing is always provided by individual owned vehicle to share cost, gain access to High Occupancy Vehicle (HOV) lane, and save resources. In addition to the individuals' direct benefits, ride sharing activities also significantly help reduce traffic flow.

B. Vehicle sharing

Vehicle sharing (car/fleet/corporate sharing) allows people to rent vehicles on a short-term (hourly or daily), as-needed basis, paying only for the time they use the car and the mileage they use the vehicle. The operators of the car sharing program provide vehicle maintenance, repair and insurance[63]. Vehicle sharing is always operated by fleet company for commercial purposes.

5.1.2 Benefits of mobility sharing

Mobility sharing market has grown tremendously in recent years as a renewed interest in urbanism. Growing environmental, energy and economic concerns have intensified the need for sustainable alternatives.

Different forms of mobility sharing services represent innovative responses to the demand for new mobility option, and offer opportunities to:

- Provide last mile and first mile solutions
- Reduce the number of vehicles in traffic flow
- Mitigate cumulative tailpipe pollution
- Reduce energy usages

- Reduce pressure on parking spaces
- Reduce external cost related to traffic congestion, air pollution and climate change

5.2 Vehicle occupancy rates and facts

5.2.1 Definition of vehicle occupancy rate

Vehicle occupancy rate is the number of passengers in a vehicle during a trip. The author uses VOR as the abbreviation of vehicle occupancy rate in the research. This rate can be expressed as the number of persons per vehicle or by the percentage of occupied seats.The latter is a more useful metric when referring to public transport. The scope of this research is urban traffic that is generated by passenger cars. Therefore, the author will express the VOR as the number of persons per vehicle in the research.

5.2.2 VOR in the United States

VOR is an indicator to monitor the efficiency of transportation, especially in urban areas. Since 1977 the average VOR has always been under 2, indicating that each vehicle had less than two people in it during each trip. The average VOR has continued to decline since 1977.

Table 24: Average VOR for selected purpose from 1977 – 2013[64] [61]

Trip Purpose	1977	1983	1990	1995	2001	2009	2013

Work	1.30	1.29	1.14	1.14	1.14	1.13	-
Personal	2.10	1.79	1.71	1.74	1.79	1.78	-
Social	2.40	2.12	2.08	2.04	2.03	2.20	-
All Purposes	1.90	1.75	1.64	1.59	1.63	1.67	1.50

5.3 Scenario design

The author has demonstrated different methods of mobility sharing from research perspectives. The research focuses on the potential external economic impacts of increasing VOR per vehicle in urban traffic rather than the commercial outputs of current mobility sharing services. An increased in VOR offers an opportunity to lower total vehicle miles traveled in a given urban area. The major purpose of this chapter is to study the impacts of increasing VOR in urban traffic.

In this chapter, the author will introduce some mobility sharing service models, and quantify mobility sharing scenarios for comparison.

5.3.1 Mobility sharing service models

A. Traditional rental car service

Traditional rental car services are short-term services. Passengers always use rental cars for business trips, vacations, and etc.; when they do not have access to their own vehicle at the moment. This is the industry's traditional vehicle sharing business model that charges users by usage period (days).

B. Corporate fleet sharing – The sharing economy in the mobility space

Rental car service offers a better quote to consumers who plan ahead, but the pick-up places are not well distributed in urban area. For hour usage, rental car services are complicated, and inconvenient.

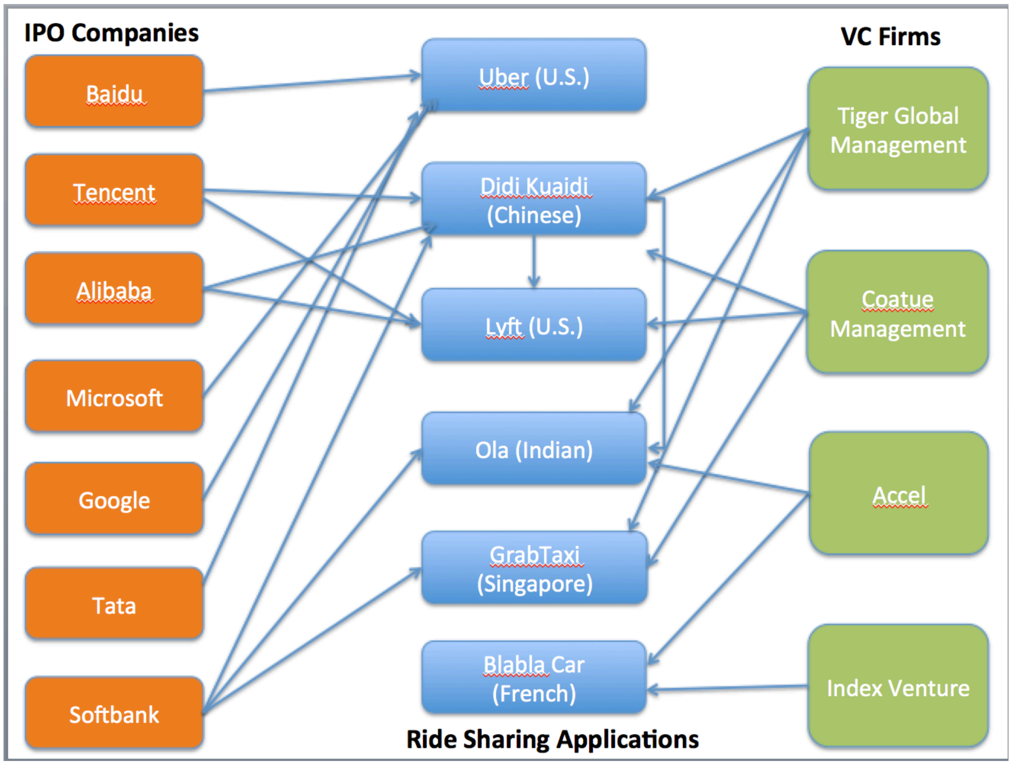
Zip Car started offering hour-based car rental services in Boston area in 2009. The founder, Robin Chase, started viewing vehicles as tools instead of personal assets, and proposed the concept – sharing economy in the mobility sector. The business was a quite a success due to the reasonable hourly rate, and convenient pick-up locations in Boston. As of May 2012, the company had 700,000 members and a fleet of more than 9,000 vehicles[65]. However, Zip Car still faced difficulties when the company tried to expand the service into other cities.

BMW offers an hourly car-renting service – DriveMe in Germany. The service uses BMW brand compact vehicles, especially Mini Coopers. German Transportation Department supports DriveMe by offering premium parking spots in busy urban areas to encourage DriveMe's sharing program. The strategic local governmental support helps DriveMe stand out among competitions.

C. Ride sharing service – last mile solution

While semi-new fleet sharing businesses are offering passengers hourly-based mobility services; Uber started minute-based last mile mobility service in 2009. Uber does not own cars as assets, but leverages the commuting ability of individual owned vehicles. Uber offers a last-mile solution at a reasonable price through a mobile application.

Uber-like businesses have started in different regions and different countries. Lyft has been popular in Silicon Valley, California, while Ola dominates the Indian market. Figure 5-1 shows relationships between ride-sharing businesses, investors and partners worldwide.



* IPO companies stands for initial public offering companies

Figure 23: Ride sharing investment ecosystem

The governmental support and regional protection of local business have ensured competitive advantages of local mobility businesses over outsiders. The ride sharing market place has been increasing worldwide. However, it is still unclear that whether the ride sharing business will increase or decrease the total VMT in urban areas. This research will illustrate the benefits of increased VOR at different level theoretically, regardless of the existing ride sharing data from ride sharing venders due to data availability.

5.3.2 Research scenarios design

A. Mobility sharing scenario with ICE vehicles

The author integrates new variable – VOR into the mobility sharing scenarios and compare the results to the baseline scenario. The VMT in the baseline scenario will change to new VMT (VMT_n) in mobility sharing scenario with ICE vehicles. The original VMT is under the assumption that 1.6 passengers average per vehicle in urban traffic in 2013[64]. The converted VMT_n is listed in the table below.

$$VMT_{\mathbf{n}} = \frac{VMT_o \times VOR_o}{VOR_n}$$

Equation 9: VMT in mobility sharing scenario

* VMT_n – New VMT in the mobility-sharing scenario

* VMT_o – Original VMT in the baseline scenario (urban transportation data in 2013)

* VOR_o – Original VOR in the baseline scenario in 2013; 1.6 passengers per vehicle

* VOR_n – New VOR in the mobility-sharing scenario

Table 25: VMT in mobility sharing scenario

VOR	VMT_o [Billion miles]	PMT [Billion miles]	VMT_n [Billion miles]
1.6	1,845	2,952	1,845
2	1,845	2,952	1,476
3	1,845	2,952	0.984
4	1,845	2,952	0.738
5	1,845	2,952	0.590

B. Mobility sharing scenario with Electric Vehicles at different penetration rate

In the shared EV scenario, the author integrates different penetration rates of electric vehicles. All other factors remain the same when compare to the previous mobility sharing scenario.

Table 26: Independent variables in mobility sharing scenario

Independent variables at different penetration rates					
VOR	1.6	2	3	4	5
EV adoption rate	0%	25%	50%	75%	100%

5.4 Transportation externalities for mobility sharing with ICE vehicles

5.4.1 Overview

Detailed calculation and data analysis will be found in chapter 5.4. The author will analyze Scenario A – mobility sharing with ICE vehicles, then analyze Scenario B – mobility sharing with EV at different penetration rates. In each scenario, the author defines and integrates the new independent variables.

5.4.2 Externality for traffic congestion

Congestion externality is a cost per mile based cost function. Two major variables are the unit cost that occurs because passengers' time loss in traffic congestion, and total vehicle miles traveled in urban area.

Cost function formula:

$$\text{Congestion externality} = \text{Unit cost per mile} \cdot \text{VMT}$$

Equation 10: Congestion cost function

The author observed increasing mobility sharing activities in passenger-sized vehicles. The major transportation purpose for heavy-duty vehicles is to transport cargo. Therefore, the VMT of heavy-duty vehicles will not be discussed in this chapter since the distance will remain constant regardless of mobility sharing. There are different sizes of vehicles in light-duty vehicle category; the PCE is calculated based on the average sales of different types of vehicles in the past ten years in urban automotive markets.

A. Unit congestion cost per vehicle miles traveled

$$CC = tf \cdot \alpha \cdot \ [\left(\frac{Vol+PCE}{Cap}\right)^{\beta} - \left(\frac{Vol}{Cap}\right)^{\beta}] \cdot Vol \cdot VOTT \cdot p$$

Equation 11: Unit congestion cost in mobility sharing scenario

Table 27: Define variables and constants in unit congestion cost

Factors	**Definition**
t_f	Travel time at free flow conditions. The average congested roadway was assumed to have a free-flow speed of 40 mph, corresponding to 1.5 minutes of travel time per mile traveled at free flow conditions.
α, β	BPR-required parameters; 0.84 and 5.5 (fixed value)
Vol	Road capacity is assumed to be 2000 vehicles per hour per lane (vphpl) and demand is assumed to be right at 95% of total available capacity in the baseline scenario. The capacity changes with penetration rate of autonomous vehicles as shown in Table 29.
PCE	PCE measures Passenger Car Equivalence. It is calculated based on sales volume of different vehicles in urban areas. PCE is considered constant at 1.104 for these scenarios.
Cap	Road capacity - Road capacity is assumed to be 2000 vehicles per

	hour per lane (vphpl)
VOTT	VOTT is a constant measurement of the Value of the Traveler's Time. The Victoria Transport Policy Institute estimates that the value of travel time for personal purposes is about 30% of household hourly income [46]. In 2006, the U.S. household hourly income was 16.83 dollars. After accounting for inflation, the VOTT is 6.04 dollars in 2013. Therefore, the VOTT here is estimated to be \$5 per passenger hour, \$8 per vehicle hours[47].
p	Congested conditions - The travel condition p is calculated from the travel time index found in Texas A&M's Urban Report 2013. In both baseline scenario and this scenario, p value is 0.1736.

Table 28: Value change of variables in unit congestion cost formula

Variables	Baseline scenario	Mobility sharing Scenario
t_f	Travel time at free-flow conditions per mile traveled	Remain the same
α, β	BPR-required parameters; 0.84 and 5.5 (fixed value)	Remain the same
Vol	Road capacity per hour per lane * travel demand	Travel demand changes based on the number of vehicles on road
PCE	Passenger car equivalent	Remain the same
Cap	Road capacity	Remain the same
VOTT	Value of travel time	Remain the same
p	Congested conditions	Remain the same

Table 29:Redefine vehicle volume per hour per lane

VOR	Road capacity per hour per lane
1.6	2000*95% = 1900
2	1520
3	1013
4	760
5	608

Table 30:The unit cost model at different VOR

VOR	Cost Model
1.6	$CC = tf \ast \alpha \ast \left[\left(\frac{1900 + 1.104}{2000}\right)^{\beta} - \left(\frac{1900}{2000}\right)^{\beta}\right] \ast 1900 \ast 6.04 \ast 0.1736$
2	$CC = tf \ast \alpha \ast \left[\left(\frac{1520 + 1.104}{2000}\right)^{\beta} - \left(\frac{1520}{2000}\right)^{\beta}\right] \ast 1520 \ast 6.04 \ast 0.1736$
3	$CC = tf \ast \alpha \ast \left[\left(\frac{1013 + 1.104}{2000}\right)^{\beta} - \left(\frac{1013}{2000}\right)^{\beta}\right] \ast 1013 \ast 6.04 \ast 0.1736$
4	$CC = tf \ast \alpha \ast \left[\left(\frac{760 + 1.104}{2000}\right)^{\beta} - \left(\frac{760}{2000}\right)^{\beta}\right] \ast 760 \ast 6.04 \ast 0.1736$
5	$CC = tf \ast \alpha \ast \left[\left(\frac{608 + 1.104}{2000}\right)^{\beta} - \left(\frac{608}{2000}\right)^{\beta}\right] \ast 608 \ast 6.04 \ast 0.1736$

Table 31: Redefined unit costs based on different VOR

VOR	Unit congestion cost [Dollars/mile]
1.6 baseline scenario	0.1006
2	0.0295
3	0.0032
4	0.0007
5	0.0001

B. Experimental results

The author integrated the unit congestion cost and VMT into cost function Equation 2. The results of external congestion cost in the sharing scenario are listed in Table 8.

Table 32: Congestion externalities in mobility sharing with ICE scenario

VOR	Unit Cost [Dollar/mile]	VMT new [Billion miles]	Total cost [Billon dollars]
1.6	0.1006	1,844	185.59
2	0.0295	1,475	43.53
3	0.0032	0.983	3.12
4	0.0007	0.737	0.48
5	0.0001	0.590	0.11

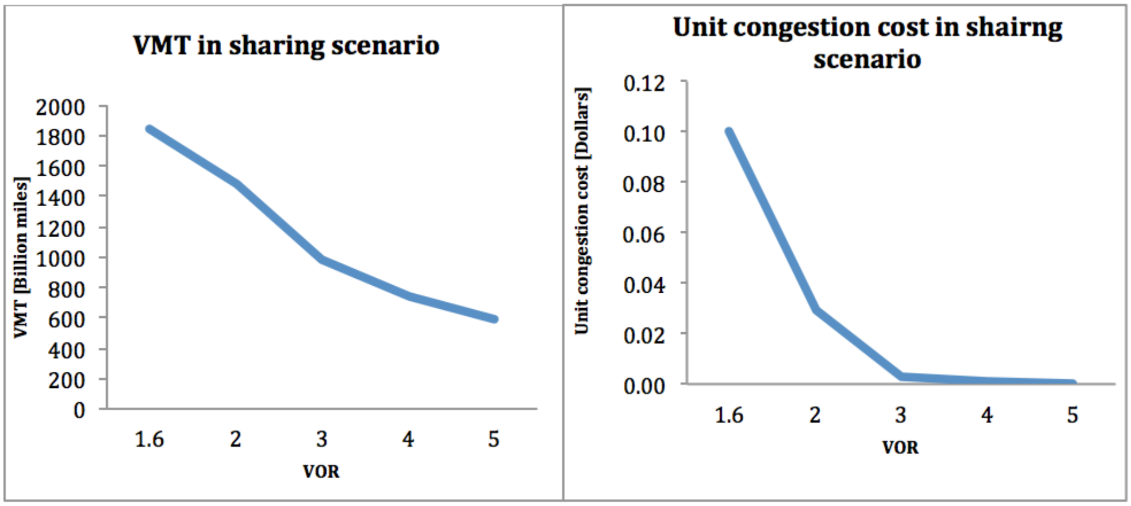


Figure 24: Unit congestion cost and VMT in sharing scenario

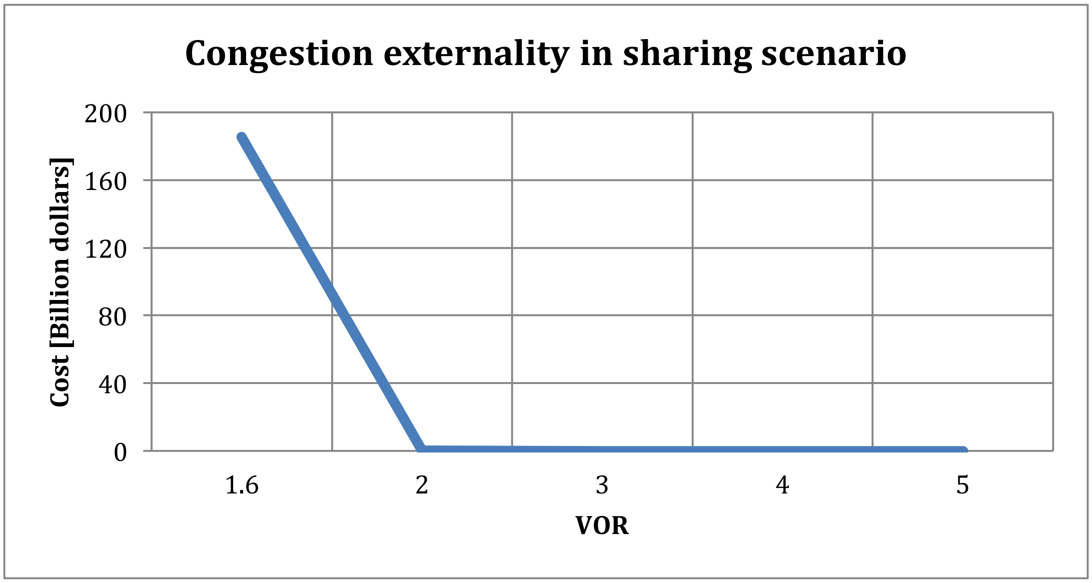


Figure 25: Total congestion externality in sharing scenario

5.4.3 External cost of human health impacts

A. *Introduction of human health impacts*

Transportation significantly impacts air pollution in the immediate area around it. Road transportation is responsible for emission of nitrogen oxides, sulphur dioxide, volatile organic compounds, carbon monoxide, lead and particulate matter with a diameter of less than 10 μm. Air pollution in the transportation sector affects human health in a number of ways.

I define the external cost function for human health impact as:

$$Human\ health\ externality = Unit\ cost\ of\ Pollutans \cdot VMT$$

Equation 12: Human health externality cost function

B. *General screening procedure, unit cost of criteria pollutants, and vehicle miles traveled*

a. General procedure

The author proposed the general procedure in Chapter 4 after reviewing and comparing two common procedures with worldwide adoption. For a detailed description of the procedure, please refer to chapter 4.

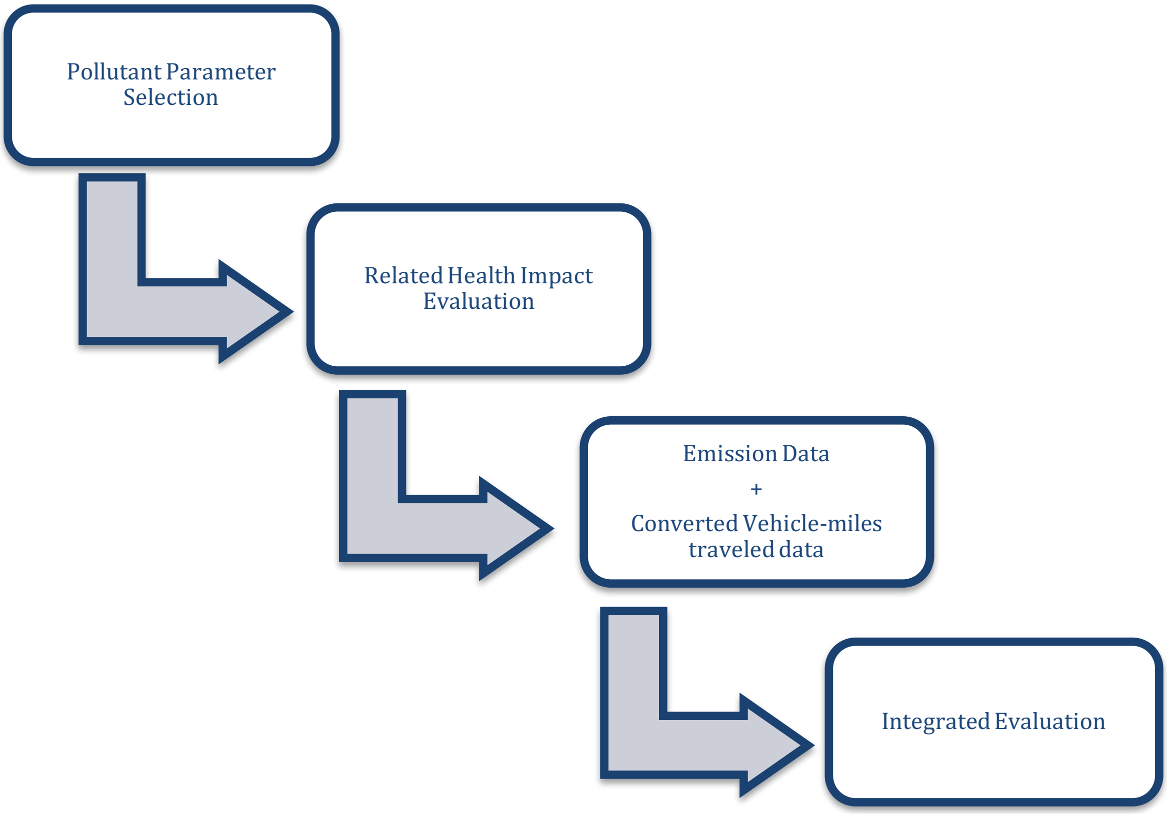


Figure 26: Human health externality screen process

b. Harmful pollutants and unit cost of each

EPA has defined a set of commonly found air pollutants in the Unites States as/the “criteria pollutants”. They are particle matter, photochemical oxidants, ground-level ozone, carbon monoxide, nitrogen oxides, and lead.

This dissertation will utilize McCubbin and Delucchi’s unit cost values of emission factors. The costs are listed in the Table 9 in 2013 dollars.

Table 33: Unit cost of criteria pollutants

Emission	Ambient Pollutants	Cost in 2013 inflation rate [Dollars/kg]	
		Low	High
$PM_{2.5}$	$PM_{2.5}$	25.33	385.46
$PM_{2.5-10}$	$PM_{2.5-10}$	15.55	40.86
NO_x	Total	2.72	39.92
VOC	Organic PM_{10}	0.22	2.48
CO	CO	0.02	0.17

c. Vehicle miles traveled

Table 34: VMT in mobility sharing with EVs

VOR	VMT_o [Billion miles]	PMT [Billion miles]	VMT_n [Billion miles]
1.6	1,845	2,952	1,845
2	1,845	2,952	1,476
3	1,845	2,952	0.984
4	1,845	2,952	0.738
5	1,845	2,952	0.590

C. Experimental results

Table 35: Modeled results in human health externality

VOR	VMT_n [Billion miles]	Total unit cost of pollutants [Dollars]	Total cost [Billion dollars]
1.6	1,845	0.0199	36.70
2	1,476	0.0199	29.36
3	0.984	0.0199	19.58

4	0.738	0.0199	14.68
5	0.590	0.0199	11.75

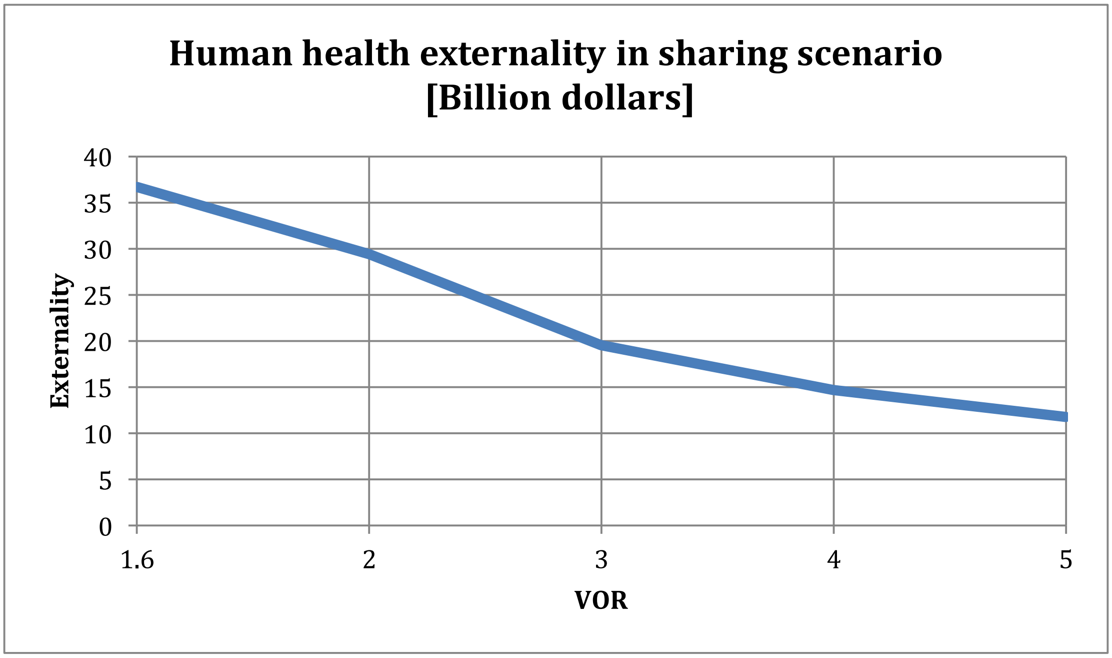


Figure 27: Human health externality in sharing scenario

5.4.4 External costs of climate change in the mobility sharing scenario

A. General introduction

All transportation modes emit pollutants that affect global climate. These climate-changing pollutants are called greenhouse gases (GHG). Light-duty vehicles account for approximately 20% of US domestic of carbon dioxide, which is the most abudant greenhouse gas.

The climate change costs of transport can be estimated as a product of two factors: CO_2 equivalent emissions of GHGs (in VMT), and the damage cost of a unit GHG emission.

The cost function is described as below:

$$ExternalCostofClimateChange = UnitGHGCost \cdot VMTnew$$

Equation 13: Cost function of climate change in urban areas

B. *Unite GHG cost and VMT in mobility sharing scenario*

a. Unit GHG cost per VMT

Table 36: Unit GHG cost per VMT

	In 2013 dollar [Dollar per ton]	Unit Emission [Kg per VMT]	PCE	Unit Cost in 2013 [Dollar per VMT]
5%	11	0.368	1.104	0.00455
3%	36	0.368	1.104	0.01489
2.5%	56	0.368	1.104	0.02315

b. VMT in mobility sharing scenario

Table 37: VMT in mobility sharing scenario with EVs

VOR	VMT_o [Billion miles]	PMT [Billion miles]	VMT_n [Billion miles]
1.6	1,845	2,952	1,845
2	1,845	2,952	1,476
3	1,845	2,952	0.984
4	1,845	2,952	0.738
5	1,845	2,952	0.590

C. *Experimental results*

Table 38: Climate change externality in mobility sharing with ICE vehicles

VOR	VMTn [Billion miles]	Unit cost of GHG [Dollars per VMT]	Total cost [Billion dollars]
1.6	1,845	0.01489	30.32
2	1,476	0.01489	24.25
3	0.984	0.01489	16.17

4	0.738	0.01489	12.13
5	0.590	0.01489	9.70

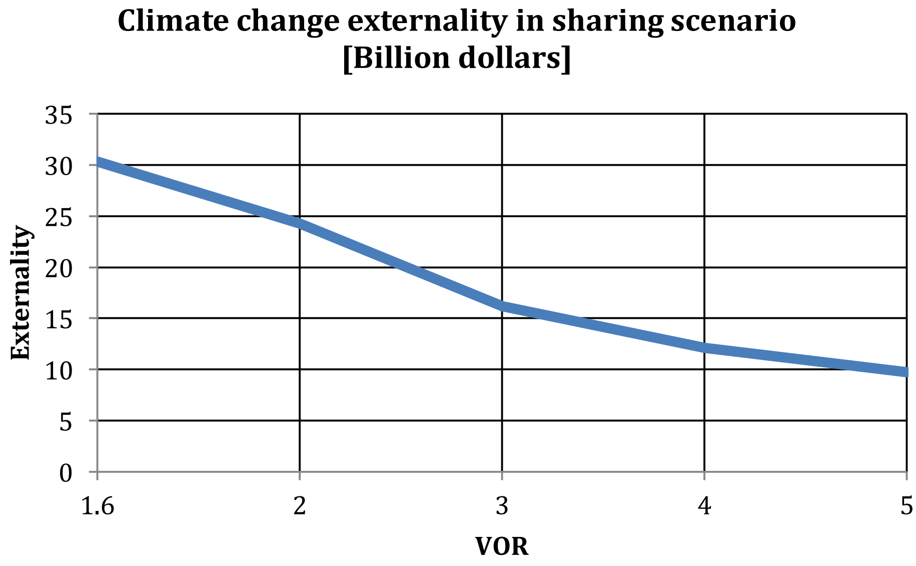


Figure 28: Climate change externality in sharing scenario

5.5 Transportation externality for mobility sharing scenario B

5.5.1 Overview

Scenario B is a sub-scenario of mobility sharing that explores the impact of different vehicle energy sources. The only difference between Scenario A and Scenario B is the energy source for passenger vehicles in urban traffic.

Increasing sales of electric vehicles indicates the alternative fuel adoption trend in the automotive industry. The author proved that the adoption of electric vehicles will reduce the external human health and climate costs of urban transportation in Chapter X. The new variable in the Scenario B is the electric vehicle adoption rate.

As discussed in chapter 4, the adoption of electric vehicles at different penetration rates do not affect the external cost of traffic congestion. Therefore, the author will only illustrate the reduced external cost in human health impacts and climate change.

5.5.2 External costs of human heath impacts for mobility-sharing scenario B

A. *Cost function*

$$External\ HHC = Unit\ Cost\ of\ E\mathrm{Vp} \cdot VMT_{ev} + Unit\ cost\ of\ IC\mathrm{Ep} \cdot VMT_{ice}$$

Equation 14: External climate change cost function

B. *Unit costs of EV and ICE's pollutants*

Table 39: Unit pollutant costs of EV and ICE

VOR	Unit Pollutant Cost [Dollars per VMT]	
	ICE	EV
1.6	0.0199	0
2	0.0199	0
3	0.0199	0
4	0.0199	0
5	0.0199	0

C. *Calculation result*

a. 0% EV adoption

Table 40: 0% EV adoption rate in sharing scenario

VOR	Total VMT [Billion miles]	0% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
1.6	1,845	1,845	0	36.70
2	1,476	1,476	0	29.36
3	0.984	0.984	0	19.58
4	0.738	0.738	0	14.68
5	0.590	0.590	0	11.75

b. 25% EV adoption

Table 41: 25% EV adoption rate in sharing scenario

VOR	Total VMT [Billion miles]	25% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
1.6	1,845	1,384	0.461	25.53
2	1,476	1,107	0.369	22.02
3	0.984	0.738	0.246	14.68
4	0.738	0.553	0.184	11.01
5	0.590	0.443	0.148	8.81

c. 50% EV adoption

Table 42: 50% EV adoption in mobility sharing scenario

VOR	Total VMT [Billion miles]	50% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
1.6	1,845	0.922	0.922	18.35
2	1,476	0.738	0.738	14.68
3	0.984	0.492	0.492	9.79

4	0.738	0.369	0.369	7.34
5	0.590	0.295	0.295	5.87

d. 75% EV adoption

Table 43: 75% EV adoption in mobility sharing scenario

VOR	Total VMT [Billion miles]	75% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
1.6	1,845	0.461	1,384	9.18
2	1,476	0.369	1,107	7.34
3	0.984	0.246	0.738	4.89
4	0.738	0.184	0.553	3.67
5	0.590	0.148	0.443	2.94

e. 100% EV adoption

Table 44: 100% EV adoption in sharing scenario

VOR	Total VMT [Billion miles]	100% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
1.6	1,845	0	1,845	0
2	1,476	0	1,476	0
3	0.984	0	0.984	0
4	0.738	0	0.738	0
5	0.590	0	0.590	0

f. Comparison of different penetration adoption rates

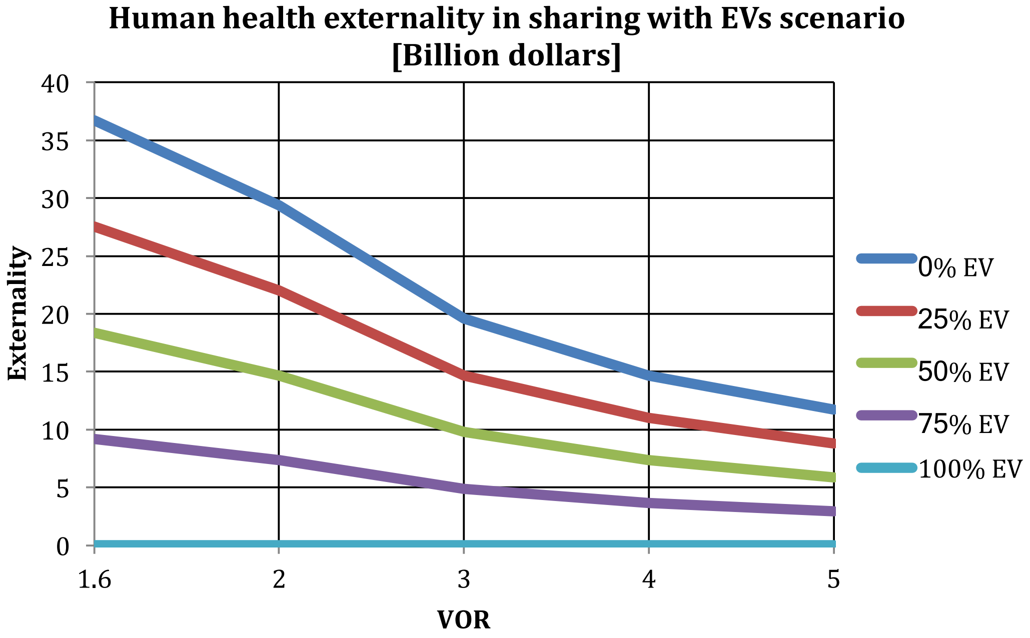


Figure 29: Human health externalities at different penetration rates

5.5.3 External costs of climate change in Scenario B

A. Cost function

$$Externality_{cliamtechange} = Unit\ cost\ of\ EV_{ghg} \cdot VMT_{ev} + Unit\ cost\ of\ ICE_{ghg} \cdot VMT_{ice}$$

Equation 15: External climate change cost function

B. Unit costs of EV's and ICE's GHG

Table 45: Unit GHG costs of EV and ICE

VOR	Unit Pollutant Cost [Dollars per VMT]	
	ICE	EV
All rates	0.0149	0

C. Calculation results

a. 0% EV adoption rate

Table 46: Climate change externality at 0% EV adoption

VOR	Total VMT [Billion miles]	0% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
1.6	1,845	1,845	0	27.46
2	1,476	1,476	0	21.97
3	0.984	0.984	0	14.65
4	0.738	0.738	0	10.98
5	0.590	0.590	0	8.79

b. 25% EV adoption rate

Table 47: Climate change externality at 25% EV adoption

VOR	Total VMT [Billion miles]	25% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
1.6	1,845	1,384	0.461	20.60
2	1,476	1,107	0.369	16.48
3	0.984	0.738	0.246	10.98
4	0.738	0.553	0.184	8.24
5	0.590	0.443	0.148	6.59

c. 50% EV adoption rate

Table 48: Climate change externality at 50% EV adoption

VOR	Total VMT [Billion miles]	50% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
1.6	1,845	0.922	0.922	13.73
2	1,476	0.738	0.738	10.98
3	0.984	0.492	0.492	7.32

4	0.738	0.369	0.369	5.49
5	0.590	0.295	0.295	4.39

d. 75% EV adoption rate

Table 49: Climate change externality at 75% EV adoption

VOR	Total VMT [Billion miles]	75% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
1.6	1,845	0.461	1,384	6.87
2	1,476	0.369	1,107	5.49
3	0.984	0.246	0.738	3.66
4	0.738	0.184	0.553	2.75
5	0.590	0.148	0.443	2.20

e. 100% EV adoption rate

Table 50: Climate change externality at 100% EV adoption

VOR	Total VMT [Billion miles]	100% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
1.6	1,845	0	1,845	0
2	1,476	0	1,476	0
3	0.984	0	0.984	0
4	0.738	0	0.738	0
5	0.590	0	0.590	0

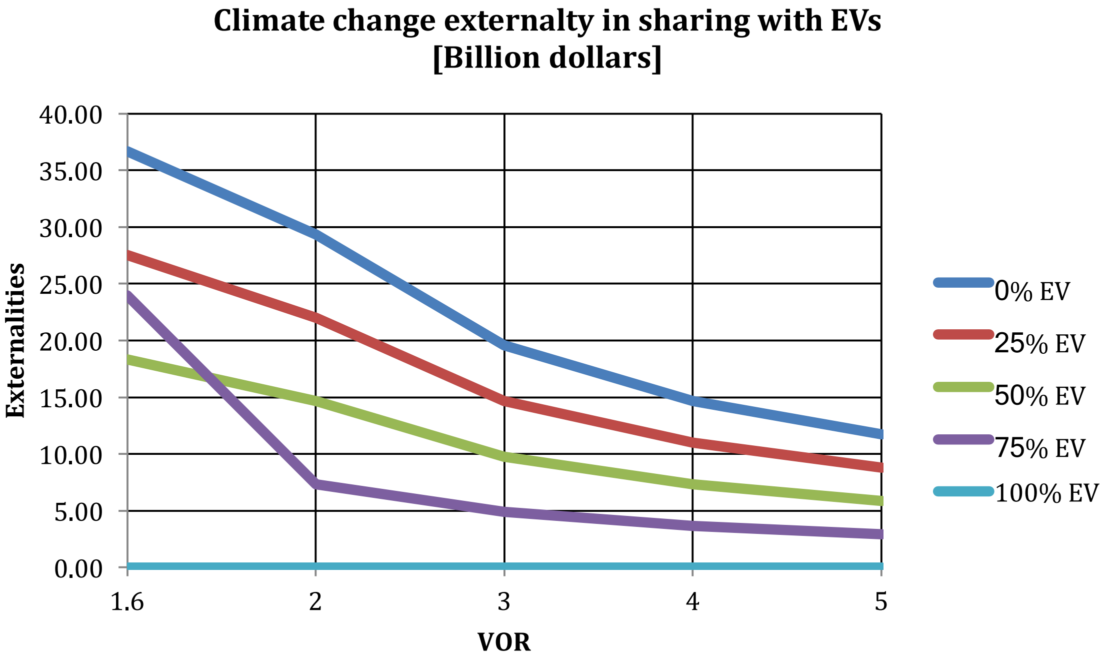


Figure 30: Climate change externality at different penetration rates

5.6 Summary

The integration of mobility sharing at different VOR rates causes a significantly decreased total external cost. The more occupants per vehicle, the less externality. When vehicles in urban traffic with full capacity (5 occupants include driver), the total external costs are reduced to 21.54 billion dollars – 8.53% of the baseline scenario.

The integration of mobility sharing diminishes external costs in all cost categories due to the decreased vehicle-miles traveled. The most significant cost change happens when the author increased the VOR rate from 1.6 (baseline) to 2.

The adoption of mobility sharing effectively eliminated the external cost of traffic congestion. No congestions occur when average vehicle occupancy rate reaches three; urban traffic flows freely due to the decreased numbers of vehicle per mile per lane.

The externals costs of human health and climate change will not be prevented by adoption mobility sharing only. The author suggests combining the adoption of mobility sharing with alternative fuel technology to address the human health and climate change costs.

CHPATER SIX

6. EXTERNALITIES IN AUTOMATED DRIVING SCENARIO

6.1 Introduction of automated driving concept

6.1.1 Definition of automated driving

A driverless car (also known as robotic car, self-driving car, autonomous car) is a vehicle that is capable of sensing its environment and navigating without human inputs[66]. The author adopted the term "automated driving" for this research.

An automated driving system is a complex combination of components that can be defined as systems where perception, decision making, and operation of the automobile are performed by electronics and machinery instead of a human driver, and as introduction of automation into road traffic[67].

6.1.2 Regulation and standardization

The National Highway Traffic Safety Administration (NHTSA) defines automated vehicles as those in which operations occur without human drivers' input. NHTSA classified 5 levels of automation, from level 0 (no automation) to level 4 (fully automated vehicle). SAE defined automation levels from level 1 – level 5, the author adopts NHTSA standards in the research.

Table 51: NHTSA standards for automated driving systems

Level	Definition
Level 0	Human driver controls all functions
Level 1	Function-specific automation: e.g. cruise control
Level 2	Combined function automation: e.g. adaptive cruise control

	with lane guidance
Level 3	Limited self-driving automation; human driver may need to re-engage
Level 4	Full automation; no human driver required

6.1.3 Potential impacts of automated driving technology

Automated driving systems of varying levels have been proven to affect urban traffic in several ways:

- Increased safety for both drivers and passengers
- Increased convenience and productivity due to lower requirements for human input
- Increased traffic efficiency and lower congestion when automated driving technology is mass adopted in traffic.
- Enabling technology for widespread car sharing.

6.1.4 Obstacles during implantation

The process of implementing automated driving technology is not as easy as running simulations *in silicos*. Automated driving technology is a major disruptive technology in the history of the automotive industry. Developments in machine learning language, and the digitalization of vehicle components accelerate the revolution in vehicle automation. At the same time, Gen Y (1977 – 2000) prefers to stay connected with shared mobility services to be economical, and efficient. To these consumers, cars are viewed as mobility services or tools rather than individual owned assets.

The transition from the current product-focused marketplace to a service-based marketplace faces the following obstacles:

- Consumers' uncertainty of overall performance during the technology adoption process
- The unclear competitive pathways among traditional participants in the automotive industry, new entrants, and entrepreneurs
- The incomplete standardization and regulation of automated driving related products and services

A. Uncertainty of technology compatibility and the transition period

The P2S transition was defined in Chapter X. This transition can also be interpreted as the period when human drivers and automated driving cars co-exist in traffic.

Human drivers' behavior and actions are the most unpredictable elements of live traffic. Computer science engineers have been working on machine learning language to predict human drivers' behaviors by learning from real traffic data. However, ethical concerns beyond the scope of these algorithms exist. For example, during an unavoidable traffic accident, should an automated driving system save its passengers or the other would-be victims? What if the would-be victims are pregnant women or young children? Who is responsible for the action and following liabilities when the driver was undisputably not operating the vehicle?

Scientists and engineers can do their best to train machines to learn interactive human driving behaviors. They may also assume that regulations will be in place before the mass adoption of such technology, and bet on taking irrational drivers out of the traffic. Beyond these two scenarios, the transition period is still the biggest challenge that automated driving system is facing.

B. Uncertainty during technology adoption process

The technology adoption lifecycle is a sociological model that describes the adoption or acceptance of a new product or innovation[68]. Consumers adopt new services because of the inconvenience of previous user experiences or curiosity about novel products. Customers adopt new services at different rates based on individual prioritized consuming demands.

The adoption process interferes with the product development cycle. Customers do not know what to expect until they can see and touch the design. Designers do not understand how to revise products until they receive feedback from potential customer segments.

To a capital-intensive and disruptive technology like autonomous vehicles, there is always a longer product design cycle, and increased risk once the product is in the marketplace.

C. Unclear competitive pathways

The adoption of automated driving technology brings new opportunities to the mobility marketplace. Digitalized services lower the barrier to entry to the automotive industry. Tesla is the only successful entrepreneurial vehicle manufacturer since 1745. However, the author has observed new entrants and entrepreneurial companies in the marketplace since automated driving technology was introduced.

Google has been testing its autonomous vehicles in California since 2009. Uber started testing its self-driving cars in Pittsburgh, PA in 2016. Drive AI is a Silicon Valley based start-up firm who focuses on automated-driving software while foregoing hardware design. This highly competitive marketplace with unclear technology adoption pathways gives little certainty about the future. Will it be a winner takes all market where only one autonomous system can exist? Alternatively, can regulations ensure an open and fair market where innovation, service, and cost-efficiency are the most important elements?

D. Incomplete regulations and standardization

Automated driving technology, also known as autonomous vehicles, self-driving car, robotic car, etc. Researchers have been arguing about terminology as well as standards. SAE defines automation levels from 1-5, while NHTSA defines automation levels from 0-4.

The California State Government encourages companies to test automated driving technologies in their state. In contrast, some Texas cities (such as Austin) have been conservative, not even allowing new types of mobility sharing businesses to operate within city limits. Some technology providers suggest using 5G signals to connect vehicles in traffic while others arguing that SDRC (short-range radio communication) is more cost-efficient.

Automated driving systems involve more complicated technologies, and integration on a system of systems level. Incomplete regulations and standardization confuses technology providers, technology adopters, and regulators. This causes issues for every role in the value chain.

6.2 Overview of automated driving technology

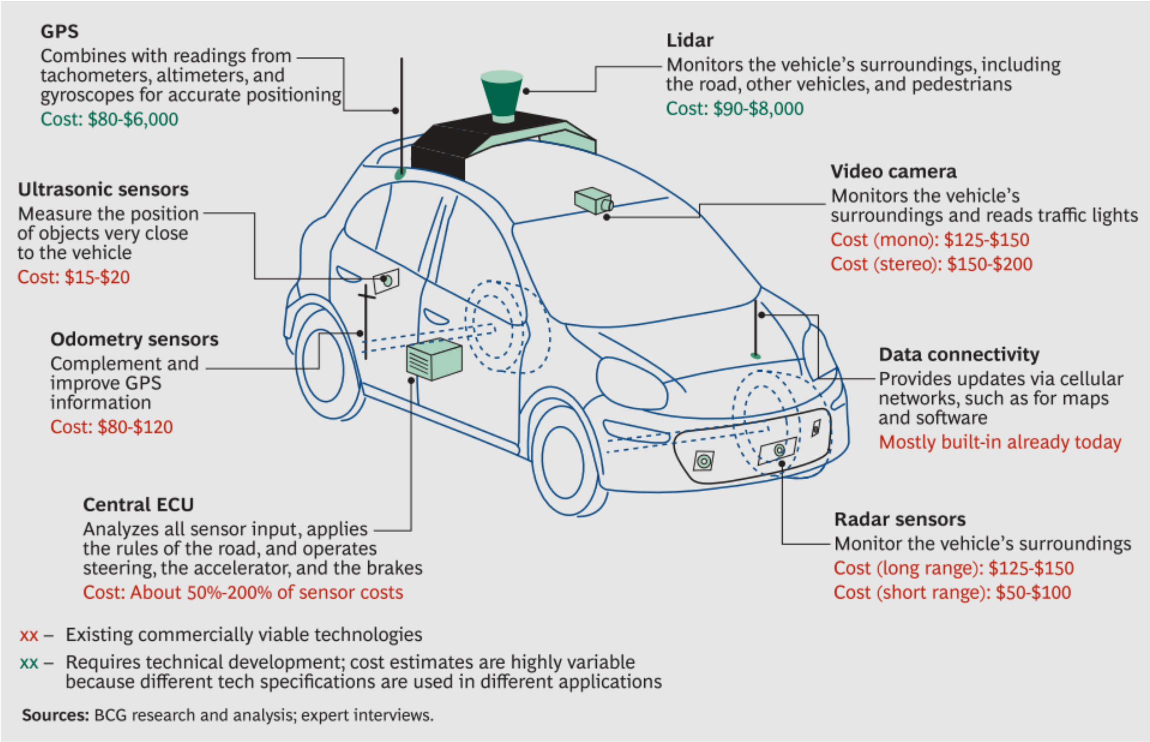
The author has demonstrated the concept and marketplace of automated driving technology in Sections X and Y, respectively. The author is going to introduce how automated driving system work from a technical perspective, both software and hardware in this section.

Table 52: Overview of hardware and software components of automated driving systems[69]

System	Definition
Hardware	Sensors: four major types of sensors – Lidar, Radar, Sonic, and Camera system
	On board computer or processing system for electronic control unit
Software	Sensor data preprocessing
	Localization and obstacle tracking
	Path planning
	Behavior learning and analyzing
	Control and operate

6.2.1 Hardware of an automated driving system

Automated driving technology has shown tremendous progress in the last X years. With Google leading the field there is little doubt that the technology will mature within the next 2 decades. The main concerns are hardware cost and selection. The figure below demonstrates the sensors on Google's autonomous vehicles, and the expected price range of each component. However, a number of consulting firms and IHS have predicted that the manufacturing cost of automated driving systems will drop significantly in the next 15 years. The cost of automated driving technology is still very high due to the cost of Lidar.



Sources: BCG research and analysis; expert interviews.

Figure 31: Automated driving system and the costs of components

The author will define four major types of sensors that are required in automated driving systems, and explain different technical approaches.

A. LIDAR

Lidar systems are currently large, expensive and must be mounted outside of vehicles. The system Google uses is in the range of 80kg and $70,000. LIDAR works well in all light conditions, but is susceptible to reduced performance or failure in snow, fog, rain or large amounts of dust particles in the air. The high concentration of airborne particles interfere with the LIDAR's use of light spectrum wavelengths.

B. Radar

Solid-state radar-on-a-chip systems are common, small, and inexpensive. They have good range, but poorer resolution than other sensors. They work equally well in light and dark conditions, and 77 GHz systems are able to better sense through fog, rain, and snow than Lidar system. Representative manufacturers include Delphi, Kypcera, Valeo, and Visteon.

C. Ultrasonic sensors

Ultrasonic sensors actively emit high-frequency noise imperceptible to humans. They have very poor range, but are excellent for very-near-range three-dimensional mapping, as sound waves are comparatively slow, so differences in distance in a centimeter or less are detectable. Ultrasonic systems work without light, but the limitation is the extremely short distance detection.

D. Camera system

Camera image recognition systems have become very small, cheap, and effective in recent years. They are more useful for distant assessments than they are for very close proximity assessments. Their color, contrast, and optical-character recognition capabilities give them a capability set entirely missing from all other sensors. Digital signal processing makes it possible to determine speed, but not at the level of accuracy of radar or LIDAR systems.

6.2.2 Examples of existing automated driving systems

Due to the cost efficiency of automated driving systems, different vendors have selected different sets of sensors to achieve automated driving. Google has equipped a prototype with all four types of sensors to ensure safety for Level 4 automation. Tesla offers Level 2 and Level 3 automation in all consumer models to prepare for mass adoption. Tesla avoided LIDAR to minimize costs, instead focusing on the other three types of sensors for its autonomous-functional vehicles. The table below shows how different manufacturers choose different technologies.

Table 53: Automated driving pilot systems in the marketplace

	LIDAR	Radar	Ultrasonic	Camera
Tesla	✖	✔	✔	✔
Google	✔	✔	✔	✔
Baidu	✔	✔	✔	✔
Ford	✔	✔	✔	✔

The author looked into the functionality of each type of sensor and compared outcomes of different combinations of sensors. Since there are no standards for how automated driving systems should perform yet, the author went through a list of consulting studies and picked the metrics she thinks are critical.

Table 54: The metrics to evaluate hardware system in automated driving technology

Code	Metric	Description	Evaluation
1	Range	Detection range	The farther the better.
2	Proximity Detection	Short range detection	The closer the better
3	Resolution	Measured in pixels per inch	The more the better

4	Detection Speed	The feedback speed	The faster the better
5	Sensor Size	Size and weight of the sensor	The smaller (less invisible) the better
6	Sensor Cost	The cost of the sensors	The less the better
7	Function in Bright Environments	The image or detection resolution of sensors in bright conditions	The higher resolution the better
8	Function in Low Light Environments	The image or detection resolution of sensors in dark conditions	The higher resolution the better
9	Function in Snow, Fog and Heavy Rain	The image or detection resolution of sensors in troubled conditions (snow, fog and heavy rain)	The higher resolution the better
10	Color/Contrast	The ability to detect black/white or colorful image	Color VS no color

Table 55: Comparison of four sensors

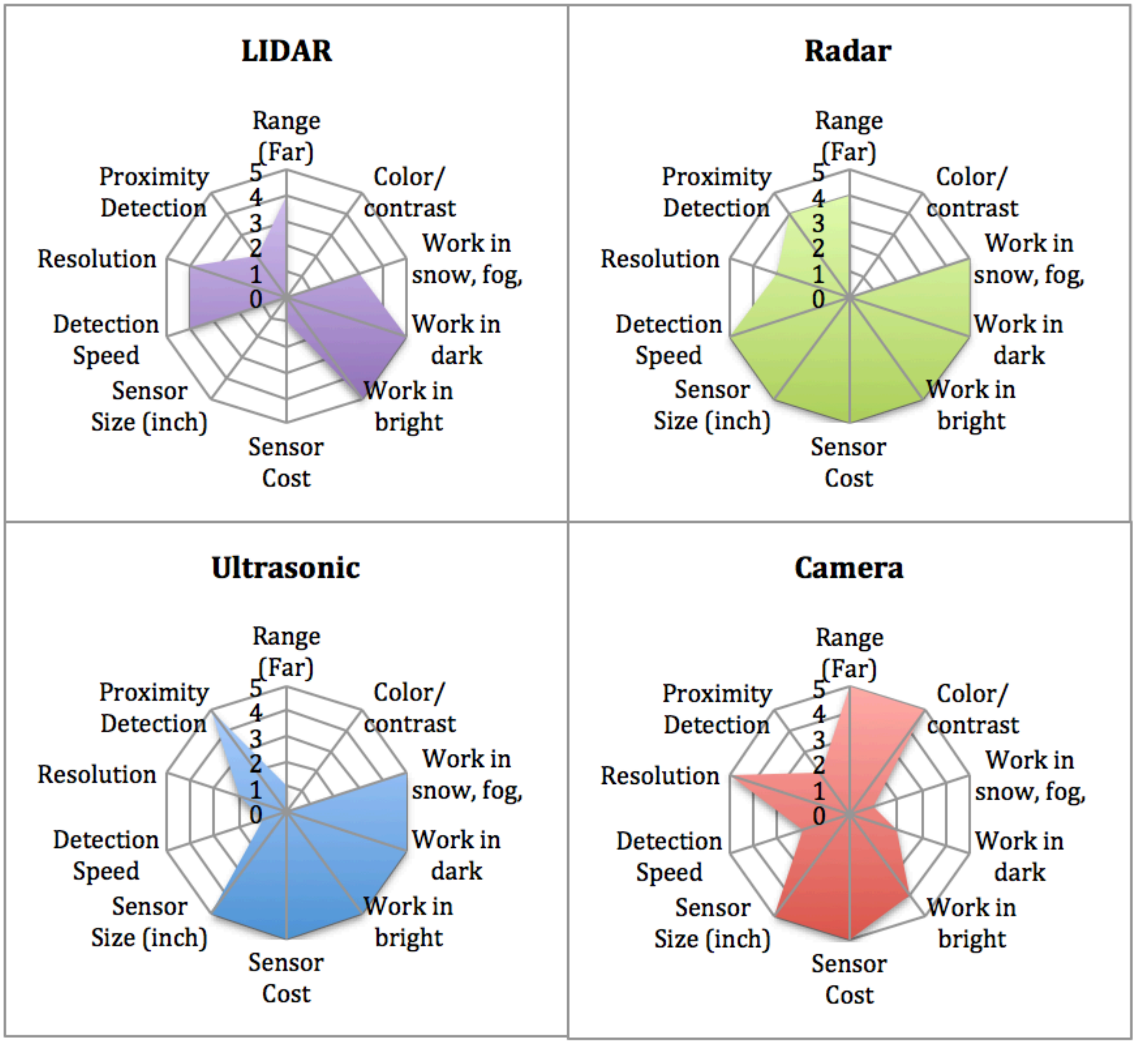
Comparison of four types of sensor

	LIDAR		Radar		Ultrasonic		Camera system	
	Desc.	Score	Desc.	Score	Desc.	Score	Desc.	Score
1	Up to 120	4	100-200	4	Good	5	Very close	1
2	>30	2	Fairly good	4	Less useful	2	Very effective	5
3	64 pixel at 10 hz	4	Good	3	3,000 pixel	5	Acceptable	2
4	Effective (100MBPS)	4	Very effective	5	Long	2	Slow	1

5	7*8*10.3 (80KG)	0	Very small	5	Very small	5	Very small	5
6	$80,000	1	<$200	5	<$200	5	$15-$20	5
7	Y	5	Y	5	Y	4	Y	5
8	Y	5	Y	5	Troubled	2	Y	5
9	Decreased performance	3	Y	5	Good	1	Y	5
10	N	0	N	0	Y	5	N	0

Table 56: The metrics to evaluate sensors

	Metrics					
	5	4	3	2	1	0
1	>200	100 - 200	-	-	<5	-
2	Very close	Fairly good (5-15 m)	Good (15-30 m)	>30 m	-	-
3	Thousand pixels	<100 pixel	Good	Acceptable	-	-
4	Very effective	Effective	Good	Long time	Slow	-
5	Small	-	-	-	Huge	-
6	<$200	-	-	-	>$50,000	-
7	Very well	Conditionally well	Significantly decreased performance	Troubled	Poor	-
8	Very well	Conditionally well	Significantly decreased performance	Troubled	Poor	-
9	Very well	Conditionally well	Significantly decreased performance	Troubled	Poor	-
10	Y	-	-	-	Y	No


LIDAR

Radar

Ultrasonic

Camera

Figure 32: Spider chart comparisons of four types of sensors

6.2.3 Comparison of Google and Tesla’s approaches

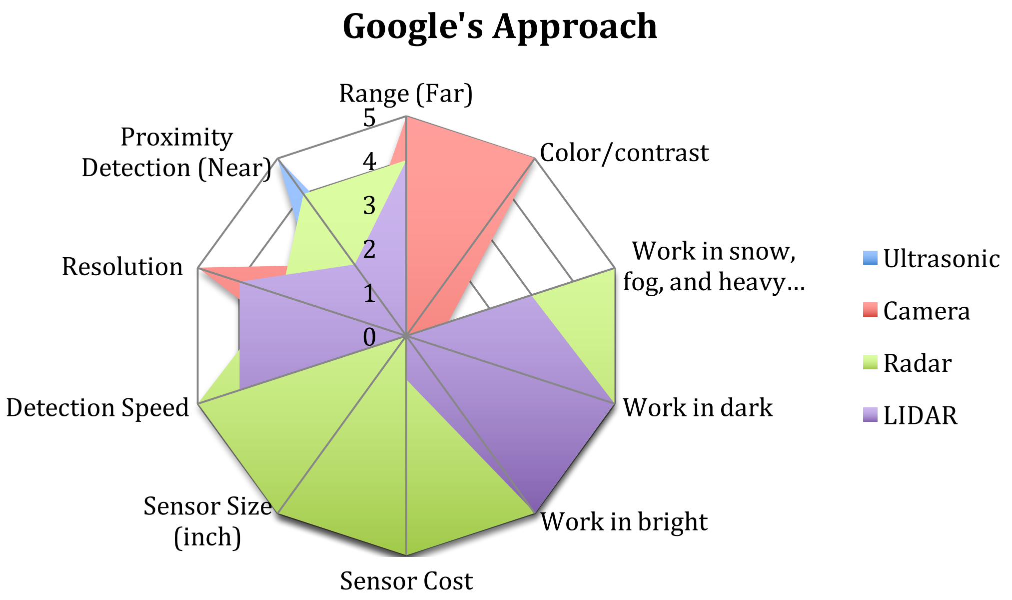


Figure 33: Google's automated driving system evaluation

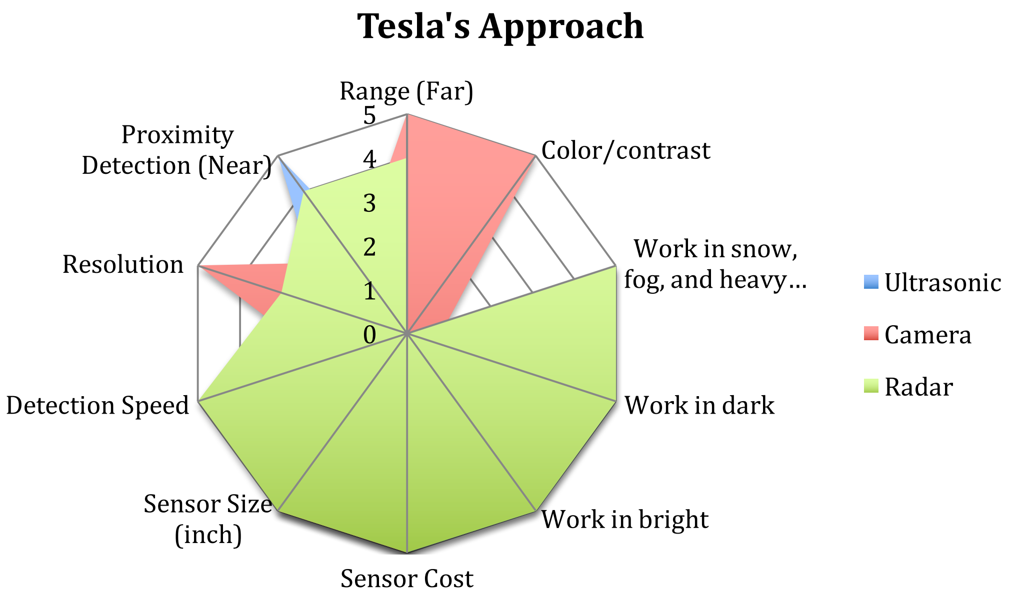


Figure 34:Tesla's autopilot system

Different R&D institutions invented different sets of automated driving systems. The author has reviewed the functionalities of all four types of sensors in the previous section. “Is LIDAR necessary?” People always ask such question. Tesla’s autopilot is the only commercially offered Level 3 automation system without

LIDAR due to the cost and technology maturity. A slight delay on detection time has been observed from Figure 34 when compare Tesla's system to Google's automated driving system.

6.2.4 Software systems of automated driving technologies

If the hardware is the body of an automated driving technology, the software is the brain of the automated driving system. Different sources divide software into various control areas.

One approach separates tasks undertaken by the software in six areas:

- Sensor data preprocessing
- Localization
- Obstacle tracking
- Path planning
- Behaviors
- Control

Three major tasks for software system are predicting, planning, and controlling.

6. 3 Define variables for automated driving scenarios

The author is going to compare two scenarios in this chapter: an Individually Owned AV Scenario and a Shared EV AV Scenario. The impact of automated driving technology adoption on traffic efficiency is very complicated to measure due to different traffic simulation model selection. Two variables need to be evaluated carefully in these scenarios: total vehicle miles traveled and increased lane capacity by efficient connected driving.

6.3.1 Total vehicle miles traveled

A number of complex factors will cause changes to travel behavior patterns, resulting in either increases or decreases in total vehicle-miles traveled (VMT). In order to understand the uncertain nature of these elements, the following perspectives need to be addressed.

A. Driver experience

If the adoption of autonomous vehicles significantly enhances the driving experience, people may travel more than they currently do. If the adoption at a certain penetration rate cannot significantly relieve traffic congestion, the external congestion cost might not be mitigated.

Non-traditional (junior, senior, and disabled people) drivers that are not capable of driving before the adoption of automated driving system may also increase total VMT due to the availability of traveling,

B. The availability of current mass-transit options in urban areas

Different urban areas have varying philosophies on mass-transit systems. Asian megacities have well-established mass transit systems due to their high population densities. The mass-transit system in Beijing connects light rail system, underground system, and bus lines. The mass-transit service is provided at an affordable rate for passengers, with lower rates for senior and junior citizens. The introduction of automated driving systems within a connected network may increase the total VMT of passenger size vehicles in these kind of cities.

However, compared to the rest of the world, the majority of the megacities in the United States do not have efficient mass-transit systems. This is due to the American travel behavior. The impact of autonomous vehicles on total VMT in urban areas is uncertain.

C. Cost of vehicle ownership or cost of mobility per VMT

The cost of travel influences the user's decision-making process. The manufacturing cost of automated driving vehicles influences the adoption of automated driving technologies. The shared mobility business model influences the cost per mile traveled under different mobility plans. All changing factors lead to either an increase of decrease of total VMT.

The author has reviewed a series literatures, the summarized results are listed in Table 26. Increased VMT at different rates in urban travel is expected. Tables 26and 27 present the range of changes in VMT dependent on regional variations[70]. This study will adopt the values for "Mixed freeway lanes and ramps", highlighted in red below.

Table 57: Increased VMT by automated driving in urban areas without mass-transit systems

Increase in VMT per capita in auto-dependent regions				
Permitted usage locations	Penetration Rate			
	25%	50%	75%	100%
Exclusive freeway lanes	+10%	+20%	+30%	+35%
Mixed freeway lanes and	+5%	+10%	+20%	+30%

ramps				
Auto-dominated arterials	-	+5%	+10%	+20%
All multi-model streets	-	-	+5%	+10%
Without a legal driver aboard	-	-	+35%	+35%

Table 58: Increased VMT by automated driving in urban areas with mass-transit systems

Increase in VMT per capita in multi-model regions				
Locations where use Permitted	Penetration Rate			
	25%	50%	75%	100%
Exclusive freeway lanes	+5%	+10%	+15%	+20%
Mixed freeway lanes and ramps	+0%	+5%	+10%	+15%
Auto-dominated arterials	-	+0%	+5%	+10%
All multi-model streets	-	-	+0%	+5%
Without a legal driver aboard	-	-	+25%	+35%

6.3.2 Automated driving systems' impact on traffic capacity and efficiency

Automated driving systems change the interactions between vehicles in traffic and road infrastructure. Traditionally, freeway capacity and traffic efficiency are measured according to the following criteria:

- Freeway capacity is measured by hourly traffic volume, delay, travel time, and travel time variability
- The fleet mix in traffic, the PCE (passenger car equivalent), is calculated based on vehicle sales data

- Operating parameters and duration in congestion
- Different types automation
    - Cooperative automation – connected vehicles with automated driving technology, also known as an cooperative adaptive cruise control
    - Adaptive cruise control – vehicles with level 2~3 but not connected to other vehicles or infrastructure within the network

Based on the literature review in Chapter X there are significant differences with different fleet mix ratios. Arem, Driel and Visser found that the penetration rate of autonomous vehicles needs to exceed 40% before significant impacts are noticed [71]. Jones and Philips reviewed simulations and conclude that positive impacts on flow stability and capacity are achieved only when fleet penetration rate of vehicles with Cooperative Adaptive Cruise Control (CACC) exceeds 40% [72]. Davis found that 50% penetration rate is effective [73]. Tientrakool finds that capacity improves little until the CACC penetration rate exceeds 85% [74]. Shladover finds that capacity improves linearly from 2,000 to 2,300 vphpl at 50% CACC, but the increase non-linearly and reaches nearly 4,000 vphpl at 100% CACC [75].

Table 59: Different lane capacities at different penetration rates

CACC penetration rate	Lane capacity [Vphpl]
25%	2,000
50%	2,300
75%	3,000
100%	4,000

6.3.3 Scenario design

The author is going to analyze and compare two automated driving scenarios in Chapter 6: Automated driving with Individually Owned Autonomous ICE Vehicles (Scenario A), and Shared Autonomous Electric Vehicles (Scenario B).

A. Individually owned automated driving scenario

In Scenario A, automated driving technology will be adopted at different penetration rates. The technology adoption at different penetration influences the total VMT in urban areas, and the lane capacity per mile. Details are listed in the table below.

Table 60: VMT by CACC and ICE vehicles

Penetration rate of CACC	VMT by CACC and ICE vehicles under increased lane capacity		
	VMT_{CACC}	VMT_{ICE}	Lane Capacity
0%	VMT*0%	VMT*100%	2,000
25%	VMT*(1+5%)*25%	VMT*75%	2,000
50%	VMT*(1+10%)*50%	VMT*50%	2,300
75%	VMT*(1+20%)*75%	VMT*25%	3,000
100%	VMT*(1+30%)	VMT*0%	4,000

B. Individual owned electric and automated driving system scenario

Scenario B will demonstrate mobility services offered by individually owned electric and autonomous vehicles. Electric vehicle technology emits no tailpipe pollution, and the automated driving technology has significant impacts on traffic efficiency and total vehicle-miles traveled in urban areas.

6.4 Externality calculations for automated driving Scenario A

6.4.1 Overview

Detailed calculations and data analysis will be illustrated in this section. The author will analyze Scenario A – Individually owned automated driving vehicles, and Scenario B – Individually owned electric and automated driving vehicles. In each scenario, the author is going to define new independent variables, and redefine any changed dependent variables.

6.4.2 External traffic congestion cost for Scenario A

Congestion externality is a per-time cost function. The major variables are the unit cost of passengers' time lost in traffic congestion, and total vehicle miles traveled in urban area.

Cost function formula:

$$Congestion\ Externality = Unit\ cost\ per\ mile \cdot VMT$$

Equation 16: Congestion cost in automated driving scenario

A. *Unit cost per vehicle mile traveled in Scenario A*

$$CC = tf \cdot \alpha \cdot \left[\left(\frac{Vol + PCE}{Cap}\right)^{\beta} - \left(\frac{Vol}{Cap}\right)^{\beta}\right] \cdot Vol \cdot VOTT \cdot p$$

Equation 17: Unit congestion cost in automated driving scenario

Table 61: Define variables and constants in unit congestion cost

Factors	Definition
t_f	Travel time at free flow conditions. The average congested roadway was assumed to have a free-flow speed of 40 mph,

	corresponding to 1.5 minutes of travel time per mile traveled at free flow conditions.
α, β	BPR-required parameters; 0.84 and 5.5 (fixed value)
Vol	Road capacity is assumed to be 2000 vehicles per hour per lane (vphpl) and demand is assumed to be right at 95% of total available capacity in the baseline scenario. The capacity changes with penetration rate of autonomous vehicles as shown in Table 29.
PCE	PCE measures Passenger Car Equivalence. It is calculated based on sales volume of different vehicles in urban areas. PCE is considered constant at 1.104 for these scenarios.
Cap	Road capacity - Road capacity is assumed to be 2000 vehicles per hour per lane (vphpl)
VOTT	VOTT is a constant measurement of the Value of the Traveler's Time. The Victoria Transport Policy Institute estimates that the value of travel time for personal purposes is about 30% of household hourly income. In 2006, the U.S. household hourly income was 16.83 dollars. After accounting for inflation, the VOTT is 6.04 dollars in 2013.
p	Congested conditions - The travel condition p is calculated from the travel time index found in Texas A&M's Urban Report 2013. In both baseline scenario and this scenario, p value is 0.1736.

Table 62: The comparison of factors in unit congestion cost between baseline scenario and automated driving scenario

Variables	Baseline scenario	Automated driving scenario
t_f	Travel time at free-flow conditions per mile traveled	Remain the same

α, β	BPR-required parameters; 0.84 and 5.5 (fixed value)	Remain the same
Vol	Road capacity per hour per lane * travel demand	Road capacity changes based on the penetration rate of CACC system
PCE	Passenger car equivalent	Remain the same
Cap	Road capacity	Road capacity changes based on the penetration rate of CACC system
VOTT	Value of travel time	Remain the same
p	Congested conditions	Remain the same

$$CC = tf * \alpha * \left[\left(\frac{Vol + 1.104}{Cap} \right)^{\beta} - \left(\frac{Vol}{Cap} \right)^{\beta} \right] * Vol * 6.04 * 0.1736$$

Equation 18: Revised unit cost model based on traffic data in 2013

Table 63: Integrated unit congestion cost at different penetration rates

Penetration Rate of AV	Integrated unit cost model at different penetration rates
0%	$CC = tf * \alpha * \left[\left(\frac{1900 + 1.104}{2000} \right)^{\beta} - \left(\frac{1900}{2000} \right)^{\beta} \right] * 1900 * 6.04 * 0.1736$
25%	$CC = tf * \alpha * \left[\left(\frac{1900 + 1.104}{2000} \right)^{\beta} - \left(\frac{1900}{2000} \right)^{\beta} \right] * 1900 * 6.04 * 0.1736$
50%	$CC = tf * \alpha * \left[\left(\frac{1900 + 1.104}{2300} \right)^{\beta} - \left(\frac{1900}{2300} \right)^{\beta} \right] * 1900 * 6.04 * 0.1736$
75%	$CC = tf * \alpha * \left[\left(\frac{1900 + 1.104}{3000} \right)^{\beta} - \left(\frac{1900}{3000} \right)^{\beta} \right] * 1900 * 6.04 * 0.1736$
100%	$CC = tf * \alpha * \left[\left(\frac{1900 + 1.104}{4000} \right)^{\beta} - \left(\frac{1900}{4000} \right)^{\beta} \right] * 1900 * 6.04 * 0.1736$

B. New VMT under different technology adoption rates

Table 64: VMT by CACC and ICE vehicles

Penetration Rate	Original VMT [Billion miles]	Increased percentage of total VMT	New VMT [Billion miles]
0%	1,845	0%	1,845
25%	1,845	5%	1,937
50%	1,845	10%	2,029
75%	1,845	20%	2,214
100%	1,8458	30%	2,398

C. *Modeled results for automated driving with ICE scenario*

Table 65: Modeled congestion externality in automated sharing with ICE scenario

Penetration Rate	Unit Cost [Dollars]	VMT new [Billion miles]	Total cost [Billion dollars]
0%	0.1006	1,845	185.59
25%	0.1006	1,937	194.87
50%	0.0466	2,029	94.65
75%	0.0108	2,213	23.95
100%	0.0022	2,398	5.28

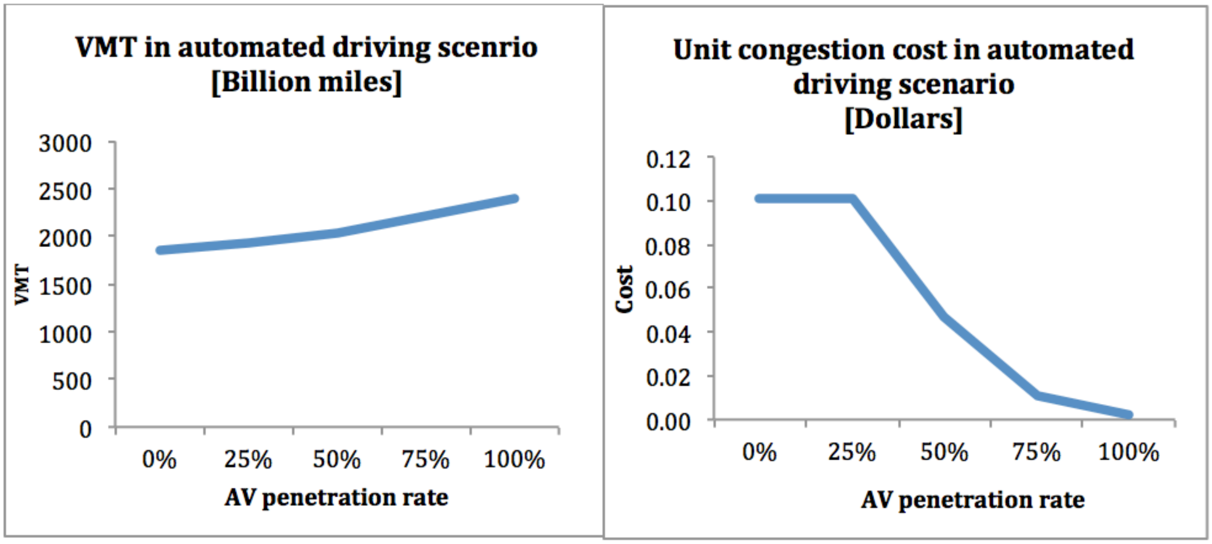


Figure 35: Unit congestion cost and VMT in automated driving scenario

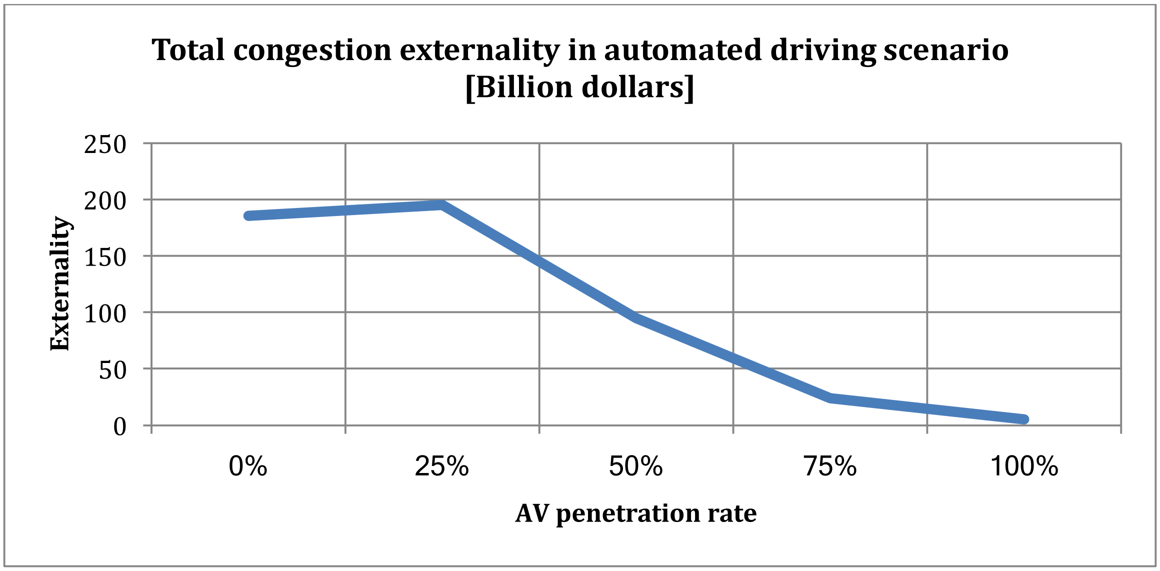


Figure 36: Total congestion externality in automated driving scenario

6.4.3 External cost of human health impacts

A. *Introduction of human health impacts*

Transportation emits significant amounts of air pollution. Road transportation is responsible for emission of nitrogen oxides, sulphur dioxide, volatile organic compounds, carbon monoxide, lead and particulate matter with a diameter of less than 10 µm. Air pollution from transportation affects human health in a variety of ways.

The author defines the cost function for air pollution related human health impacts as:

$$Human\ Health\ Externality = Unit\ cost\ of\ pollutants \cdot VMT$$

Equation 19: Human health externality in automated driving scenario

B. *Redefined variables – Unit cost and new vehicle miles traveled*

Table 66: Unit pollutant cost in automated driving scenario

Emission	Ambient Pollutants	Cost in 2013 inflation rate [Dollars/kg]	
		Low	High
$PM_{2.5}$	$PM_{2.5}$	25.33	385.46
$PM_{2.5-10}$	$PM_{2.5-10}$	15.55	40.86
NO_x	Total	2.72	39.92
VOC	Organic PM_{10}	0.22	2.48
CO	CO	0.02	0.17

Penetration Rate	Original VMT [Billion miles]	Increased percentage of total VMT	New VMT [Billion miles]
0%	1,845	0%	1,845
25%	1,845	5%	1,937
50%	1,845	10%	2,029
75%	1,845	20%	2,214
100%	1,8458	30%	2,398

C. Modeled human health externality results for automated driving scenario

Table 67: Total human health externality in automated driving with ICE scenario

Penetration Rate	Unit Cost [Dollars]	VMT new [Billion miles]	Total cost [Billion dollars]
0%	0.01990	1,845	36.70
25%	0.01990	1,937	38.54
50%	0.01990	2,029	40.37
75%	0.01990	2,213	44.05
100%	0.01990	2,398	47.72

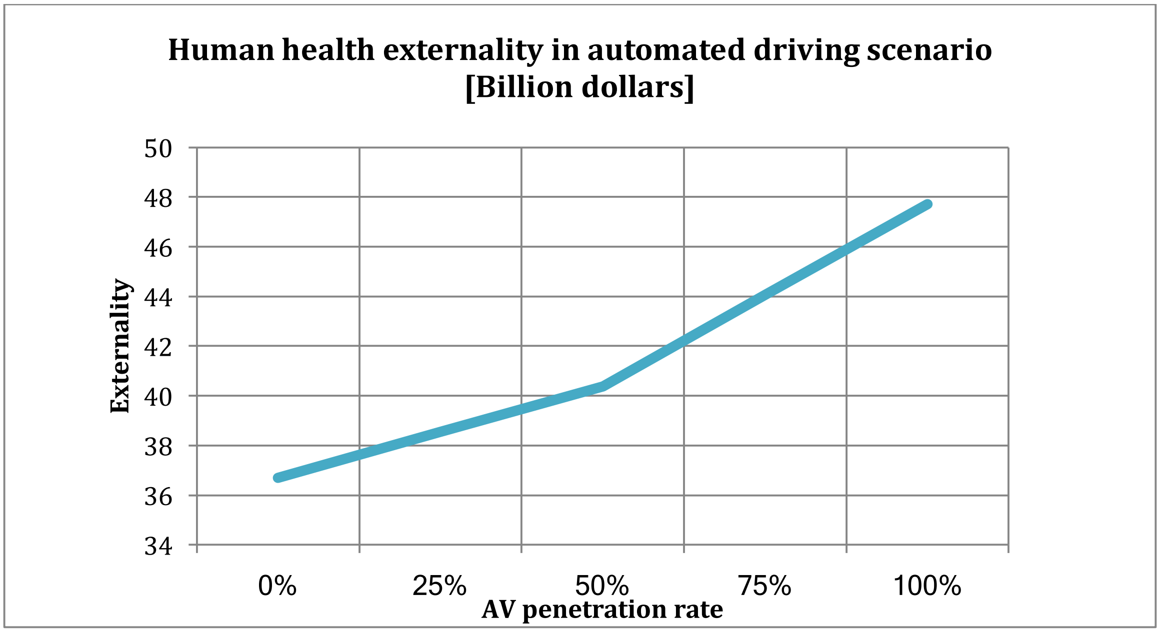


Figure 37: Human health externality in automated driving scenario at different penetration rates

6.4.4 External costs of climate change

A. General introduction

All transportation modes emit pollutants that affect global climate. These climate-changing pollutants are called greenhouse gases (GHG). Carbon dioxide (CO_2) is the most damaging greenhouse gas. Light-duty vehicles account for one fifth of domestic US CO_2 emissions.

The climate change costs of transportation can be estimated as the product of two factors: CO_2-equivalent emissions of GHGs (as a product of VMT), and the damage cost of a unit CO_2 emission.

The author describes the cost function as follows:

$$Climate\ change\ externality = Unit\ cost\ of\ CO_2 * VMT_{new}$$

Equation 20: Climate change externality in automated driving with ICE scenario

B. Unit cost and VMT

a. Unit cost

Table 68: Unit GHG cost in automated driving with ICE scenario

LDV [Dollars per VMT]	In 2013 dollar [Dollars per metric ton]	Unit Emission [Kg per VMT]	PCE	Unit Cost in 2013 [Dollars per VMT]
5%	11	0.368	1.104	0.00455
3%	36	0.368	1.104	0.01489
2.5%	56	0.368	1.104	0.02315

b. VMT

Table 69: VMT in automated driving with ICE scenario

Penetration Rate	Original VMT [Billion miles]	Increased percentage of total VMT	New VMT [Billion miles]
0%	1,845	0%	1,845
25%	1,845	5%	1,937
50%	1,845	10%	2,029
75%	1,845	20%	2,214
100%	1,8458	30%	2,398

C. Modeled results of climate change externality in automated driving scenario

Table 70: Modeled results of climate change cost in automated driving with ICE scenario

Penetration Rate	Unit Cost [Dollars]	VMT new [Billion miles]	Total cost [Billion dollars]
0%	0.01489	1,845	30.32
25%	0.01489	1,937	31.83
50%	0.01489	2,029	33.34
75%	0.01489	2,213	36.38
100%	0.01489	2,398	39.41

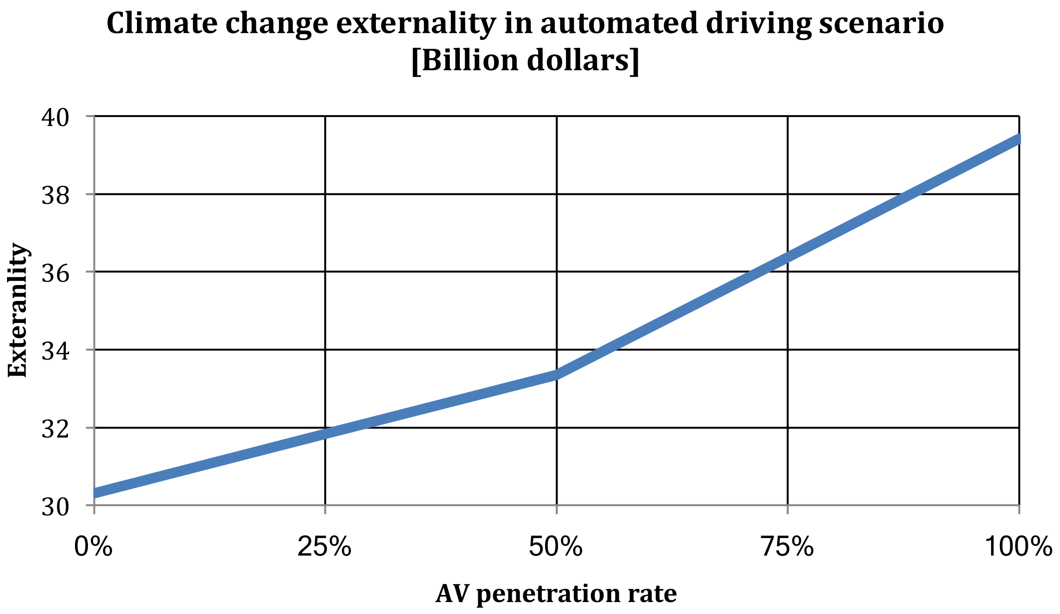


Figure 38: Climate change externality in automated driving scenario at different penetration rates

6.5 Transportation externalities for Scenario B

6.5.1 Scenario overview

Scenario B concerns individually owned autonomous electric vehicles. It is a sub-scenario in this chapter. The only difference between Scenario A and Scenario B is the energy source for passenger vehicles in urban traffic.

The increasing sale of electric vehicles indicates the alternative fuel adoption trend in the automotive industry. In Chapter X, the author proved that the adoption of electric vehicles will reduce external human health costs and external climate costs resulting from urban transportation. The new variable in Scenario B is the penetration rate of electric vehicles in this research.

As discussed in Chapter 4, the adoptions of electric vehicles at different penetration rates do not affect the external cost of traffic congestion. Therefore, the author will only illustrate the reduced external cost in human health impact and climate changing categories.

6.5.2 External cost of human heath impact for automated driving Scenario B

A. *Cost function*

HHE= $UnitcostofEV'sPollutants * VMT_{ev} + UnitcostofICE'sPollutants * VMT_{ice}$

Equation 21: Human health externality in automated driving scenario with EVs

B. *Unit costs of EV and ICE's pollutants*

Table 71: Unit pollutant cost in automated driving scenario with EVs

Unit pollutant cost [Dollars per VMT]	
ICE	EV
0.01990	0

C. *New VMT in Scenario B*

Table 72: Total VMT in automated driving with EV scenario

Penetration Rate	Original VMT [Billion miles]	Increased percentage of total VMT	New VMT [Billion miles]
0%	1,845	0%	1,845
25%	1,845	5%	1,937
50%	1,845	10%	2,029
75%	1,845	20%	2,214

100%	1,845	30%	2,398

D. Calculation results

a. 0% EV adoption

Table 73: Modeled HHC at 0% EV penetration rate in automated driving scenario

CACC penetration rate	Total VMT [Billion miles]	0% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
0%	1,845	1,845	0	36.70
25%	1,937	1,937	0	38.54
50%	2,029	2,029	0	40.37
75%	2,214	2,214	0	44.05
100%	2,398	2,398	0	47.72

b. 25% EV adoption

Table 74: Modeled HHC at 25% EV penetration rate in automated driving scenario

CACC penetration rate	Total VMT [Billion miles]	25% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
0%	1,845	1,383	0.461	27.53
25%	1,937	1,453	0.485	28.90
50%	2,029	1,522	0.507	30.28
75%	2,214	1,660	0.533	33.03
100%	2,398	1,799	0.600	35.79

c. 50% EV adoption

Table 75: Modeled HHC at 50% EV penetration rate in automated driving scenario

CACC penetration rate	Total VMT [Billion miles]	50% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
0%	1,845	0.922	0.922	18.35

25%	1,937	0.969	0.969	19.27
50%	2,029	1.015	1.015	20.19
75%	2,214	1.107	1.107	22.02
100%	2,398	1.200	1.200	23.86

d. 75% EV adoption

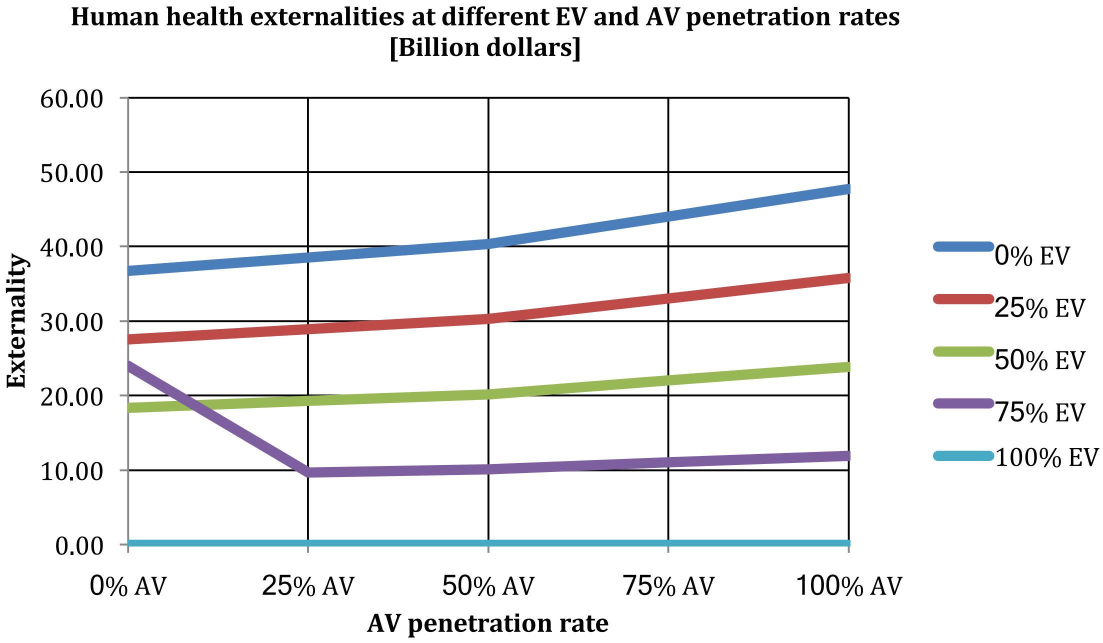
Table 76: Modeled HHC at 75% EV penetration rate in automated driving scenario

CACC penetration rate	Total VMT [Billion miles]	75% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
0%	1,845	0.461	1,383	9.18
25%	1,937	0.485	1,453	9.63
50%	2,029	0.507	1,522	10.09
75%	2,214	0.533	1,660	11.01
100%	2,398	0.600	1,799	11.93

e. 100% EV adoption

Table 77: Modeled HHC at 100% EV penetration rate in automated driving scenario

CACC penetration rate	Total VMT [Billion miles]	75% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
0%	1,845	0	1,845	0
25%	1,937	0	1,937	0
50%	2,029	0	2,029	0
75%	2,214	0	2,214	0
100%	2,398	0	2,398	0



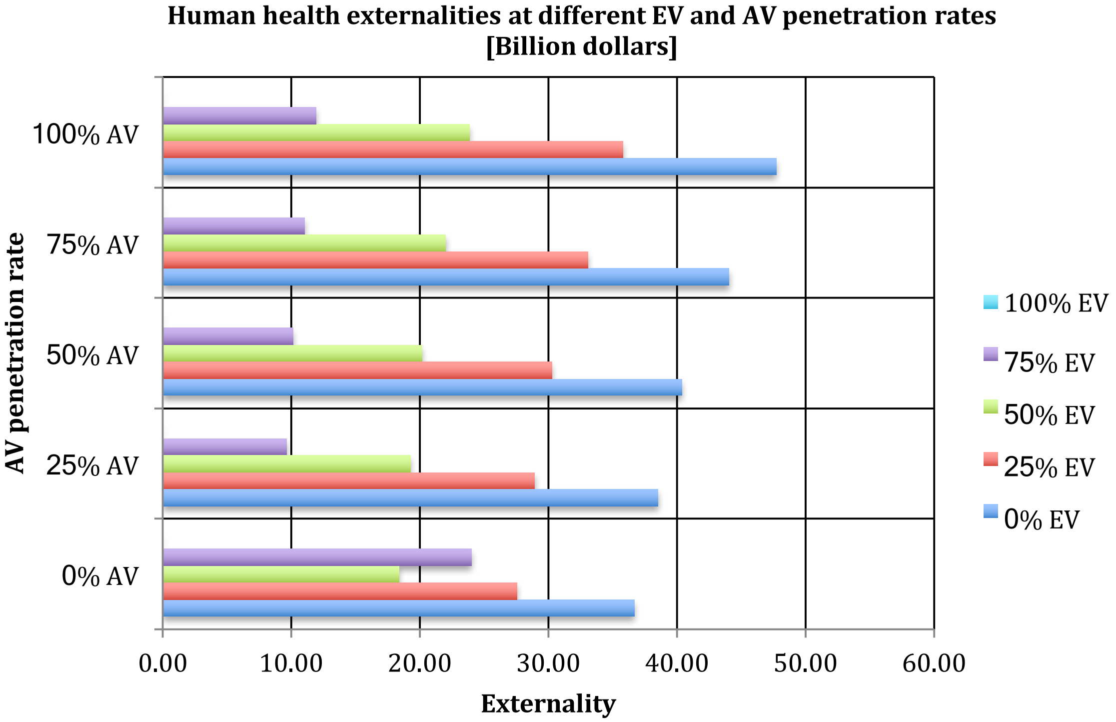


Figure 39: Two illustrations of human health externalities in AV and EV adoption scenario

6.5.3 External cost of climate change in automated driving Scenario B

A. Cost function

$$\text{CCE}= Unit\ cost\ of\ GHGev \cdot VMT_{ev} + Unit\ cost\ of\ GHG_{ice} * VMT_{ice}$$

Equation 22: Climate change externality in automated driving with EV scenario

B. Unit cost of EV's and ICE's GHG

Table 78: Unit costs of EV's and ICE's GHG in automated driving scenario

CACC penetration rate	Unit Pollutant Cost [Dollars per VMT]	
	ICE	EV
Any penetration rates	0.01489	0

C. Calculated results

a. 0% EV adoption

Table 79: Modeled CCE at 0% EV penetration rate in automated driving scenario

CACC penetration rate	Total VMT [Billion miles]	0% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
0%	1,845	1,845	0	27.46
25%	1,937	1,937	0	28.83
50%	2,029	2,029	0	30.21
75%	2,214	2,214	0	32.95
100%	2,398	2,398	0	35.70

b. 25% EV adoption

Table 80: Modeled CCE at 25% EV penetration rate in automated driving scenario

CACC penetration rate	Total VMT [Billion miles]	25% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
0%	1,845	1,383	0.461	20.60
25%	1,937	1,453	0.485	21.63
50%	2,029	1,522	0.507	22.66
75%	2,214	1,660	0.533	24.71
100%	2,398	1,799	0.600	26.77

c. 50% EV adoption

Table 81: Modeled CCE at 50% EV penetration rate in automated driving scenario

CACC penetration rate	Total VMT [Billion miles]	50% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
0%	1,845	0.922	0.922	13.73
25%	1,937	0.969	0.969	14.42
50%	2,029	1.015	1.015	15.10
75%	2,214	1.107	1.107	16.48
100%	2,398	1.200	1.200	17.85

d. 75% EV adoption

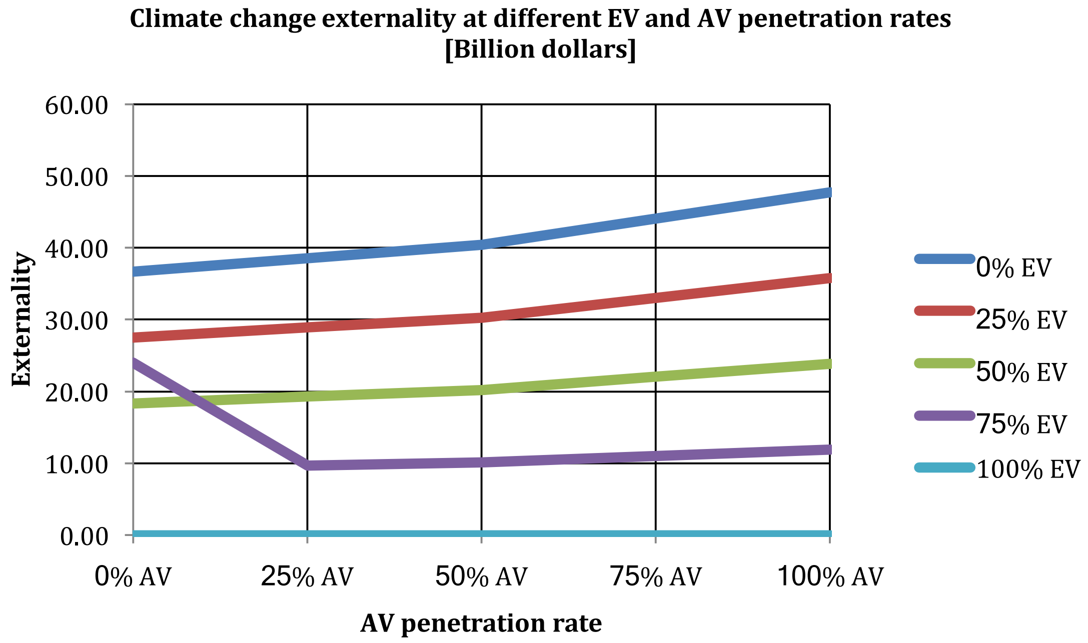
Table 82: Modeled CCE at 75% EV penetration rate in automated driving scenario

CACC penetration rate	Total VMT [Billion miles]	75% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
0%	1,845	0.461	1,383	6.87
25%	1,937	0.485	1,453	7.20
50%	2,029	0.507	1,522	7.55
75%	2,214	0.533	1,660	8.34
100%	2,398	0.600	1,799	8.92

e. 100% EV adoption

Table 83: Modeled CCE at 100% EV penetration rate in automated driving scenario

CACC penetration rate	Total VMT [Billion miles]	75% EV penetration rate		Total cost [Billion dollars]
		ICE VMT	EV VMT	
0%	1,845	0	1,845	0
25%	1,937	0	1,937	0
50%	2,029	0	2,029	0
75%	2,214	0	2,214	0
100%	2,398	0	2,398	0



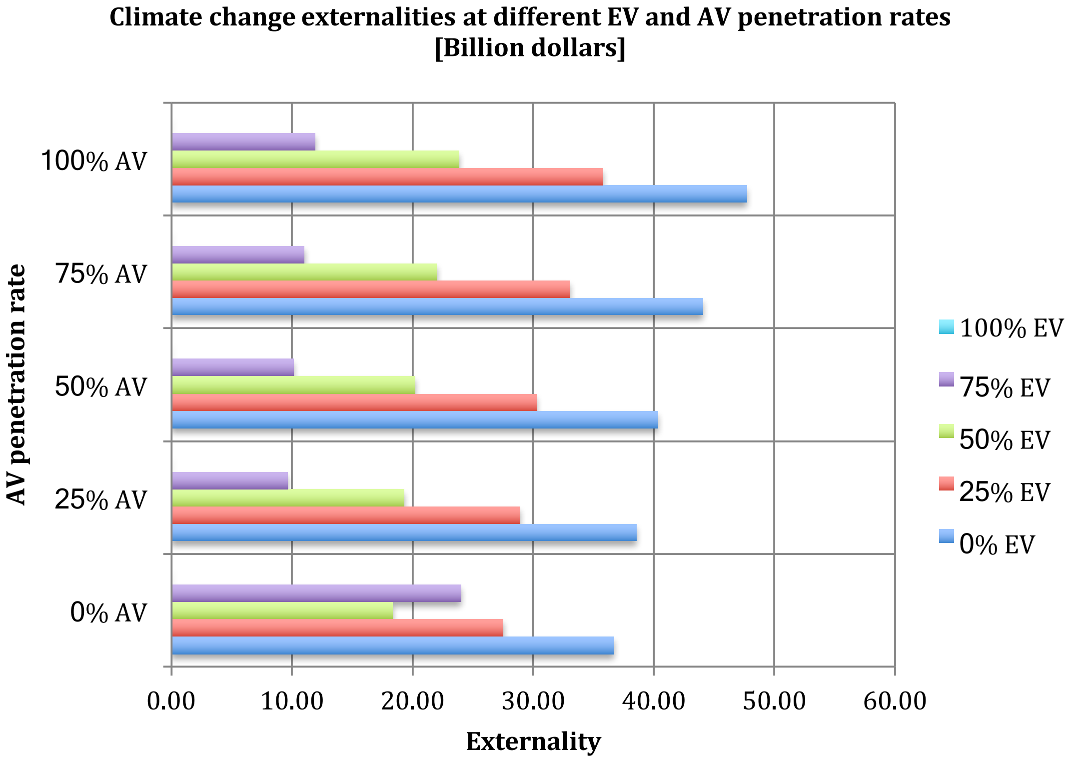


Figure 40: Two illustrations of climate change externalities at different EV and AV penetration rates

6.6 Summary

The integration of automated-driving at 25% penetration rate increases the total external cost. When the adoption of automated-driving system in traffic reaches and exceeds 40%, the total external cost drops down significantly. The abnormal cost increase at 25% penetration rate is caused by the total increased VMT and maintained unit cost in all categories.

The integration of automated-driving technology causes increased total VMT, and improved traffic efficiency (only when the penetration rate exceeds 40%). The integration at any penetration rates introduces more external cost (linear) in human health and climate change when compare to baseline scenario.

The adoption of automated-driving technology impacts on traffic congestion positively only when the penetration rate exceeds 40%. The related congestion externality starts to decrease at 40% penetration rate and can be eliminated at 100%.

The adoption of automated-driving technology is more complicated than the other two technology integrations. When the adoption rate is below 40%, the total external cost increases in all categories, which indicates less efficient urban transport system. The author suggests combining the adoption of automated-driving with other technologies during the transition when the adoption rate is low.

CHAPTER SEVEN

7. EXTERNALITIES IN VISIONARY SCENARIO: DO IT ALL

7.1 Introduction - what will the visionary stage really look like?

Chapter 7 is the chapter to illustrate the visionary stage, where mobility services will be offered through shared, autonomous electric vehicles within a well-connected mobility system. Consulting agencies and venture capital firms have predicted the trend – adopting disruptive technologies to convenient urban life, meet regulations and eliminate externalities. Traditional original equipment manufacturers had started rolling out plans to catch up with the trend. However, up until now all parties have failed to ask a fundamental question. What changes will the technical adoption pathways bring to the society as a whole?

- Will it escalate climate change while increasing convenience during peoples' day-to-day commute?
- Will it relieve traffic congestion in urban areas if 50% of travelers want to maintain traditional commuting habits?
- Which one should come first, regulation or technology adoption related user behavioral change? What difference, if any, does it make?

Scholars frequently worked on externality models in the transportation field during the 1990s due to break-through ICE technologies and the rapid increase of VMT in urban areas. Researchers use externalities as indicators of economical losses caused by transportation activities. The author adopted damage-cost functions, and revised the models to calculate the changes in externalities when adopting different technologies. In other words, the author uses the gain or loss in externalities when adopting different sets of technologies as indicators for users, technical inventors and regulation makers. A gain in externality indicates an increased economic cost on congestion cost, human health cost and climate change cost. A loss in externality indicates a decreased economic cost on total transport externality, which means the release in traffic congestion, human health impact and climate change impact.

7.2 Marketplace of electric, shared and automated vehicles

To many business-people and investors, the adoption of electric and automated driving technologies is just around the corner. However, how the marketplace will resolve remains uncertain. To engineers, the major issues are technological ones – how to make cars drive themselves among other human drivers in traffic and still reach certain efficiency. The challenge for regulators is whether to encourage or discourage adoption of certain technologies. Plenty of studies focus on the P2S Transition from technical perspectives, business perspectives, or regulatory perspectives. However, rarely is the question asked – what does each adoption pathway mean to society as a whole? Will it actually solve urban traffic related consequences? To what extent?

7.2.1 The development and adoption trend of electric vehicles

- 1889 – First electric vehicle was introduced in the United States.
- 1901 – First hybrid electric car – Lohner Porsche Mixte was introduced worldwide.

- 1920 – Research activity and sales started to decline due to the discovery of cheap crude oil in Texas.
- 1973 – Different automakers started exploring electric vehicles as alternative fuel options again. GM developed a prototype for an urban electric car.
- 1974 – Sebring-Vanguard's CitiCar produced more than 2,000 electric vehicles and ranked the sixth largest U.S. automaker by 1975.
- 1979 – The trend faded again due to the performance and shorter range when compared to gasoline-powered vehicles.
- 1990 – New federal and state regulations created a renewed interest in electric vehicles. The interest-encouraged automakers modify popular vehicle models into electric vehicles.
- 1996 – GM released the EV1, a fully electric vehicle.
- 1997 – Toyota introduced the first mass-produced hybrid vehicle – Prius. The Prius was released into international markets in 2000.
- 2006 – Tesla motors, a Silicon Valley startup, announced the plan to produce a luxury electric sports car with a range of 200+ miles.
- 2009 – The Energy Department invested in nation-wide infrastructure to encourage EV technology adoption.
- 2010 – GM released the first commercially available plug-in hybrid – the Chevy Volt. Nissan launched a fully electric vehicle – Leaf. [76]

The latest trend of electric vehicle adoption is different than the previous trends in the automotive industry. Some reasons are:

- Urgent environmental and health related issues in over-populated urban metro areas
- Entrepreneurial activities that have been challeging traditional automakers
- Regulations that encourage consumers and OEMs adopt electric vehicle technology
- The already mature internal combustion engine technology is not able to meet new environmental demands and regulations

The author believes that the latest EV adoption trend is more sustainable than previously experiences.

7.2.2 A roadmap for automated driving vehicles

Experiments have been conducted on automated-driving technology since the 1920s. A car that is able to drive itself has always been a dream to automotive engineers. We like to call it a robo-car, which is able to complete travel tasks without human inputs. Let's take a look at the activity around automated driving technology in the past, and what products were promised to deliver by technology providers.

- 1925 – Houdina Radio Control demonstrated the radio-controlled "Iinrrican Wonder" on a street in New York City.
- 2005 – Five vehicles were capable of finishing of a 150-mile course without human drivers' input in the DRAPAII Competition.
- 2010 – Many major OEMs started testing automated driving systems.

- 2014 – Google announced plans to unveil 100 automated driving cars built from scratch. Google had been working on automated driving technology since 2009, and has accumulated more than a million miles on the road by the date of publishing this document.
- 2014 – Tesla announced AutoPilot, a level 3-4 automation system that is offered commercially with Tesla Model S.
- 2016 – Tesla expected to develop technology to allow Tesla's vehicles be automated for 90% of the distance driven.
- 2018 – Google expects to have commercial automated driving cars.
- 2020 – All OEMs are expected to offer automated driving vehicles.

The automated driving technology is promising when the vehicle is tested alone. The challenge is when integrating automated driving technology into current traffic scenarios. What will happen then? Will it address all expected issues?

7.2.3 The road map of mobility sharing

The mobility sharing concepts range from carpool with neighbors to commercial ride sharing. This research illustrates the social economical impacts of vehicle sharing regardless private or public vehicle ownerships. However, many market agents have identified the "using instead of owning" trend, where vehicles will be treated as services rather than products. Figure 6 illustrates the vehicle sharing services and market participants in a time matter.

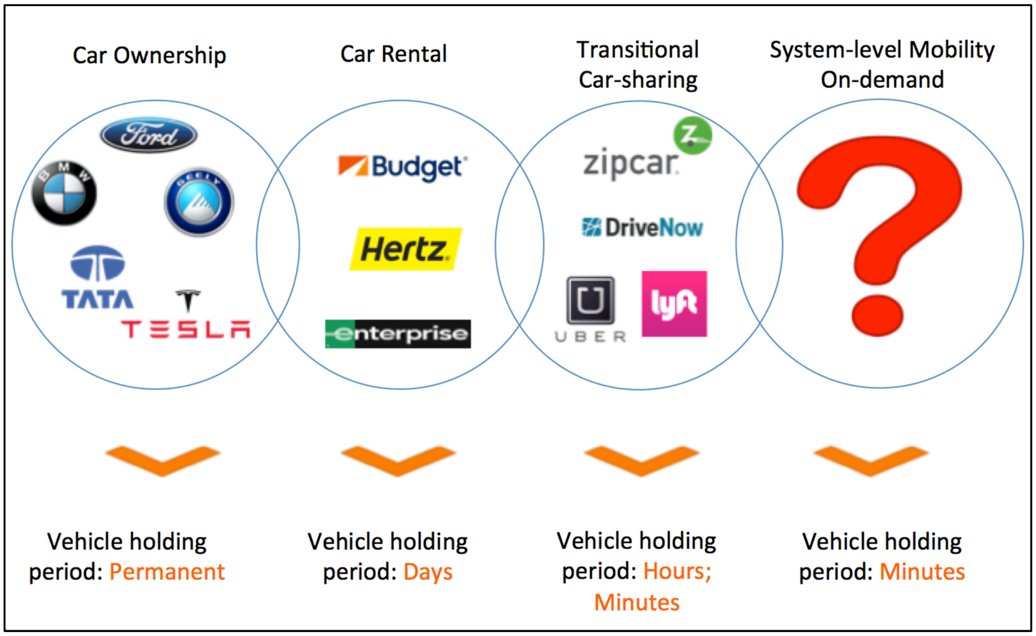


Figure 41: Vehicle sharing road map

7.3 Scenario design and calculation

7.3.1 Scenario design

In the visionary scenario, mobility services are offered by shared, electric, and automated driving vehicles. Different technology adoptions cause changes in all cost categories. Table X illustrates the dependent variables and independent variables in the visionary scenario.

Table 84: Correlationships between dependent and independent variables

External cost	EV	Mobility Sharing	Automated Driving
Traffic Congestion	-	Correlated	Correlated
Health Impact	Correlated	Correlated	Correlated
Global Warming	Correlated	Correlated	Correlated

7.3.2 External costs of traffic congestion

Congestion externality is a cost per mile based cost function. Two major variables are the unit cost that occurs due to passengers' time lost in traffic congestion, and total VMT in urban area.

Cost function formula:

$$Congestion\ Externality = Unit\ cost \cdot VMT$$

Equation 23: Congestion externality in visionary scenario

A. Unit cost per vehicle mile

$$CC = tf \cdot \alpha \cdot \ [\left(\frac{Vol + PCE}{Cap}\right)^{\beta} - \left(\frac{Vol}{Cap}\right)^{\beta}] \cdot Vol \cdot VOTT \cdot p$$

Equation 24: Unit congestion externality in visionary scenario

Table 85: Definition of variables and constants in unit congestion cost

Factors	Definition
t_f	Travel time at free flow conditions. The average congested roadway was assumed to have a free-flow speed of 40 mph, corresponding to 1.5 minutes of travel time per mile traveled at free flow conditions.
α, β	BPR-required parameters; 0.84 and 5.5 (fixed value)
Vol	Road capacity is assumed to be 2000 vehicles per hour per lane (vphpl) and demand is assumed to be right at 95% of total available capacity in the baseline scenario. The capacity changes with penetration rate of autonomous vehicles as shown in Table 29.
PCE	PCE measures Passenger Car Equivalence. It is calculated based on sales volume of different vehicles in urban areas.

	PCE is considered constant at 1.104 for these scenarios.
Cap	Road capacity - Road capacity is assumed to be 2000 vehicles per hour per lane (vphpl)
VOTT	VOTT is a constant measurement of the Value of the Traveler's Time. The Victoria Transport Policy Institute estimates that the value of travel time for personal purposes is about 30% of household hourly income. In 2006, the U.S. household hourly income was 16.83 dollars. After accounting for inflation, the VOTT is 6.04 dollars in 2013.
p	Congested conditions - The travel condition p is calculated from the travel time index found in Texas A&M's Urban Report 2013. In both baseline scenario and this scenario, p value is 0.1736.

Table 86: The changes of factors in unit congestion cost when compare to baseline scenario

Variables	Baseline scenario	Mobility sharing Scenario
t_f	Travel time at free-flow conditions per mile traveled	Remain the same
α, β	BPR-required parameters; 0.84 and 5.5 (fixed value)	Remain the same
Vol	Road capacity per hour per lane * travel demand	Travel demand changes based on the number of vehicles on road, and automated driving system penetration
PCE	Passenger car equivalent	Remain the same
Cap	Road capacity	Road capacity change based on the penetration rate of automated driving system

VOTT	Value of travel time	Remain the same
p	Congested conditions	Remain the same

a. Increased lane capacity

The adoption of automated driving technology impacts unit cost in traffic congestion due to the increased lane capacity.

Table 87: Increased lane capacity at different penetration rates of automated driving system

CACC penetration rate	Vehicles per hour per lane
0%	2,000
25%	2,000
50%	2,300
75%	3,000
100%	4,000

b. Decreased vehicle volume in urban traffic

Mobility sharing impacts the unit cost in traffic congestion due to the decreased number of vehicles in traffic, assuming static travel demand.

Table 88: Decreased vehicle volume in traffic due to mobility sharing

VOR	Vehicles in urban traffic (Vol)
1.6	1900
2	1520
3	1013
4	760
5	608

Table 89 : Correlated road capacity and volume in visionary scenario

Road capacity and volume in visionary scenario						
VOR	0% AV	25% AV	50% AV	75% AV	100% AV	Actual Cap.
	Vphpl	Vphpl	Vphpl	Vphpl	Vphpl	
1.6	2000	2000	2300	3000	4000	1900
2	2000	2000	2300	3000	4000	1520
3	2000	2000	2300	3000	4000	1013
4	2000	2000	2300	3000	4000	760
5	2000	2000	2300	3000	4000	608

Table 90:Unit cost at different VOR

CACC penetration rate	Unit congestion cost at different OR [Dollars per VMT]				
	1.6	2	3	4	5
0%	0.1006	0.0295	0.0536	0.0402	0.0322
25%	0.1006	0.0295	0.0536	0.0402	0.0322
50%	0.0466	0.0137	0.0249	0.0187	0.0149
75%	0.0108	0.0032	0.0058	0.0043	00035
100%	0.0022	0.0007	0.0012	0.0009	0.0007

B. New VMT under different penetration rates and different sharing rates

Table 91: Converted VMTs under different VOR and automated driving penetration rates in visionary scenario

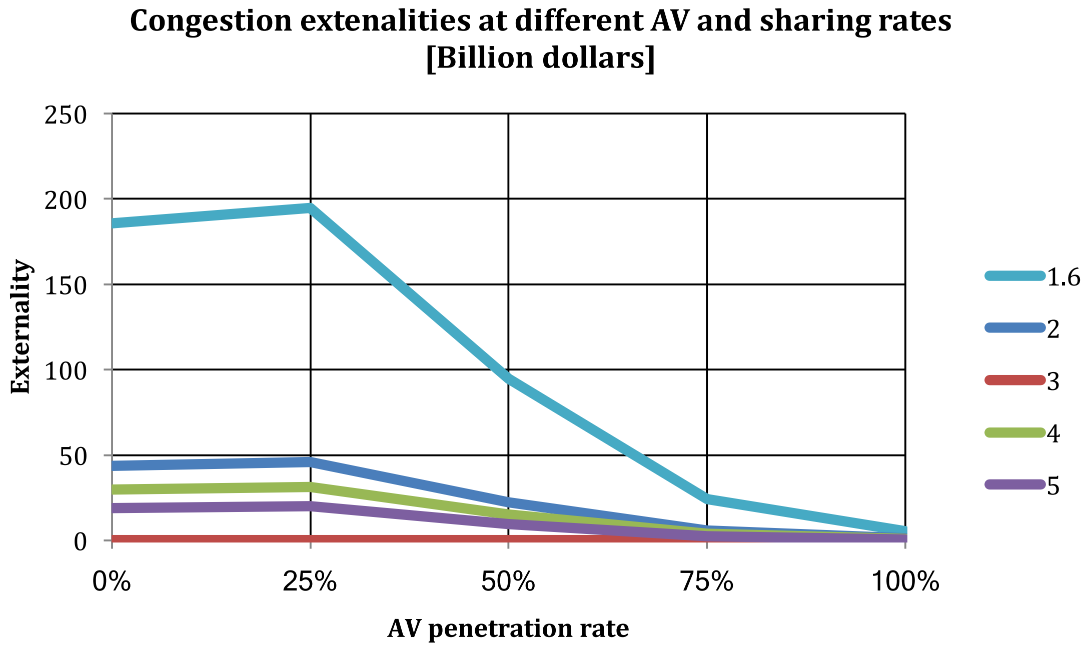
CACC penetration rate	Original VMT [Billion miles]	VMT in visionary scenario [Billion miles]				
		1.6	2	3	4	5
0%	1,845	1,845	1,476	984	738	590
25%	1,937	1,937	1,550	1,044	775	620

50%	2,029	2,029	1,623	1,082	812	649
75%	2,213	2,213	1,771	1,181	886	708
100%	2,399	2,399	1,919	1,279	959	767

C. Integrated external cost

Table 92: Congestion externalities at different technology adoption rates

CACC penetration rate	Unit congestion cost at different OR [Billion dollars]				
	1.6	2	3	4	5
0%	185.59	43.53	52.77	29.69	19.00
25%	194.87	45.71	55.41	31.18	19.95
50%	94.65	22.20	26.91	15.14	9.69
75%	23.95	5.62	6.81	3.83	2.45
100%	5.33	1.25	1.52	0.85	0.55



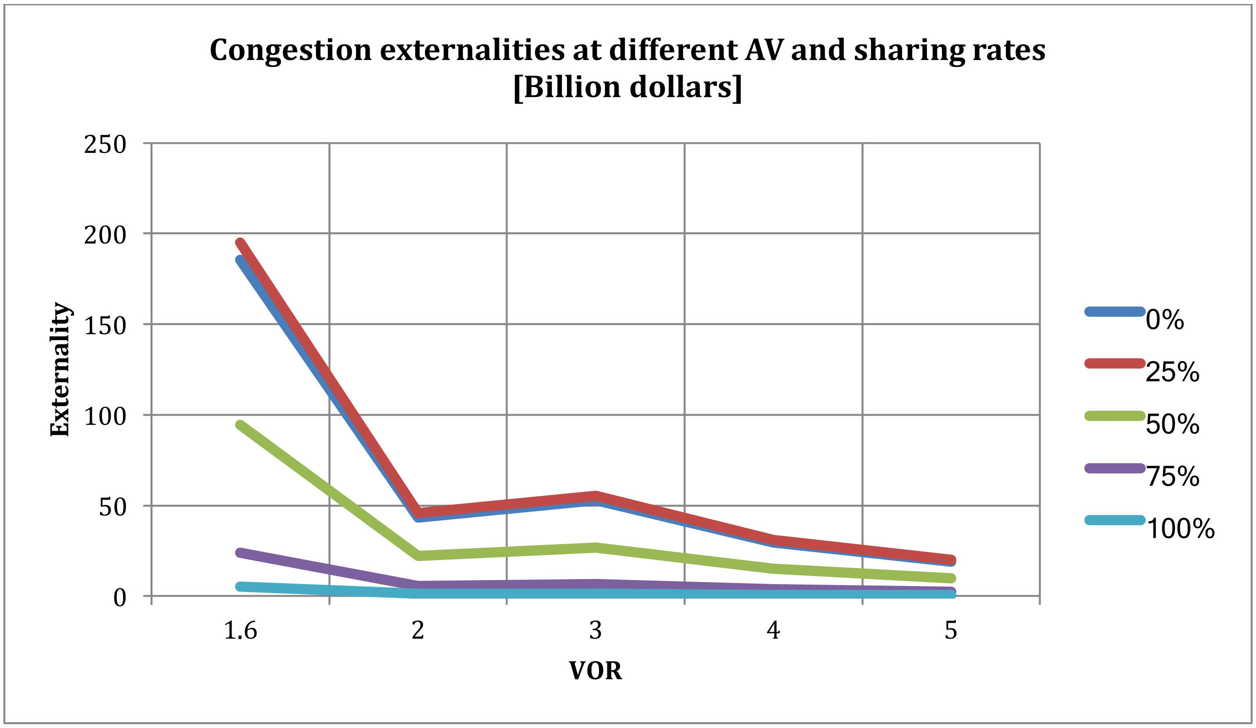


Figure 42: Two illustrations of congestion externalities in the visionary scenario

7.3.3 External costs of human health impacts

A. *Introduction of human health impacts*

Transportation significantly impacts air pollution in the immediate area around it. Road transportation is responsible for emission of nitrogen oxides, sulphur dioxide, volatile organic compounds, carbon monoxide, lead and particulate matter with a diameter of less than 10 μm. Air pollution in the transportation sector affects human health in a number of ways.

I define the external cost function for human health impact as:

$$Human\ halth\ externality = Unitcostof Pollutants \cdot VMT$$

Equation 25: Human health externality cost function in visioanry scenario

B. Redefined variables – unit cost and new VMT

A. Unit pollutants cost

Table 93: Unit pollutant costs in visionary scenario

Emission	Ambient Pollutants	Cost in 2013 inflation rate [Dollars/kg]	
		Low	High
PM $_{2.5}$	PM $_{2.5}$	25.33	385.46
PM $_{2.5-10}$	PM $_{2.5-10}$	15.55	40.86
NO_x	Total	2.72	39.92
VOC	Organic PM_{10}	0.22	2.48
CO	CO	0.02	0.17

Table 94: Unit pollutant cost of ICE and EV vehicle-miles traveled

Unit pollutant cost of ICE and EV [Dollars per VMT]	
ICE	EV
0.0199	0

Table 95: VMT for human health externality in visionary scenario

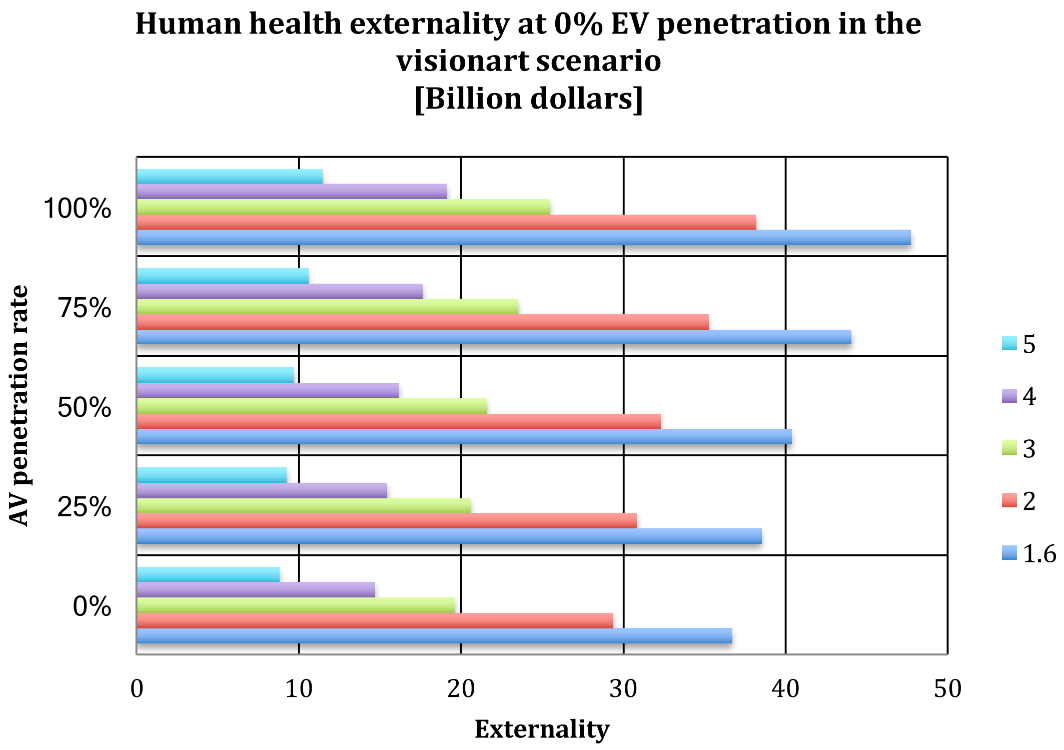
CACC penetration rate	Original VMT [Billion miles]	VMT in visionary scenario [Billion miles]				
		1.6	2	3	4	5
0%	1,845	1,845	1,476	984	738	590
25%	1,937	1,937	1,550	1,044	775	620
50%	2,029	2,029	1,623	1,082	812	649
75%	2,213	2,213	1,771	1,181	886	708
100%	2,399	2,399	1,919	1,279	959	767

C. Modeled human health externality in visionary scenario

a. Human health externality at 0% EV adoption

Table 96: Human health externality at 0% EV penetration rate

	Human health externality at 0% EV in visionary scenario [Billion dollars]				
	1.6	2	3	4	5
0%	36.70	29.36	19.58	14.68	8.81
25%	38.54	30.83	20.55	15.42	9.25
50%	40.37	32.30	21.53	16.15	9.69
75%	44.05	35.24	23.49	17.62	10.57
100%	47.72	38.17	25.45	19.09	11.45



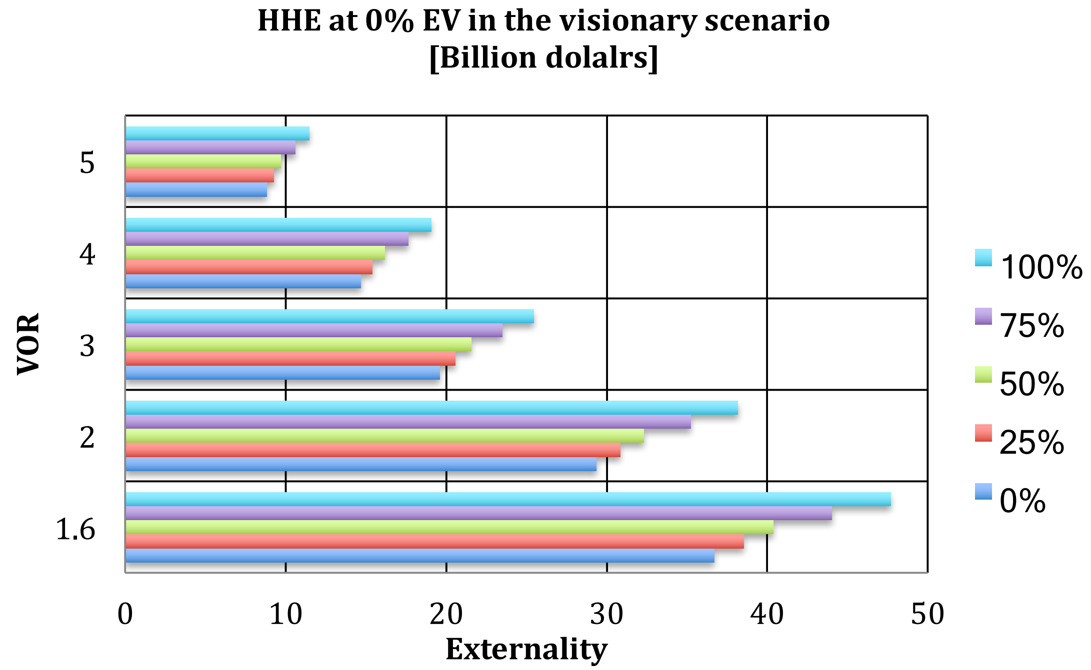
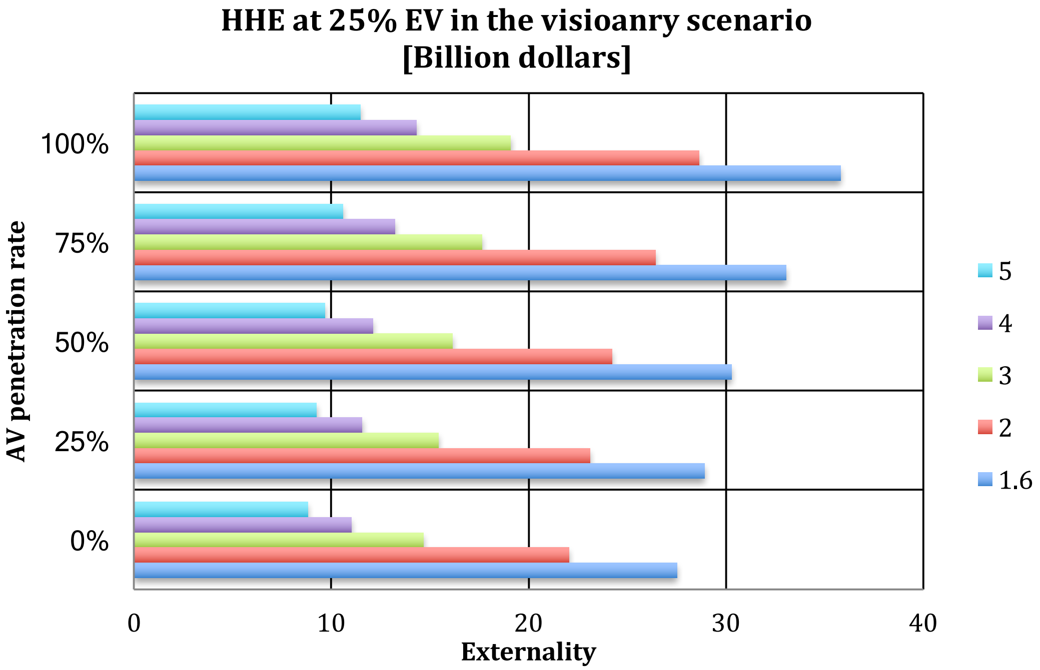


Figure 43: Two illustrations of human health externalities at 0% EV in visionary scenario

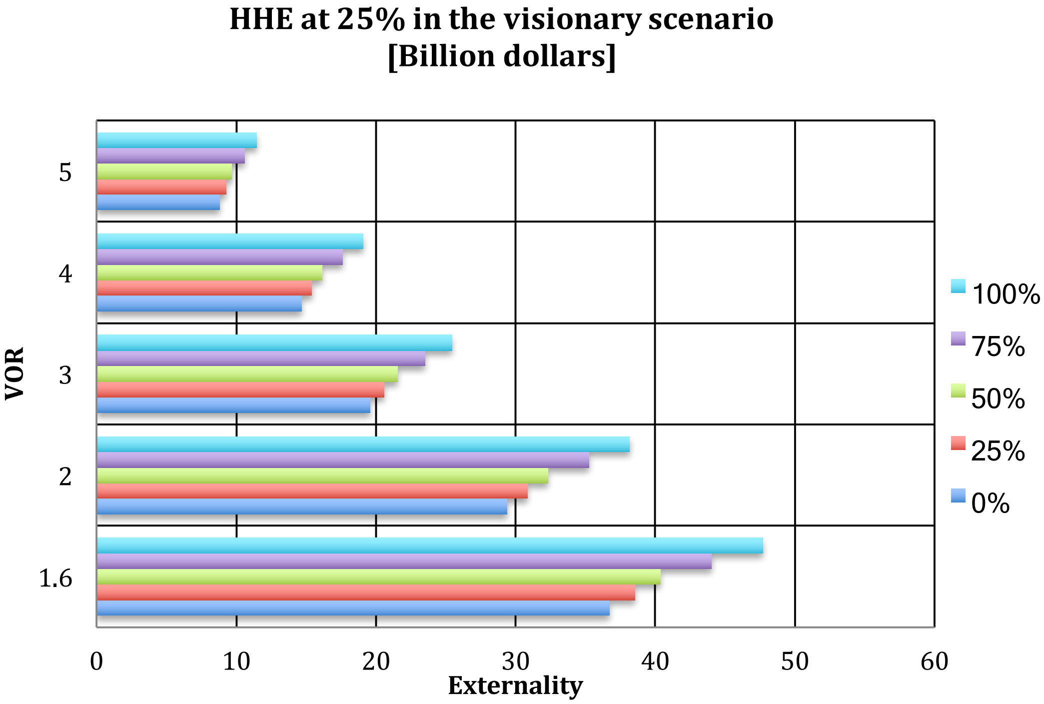
b. Human health externality at 25% EV adoption

Table 97: Human health externality at 25% EV penetration rate

	Human health externality at 25% EV in visionary scenario [Billion dollars]				
	1.6	2	3	4	5
0%	27.53	22.02	14.68	11.01	8.81
25%	28.90	23.12	15.42	11.56	9.25
50%	30.28	24.22	16.15	12.11	9.69
75%	33.03	26.43	17.62	13.21	10.57
100%	35.79	28.63	19.09	14.31	11.45



HHE at 25% EV in the visioanry scenario [Billion dollars]



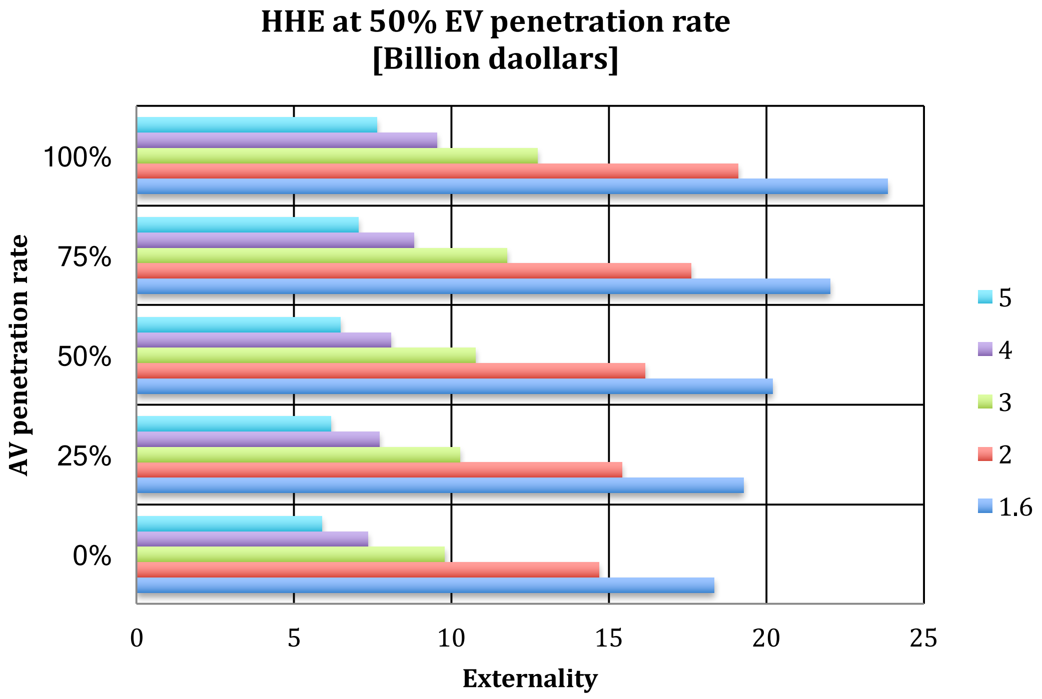
HHE at 25% in the visionary scenario [Billion dollars]

Figure 44: Two illustrations of HHE at 25% EV in the visionary scenario

c. Human health externality at 50% EV adoption

Table 98: Human health externality at 50% EV penetration rate

	Human health externality at 50% EV adoption in visionary scenario [Billion dollars]				
	1.6	2	3	4	5
0%	18.35	14.68	9.79	7.34	5.87
25%	19.27	15.42	10.28	7.71	6.17
50%	20.19	16.15	10.77	8.07	6.46
75%	22.02	17.62	11.75	8.81	7.05
100%	23.86	19.09	12.72	9.54	7.63



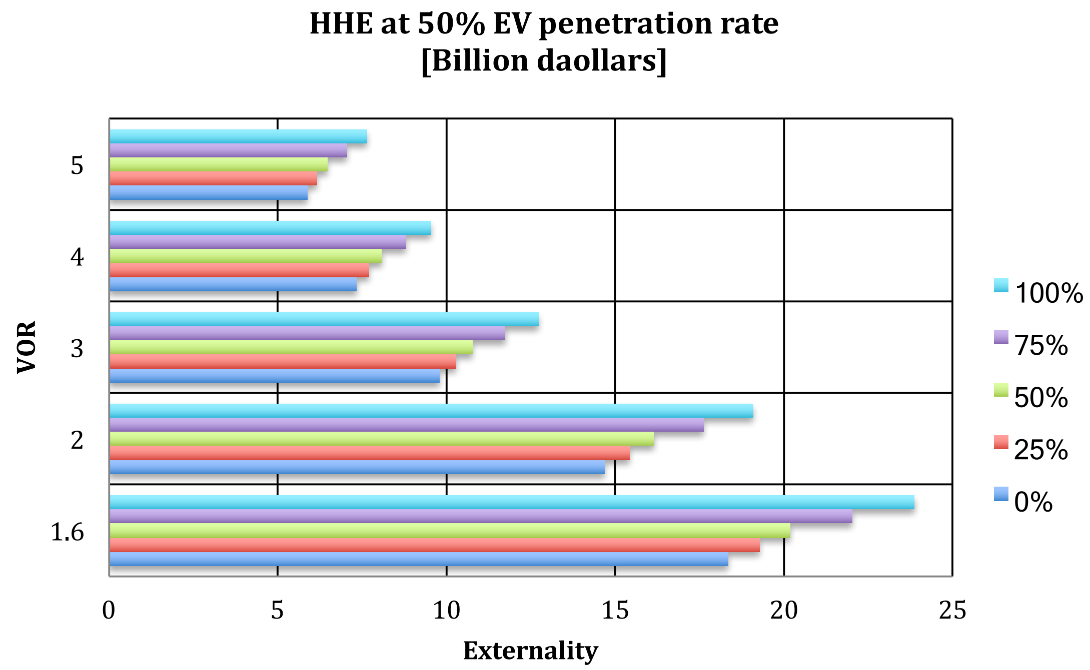
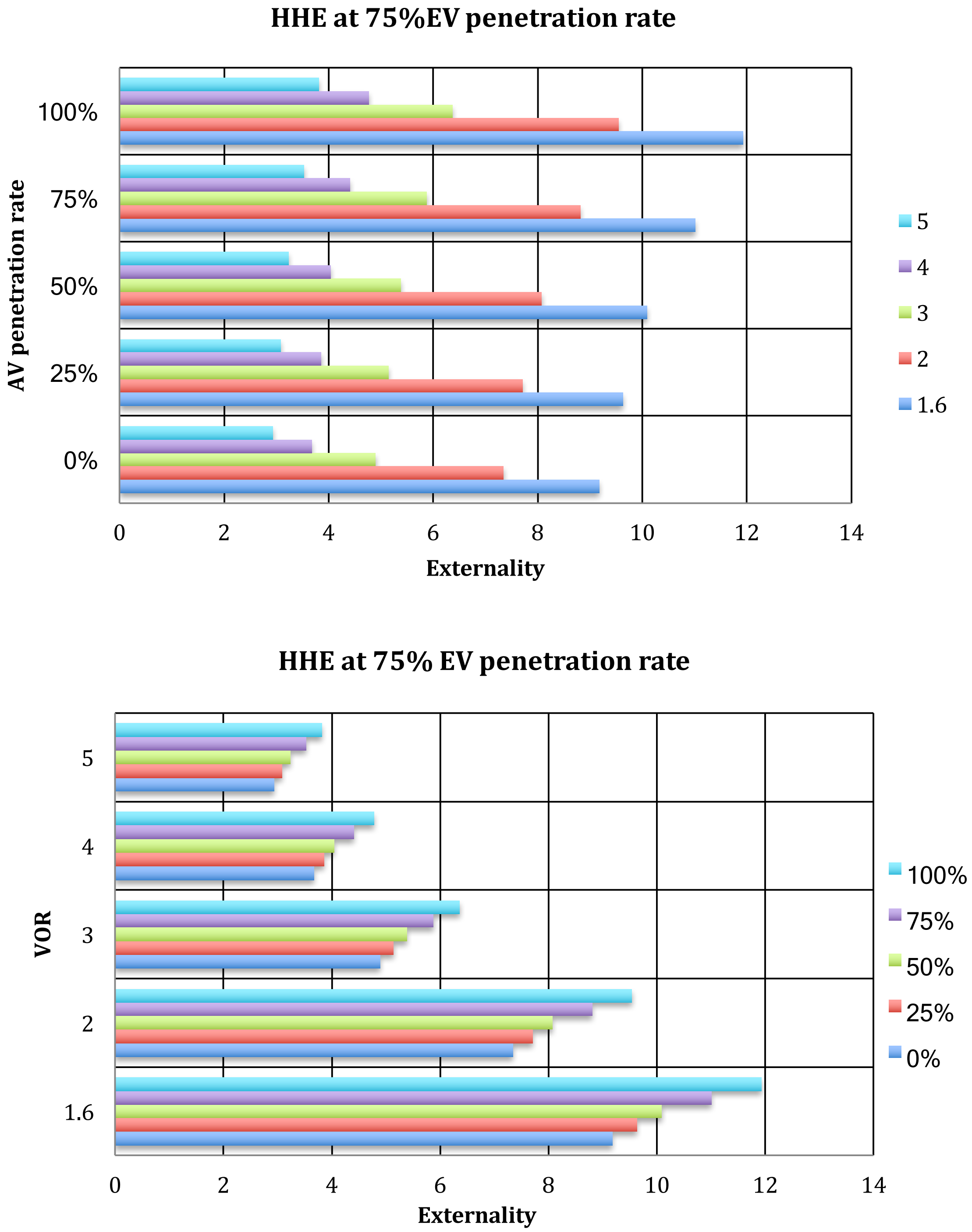


Figure 45: Two illustrations of HHE at 50% EV penetration rate in the visionary scenario

d. Human health externality at 75% EV adoption

Table 99: Human health externality at 75% EV penetration rate

	Human health externality at 75% EV in visionary scenario [Billion dollars]				
	1.6	2	3	4	5
0%	9.18	7.34	4.89	3.67	2.94
25%	9.63	7.71	5.14	3.85	3.08
50%	10.09	8.07	5.38	4.04	3.23
75%	11.01	8.81	5.87	4.40	3.52
100%	11.93	9.54	6.36	4.77	3.82


HHE at 75%EV penetration rate

HHE at 75% EV penetration rate

Figure 46: Two illustrations of HHE at 50% EV penetration rate in the visionary scenario

e. Human health externality at 100% EV adoption

Table 100: Human health externality at 100% EV penetration rate

	Human health externality at 100% EV in visionary scenario

	[Billion dollars]				
	1.6	2	3	4	5
0%	0	0	0	0	0
25%	0	0	0	0	0
50%	0	0	0	0	0
75%	0	0	0	0	0
100%	0	0	0	0	0

7.3.4 External cost of climate change

A. General introduction

All transportation modes emit pollutants that affect global climate. These climate-changing pollutants are called greenhouse gases (GHG). Carbon dioxide (CO_2) is the most damaging greenhouse gas. Light-duty vehicles account for one fifth of domestic US CO_2 emissions.

The climate change costs of transportation can be estimated as the product of two factors: CO_2-equivalent emissions of GHGs (as a product of VMT), and the damage cost of a unit CO_2 emission.

The author describes the cost function as follows:

$$Climate\ change\ externality = Unit\ cost\ of\ CO_2 * VMT_{new}$$

Equation 26: Climate change externality cost function in visionary scenario

B. Unit cost and VMT

a. Unit cost

Table 101: Unit GHG cost in visionary stage

LDV [Dollars per VMT]	In 2013 dollar [Dollars per metric ton]	Unit Emission [Kg per VMT]	PCE	Unit Cost in 2013 [Dollars per VMT]
5%	11	0.368	1.104	0.00455
3%	36	0.368	1.104	0.01489
2.5%	56	0.368	1.104	0.02315

Table 102: Unit pollutant cost for ICE and EV in visionary scenario

Unit pollutant cost of ICE and EV [Dollars per VMT]	
ICE	EV
0.01489	0

b. VMT

Table 103: VMT for climate change in visionary stage

CACC penetration rate	Original VMT [Billion miles]	VMT in visionary scenario [Billion miles]				
		1.6	2	3	4	5
0%	1,845	1,845	1,476	984	738	590
25%	1,937	1,937	1,550	1,044	775	620
50%	2,029	2,029	1,623	1,082	812	649
75%	2,213	2,213	1,771	1,181	886	708
100%	2,399	2,399	1,919	1,279	959	767

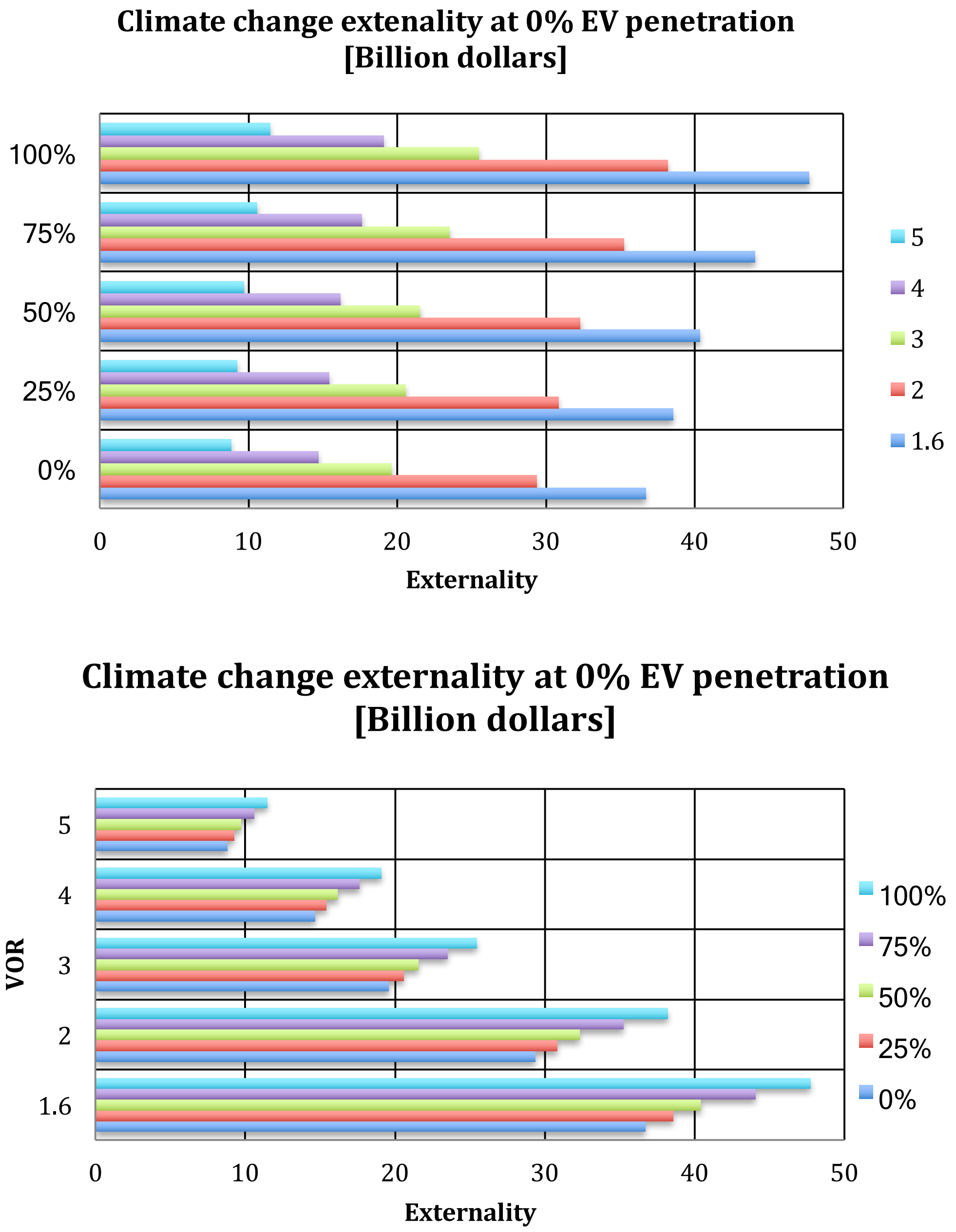
C. Integrated cost value

a. Climate change externality at 0% EV adoption in visionary scenario

Table 104. Climate change externality at 0% EV

	Climate change externality at 0% EV [Billion dollars]				
	1.6	2	3	4	5
0%	27.46	21.97	14.65	10.98	8.79

25%	28.83	23.07	15.38	11.53	9.23
50%	30.21	24.17	16.11	12.08	9.67
75%	32.95	26.36	17.58	13.18	10.55
100%	35.70	28.56	19.04	14.28	11.42


Climate change extenality at 0% EV penetration [Billion dollars]

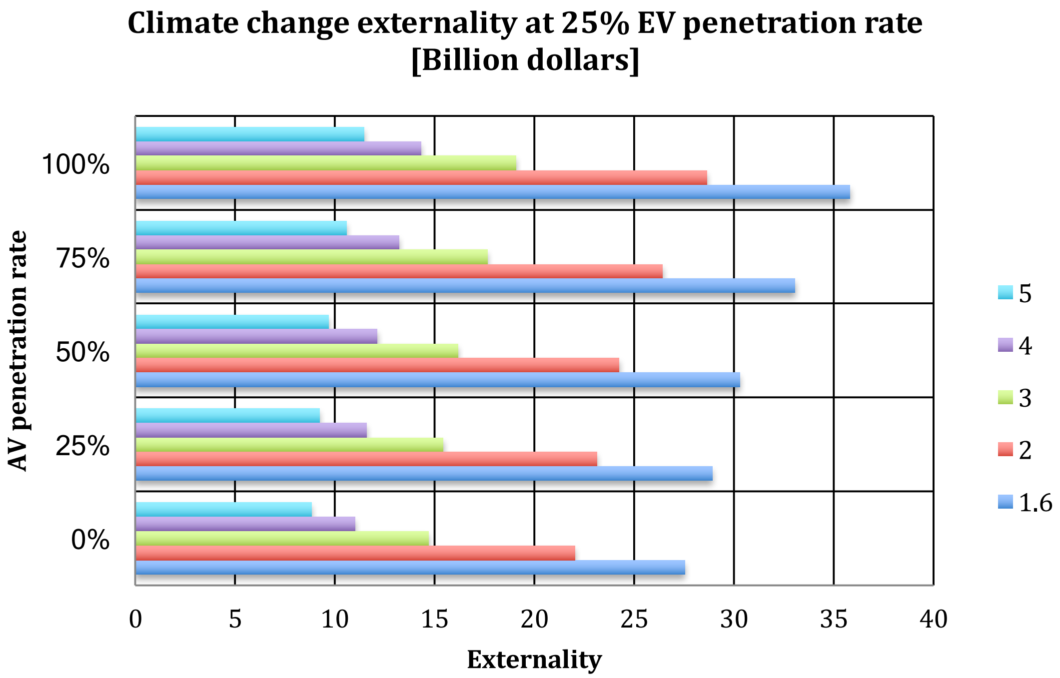
Climate change externality at 0% EV penetration [Billion dollars]

Figure 47: Climate change externalities at 0% EV in the visionary scenario

b. Climate change externality at 25% EV adoption in visionary scenario

Table 105. Climate change externality at 25% EV

	Climate change externality at 25% EV [Billion dollars]				
	1.6	2	3	4	5
0%	20.60	16.48	10.98	8.24	6.59
25%	21.63	17.30	11.53	8.65	6.92
50%	22.66	18.12	12.08	9.06	7.25
75%	24.71	19.77	13.18	9.89	7.91
100%	26.77	21.42	14.28	10.71	8.57



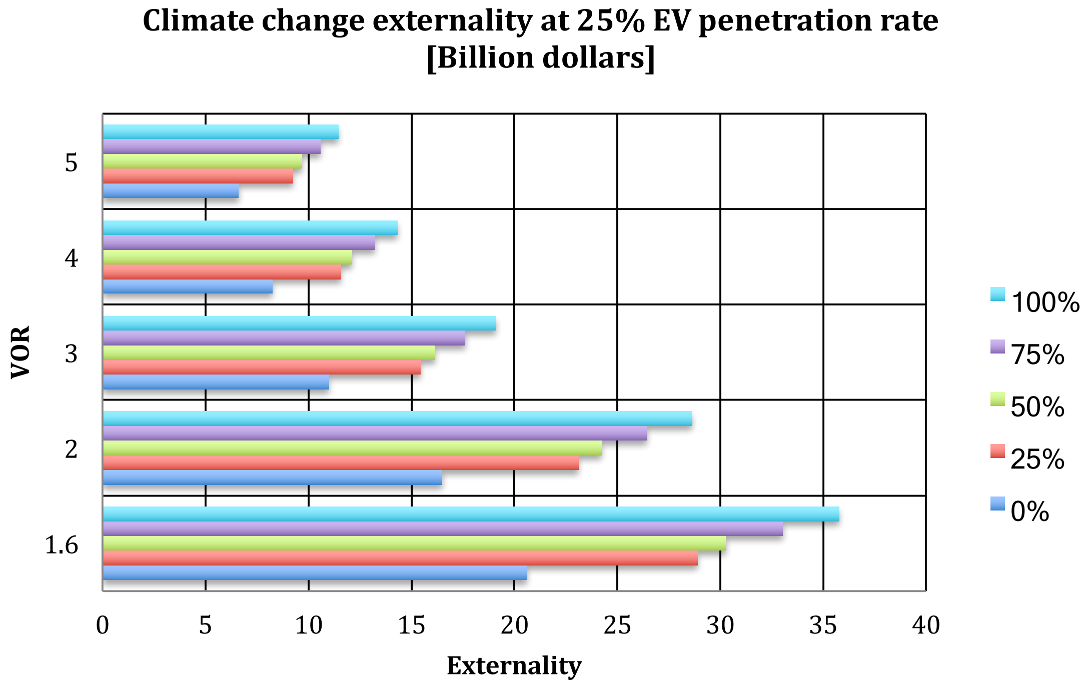
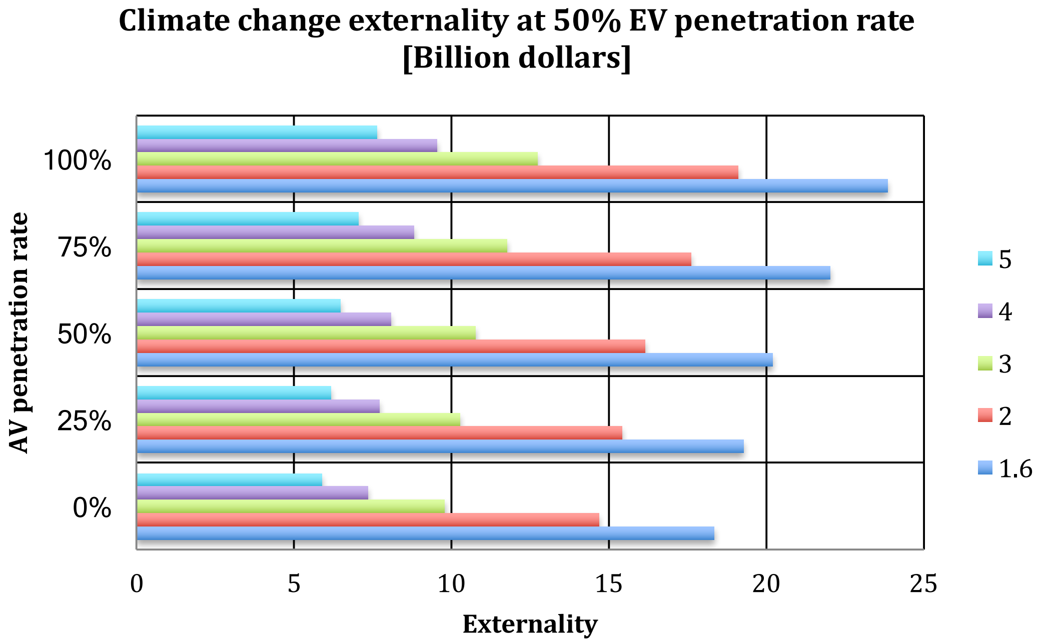


Figure 48: Climate change externalities at 25% EV penetration rate in the visionary scenario

c. Climate change externality at 50% EV adoption in visionary stage

Table 106. Climate change externality at 75% EV

	Climate change externality at 50% EV [Billion dollars]				
	1.6	2	3	4	5
0%	13.73	10.98	7.32	5.49	4.39
25%	14.42	11.53	7.69	5.77	4.61
50%	15.10	12.08	8.06	6.04	4.83
75%	16.48	13.18	8.79	6.59	5.27
100%	17.85	14.28	9.52	7.14	5.71



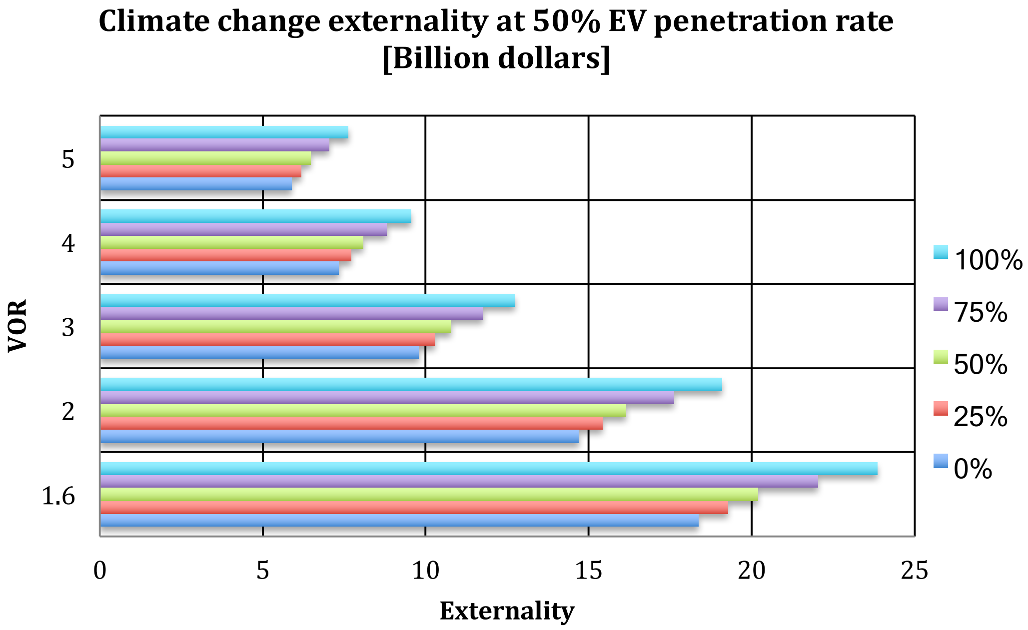


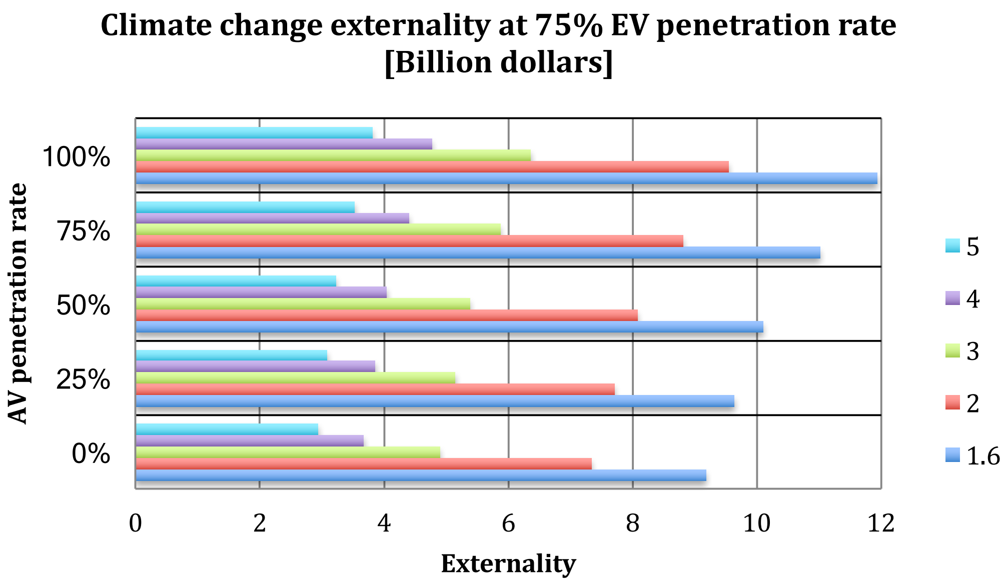
Figure 49: Climate change externalities at 50% EV penetration rate in the visionary scenario

d. Climate change externality at 75% EV adoption in visionary scenario

Table 107. Climate change externality at 75% EV

	Climate change externality at 75% EV [Billion dollars]

	1.6	2	3	4	5
0%	6.87	5.49	3.66	2.75	2.20
25%	7.21	5.77	3.84	2.88	2.31
50%	7.55	6.04	4.03	3.02	2.42
75%	8.24	6.59	4.39	3.30	2.64
100%	8.92	7.14	4.76	3.57	2.86



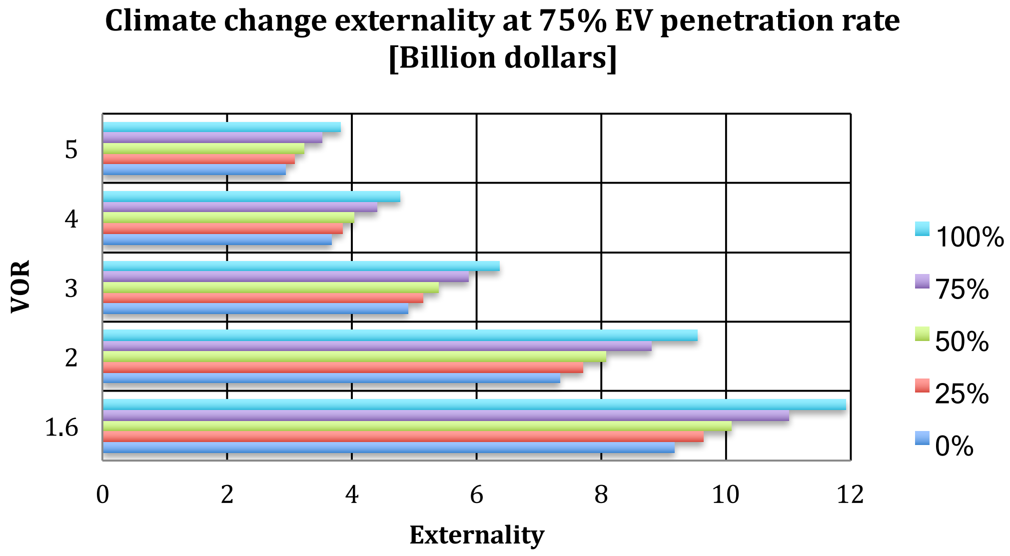


Figure 50: Climate change externality at 75% EV penetration rate in the visionary scenario

e. Climate change externality at 100% EV adoption in visionary scenario

Table 108. Climate change externality at 100% EV

	Climate change externality at 75% EV [Billion dollars]				
	1.6	2	3	4	5
0%	0	0	0	0	0
25%	0	0	0	0	0
50%	0	0	0	0	0
75%	0	0	0	0	0
100%	0	0	0	0	0

7.4 Conclusions

If 25% vehicles in traffic are electric, automated and shared (VOR at 2), the total external cost is reduced by 65%. The performance is similar to the shared EV scenario at 25% penetration rate. The automated driving adoption offset the performance due to the increased total VMT.

If 50% vehicles in traffic are electric, automated and shared (VOR at 3), the total external cost is reduced by 82%, less than the external cost in the shared EV scenario at 50% penetration rate. The automated driving adoption offsets the performance even more.

When the all technology adoption rate are at or beyond 75%, the total externality can be eliminated.

The author did not observe significant improvements when comparing the triple-technology adoption scenario to double technology adoption scenario (shared EV) or even single technology scenario (sharing). Sharing is the most efficient method of all technology adoptions.

CHAPTER EIGHT

8. VARIABILITY OF UNIT COSTS IN TRANSPORTATION EXTERNALITIES

Transportation externalities are adopted as indicators to demonstrate the economic impacts of variety of technology adoption pathways. The differences between predicted externalities of future scenario and current scenario demonstrate the economic gain or loss. The externalities are used as predictive figures more than estimations. The figures can only be compared on the same regional scale. Therefore, understanding how to estimate transportation externalities based on regional differences is important.

The total urban related external costs are based on unit input values in Chapter 4 in all categories. We assume that the figures are representative for the urban areas within the scope of the study (the United States). As an input, the unit value serves as a reference value for further studies on transportation economics.

This chapter will discuss how the unit costs of urban transportation vary with cost indexes for a selection of urban metro areas in the United States. Also included is the indexes for all cost categories and how to apply the research method into future studies.

Three cost categories are discussed in the research; congestion externalities, human health externalities and climate change externalities. The unit costs of all three cost categories and the ranges of costs found during literature review are listed in Table below.

Table 109. Unit costs in all cost categories

	Unit cost value in the research [¢/VMT]	Model Used	Unit cost value range [¢/VMT]	Relevant Articles
Unit congestion cost	10.1	Revised Lemp and Kockelman	1.41 – 11.94	Gorman et al. (2008); Lemp and Kockelman (2008); Parry et al. (2007); Delucchi (2004a); Levinson et al. (1998)
Human health impact	1.98	Adopted McCubbin and Delucchi's model	0.04 – 2.99	Delucchi (2008); Lemp and Kockelman(2008); Zhang et al. (2004); Forkenbrock (1998,2001); McCubbin and Delucchi (1999); Small and Kazimi (1995)
Climate change	1.45	EPA	0.075 – 2.39	Delucchi estimates; Lemp and Kockelman (2008); Parry et al. (2007); Zhang et al.(2004); Forkenbrock (1998, 2001);

				EPA (2013)

8.1 Geographic variability of unit congestion costs

At the simplest level, congestion delay costs are equal to the hours lost to delays, multiplied by the value of the opportunities foregone during a reference hour. This cost function was defined in Chapter 4.

For congestion costs, the unit value is calculated based on a revised version of Lemp and Kockolman’s model. The author analyzed the automobile sales in 2013 to identify the most recent PCE (passenger car equivalent) value.

$$CongestionexternalityLDV = VMTLDV \cdot unitcostLDV$$

$$CC = tf \cdot \alpha \cdot \left[\left(\frac{Vol + PCE}{Cap}\right)^{\beta} - \left(\frac{Vol}{Cap}\right)^{\beta}\right] \cdot Vol \cdot VOTT \cdot p$$

In Equation two, the VOTT is based on the average hourly income in urban areas in the United States. Different hourly incomes are expected in different regions in the world. Therefore, the author suggests that future researchers use the results from the revised model as a coefficient to be identified based on the scenario at hand instead of adopting the unit cost as a definitive measure. The method for determining the coefficient will be demonstrated in this section.

A. Evaluating local congestion externalities based on Sun’s model

$$CC = VOTT * CongestionCoefficien$$

$$CC = VOTT * 0.0167$$

The coefficient in unit congestion cost in 2013 is 0.0167. When multiplying the coefficient with regional VOTT (value of traveler’s time), the regional unit congestion cost is the result. Victoria Institution defined the value of VOTT as one third of the local average hourly income. Therefore, the average hourly income becomes the independent variable in unit congestion cost calculations. Table below shows an index of the average hourly income of the top 10 countries in the country.

B. The table of average hourly income worldwide

Table 110. Average hourly income of top 10 countries in the world

Country	**Average Hourly Income [Dollars in 2015]**	**VOTT [Dollars per hour]**	**Congestion cost [Dollars per mile]**
Switzerland	44.46	14.82	0.248
Norway	40.64	13.54	0.226
Luxembourg	37.16	12.47	0.208
Denmark	34.95	11.65	0.195
Ireland	29.85	9.94	0.166
Netherlands	28.87	9.62	0.161
Canada	28.43	9.48	0.158
Sweden	27.45	9.15	0.152
Belgium	27.06	9.02	0.151
United States	26.84	8.95	0.149

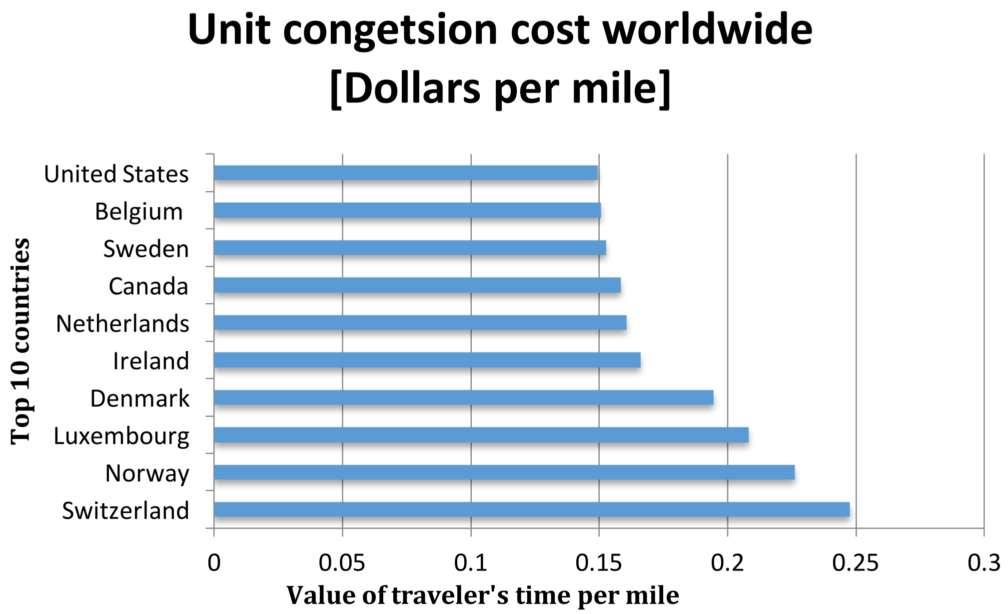


Figure 51. The value of traveler's time based on average hourly income worldwide

The unit congestion cost is the financial loss of each individual’s time due to inefficient traffic flow. There is a direct correlation between higher regional incomes and a higher VOTT. However, the total external costs in urban areas depend on both the unit congestion cost and total VMT in the region. The unit cost by itself cannot represent the congestion cost in the region.

Index below demonstrates regional congestion costs calculated from regional conditions. Although Sweden has the highest VOTT value, the overall congestion cost ranks last among the five selected countries due to the low total VMT in Sweden. Conversely, the United States generates the most congestion externalities due to the enormous VMT in urban areas.

Table 111. Total regional external congestion costs in different countries

	VMT/day [10^9 miles]	Unit cost related data			Total congestion cost in the city [$ Bn]
		Average hourly income [$/hr]	VOTT [$/hr]	Unit congestion cost [$/hr]	
United Kingdom	240.00	24.23	8.07	0.135	32.37
France	252.98	22.79	7.60	0.127	32.09
Germany	332.23	22.83	7.61	0.127	42.22
Sweden	35.56	27.44	9.15	0.153	5.43
United States	1,792	26.84	8.95	0.149	267.74

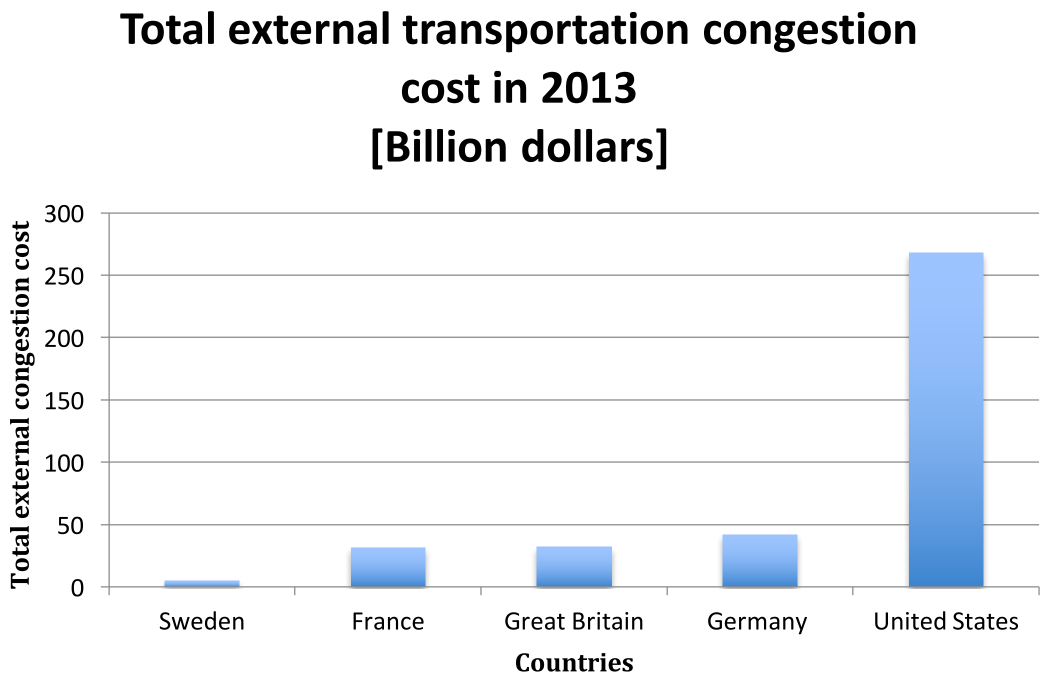


Figure 52. Total external congestion costs in different countries

8.2 Variations in human health impact costs

Road transportation causes emission of nitrogen oxides, sulphur dioxide, volatile organic compounds, carbon monoxide, lead and particulate matter with a diameter of less than 10 μm. The air pollutants affect human health in a variety of ways. The costs of these health effects are the subject of a number of studies. After evaluating a number of processes during literature review, the author adopted McCubbin and Delucchi's model.

MuCubbin and Delucchi's model evaluates all human health related pollutants generated by transportation sector in 1991 dollars. The author separated pollutants by shared characteristics and translated Delucchi's unit cost value from dollars per pound of released pollutant to dollars per mile traveled by light-duty vehicles. Table X illustrates the variation of total external human health costs in the baseline scenario in 2013 dollars. The simulated results from other studies cannot be fully applied in the dissertation due to data availability. Therefore, the author analyzed the cost range given in MuCubbin and Delucchi's research. If future researchers want to adopt other cost models for human health impact evaluations, the data screening process (proposed in Chp. 4) has to be modified accordingly. Two major changes are expected in the process, the method to calculate the unit cost and the source of travel data.

Table 112. Unit costs of tailpipe pollutants

Emission	Ambient Pollutants	Vehicle Emission Cost [$\$_{1991}$/kg]		Vehicle Emission Cost [$\$_{2013}$/kg]	
		Low	High	Low	High

$PM_{2.5}$	$PM_{2.5}$	14.81	225.36	25.33	385.46
$PM_{2.5-10}$	$PM_{2.5-10}$	9.09	23.89	15.55	40.86
NO_x	Total	1.59	23.34	2.72	39.92
VOC	Organic PM_{10}	0.13	1.45	0.22	2.48
CO	CO	0.01	0.1	0.02	0.17

Table 113. Range of the total unit pollutant cost

	Unit cost of all pollutants [¢/mile]	Total VMT [Billion miles]	Total cost [Billion dollars]
Low	0.27	1,845	4.98
Average	1.98	1,845	36.70
High	3.70	1,845	68.42

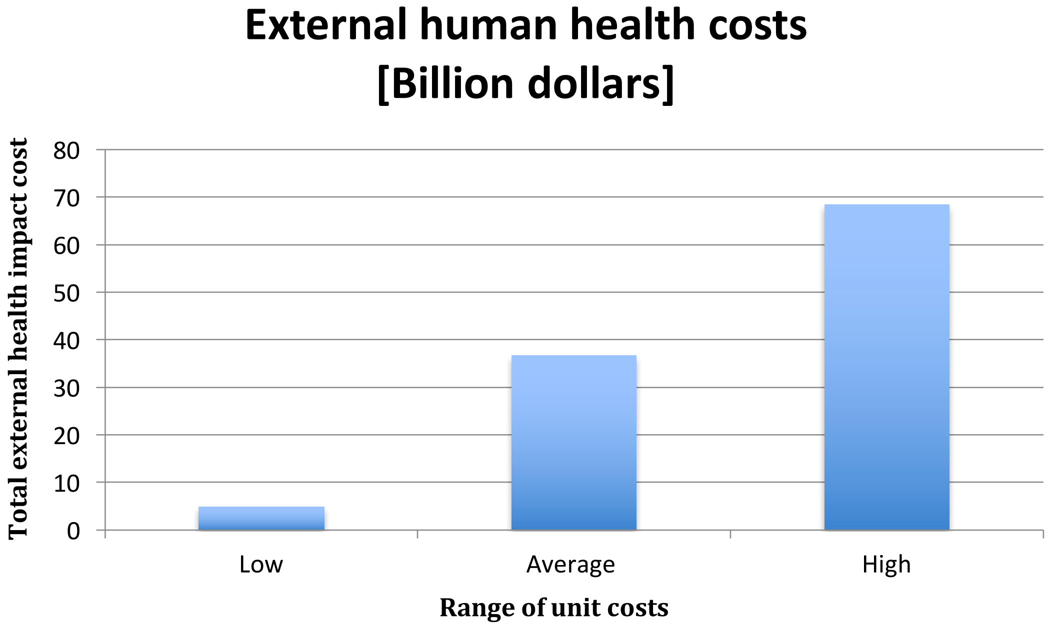


Figure 53. Different total human health impact costs

8.3 Variation in human health impact costs

Climate change induced by worldwide greenhouse gas (GHG) emissions is currently one of the key topics of global research. Light-duty vehicles account for a fifth of nationwide emissions of carbon dioxide. Carbon dioxide is the leading greenhouse gas.

A. External climate change cost model:

$$Climatechangeexternality \\ = Wheel2WheelGHGemission \cdot VMT \cdot CostofCO2perton$$

The index of GHG unit cost

Table above shows unit costs of GHG from a selection of studies. The author will apply these numbers to the baseline scenario calculation to illustrate possible variance of the model. This study adopted the EPA 3% value (details in Chapter 4).

Zhang's model focuses on urban areas in Canada, where the unit cost is low, as well as Perry's estimation of unit cost estimation. Lemp and Kockelman adopted a different method which leads to a relatively higher GHG unit cost. The author suggests future researchers consider regional impacts on GHG unit values before adopting the numbers from the Index.

Table 114. Unit GHG costs form literature review

	Road [¢/VMT]
Zhang et al. (2004)	0.0828
Parry et al. (2007)	0.1302
EPA 5% (2013)	0.4550

EPA 3% (2013)	1.4890
EPA 2.5% (2013)	2.3150
Lemp and Kockelman (2008)	2.6386

Table 115. Total climate change costs related to different unit costs

	Road [¢/VMT]	**External climate cost [Billion dollars]**
Zhang et al. (2004)	0.0828	1.52
Parry et al. (2007)	0.1302	2.40
EPA 5% (2013)	0.4550	9.26
EPA 3% (2013)	1.6439	30.32
EPA 2.5% (2013)	2.5558	47.15
Lemp and Kockelman (2008)	2.6386	48.68

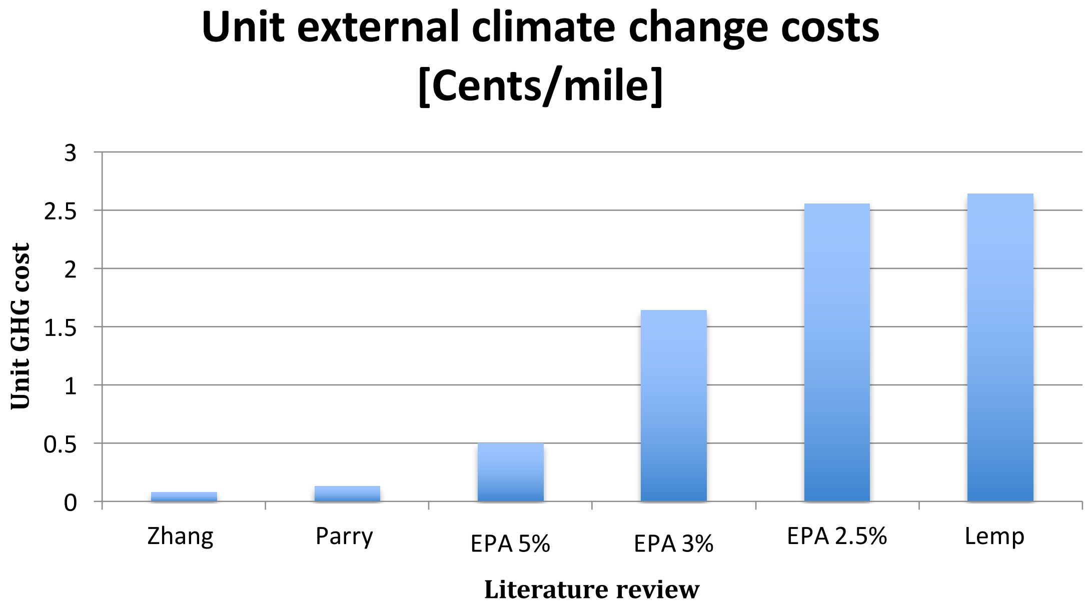


Figure 54. Unit costs of GHG in different literatures

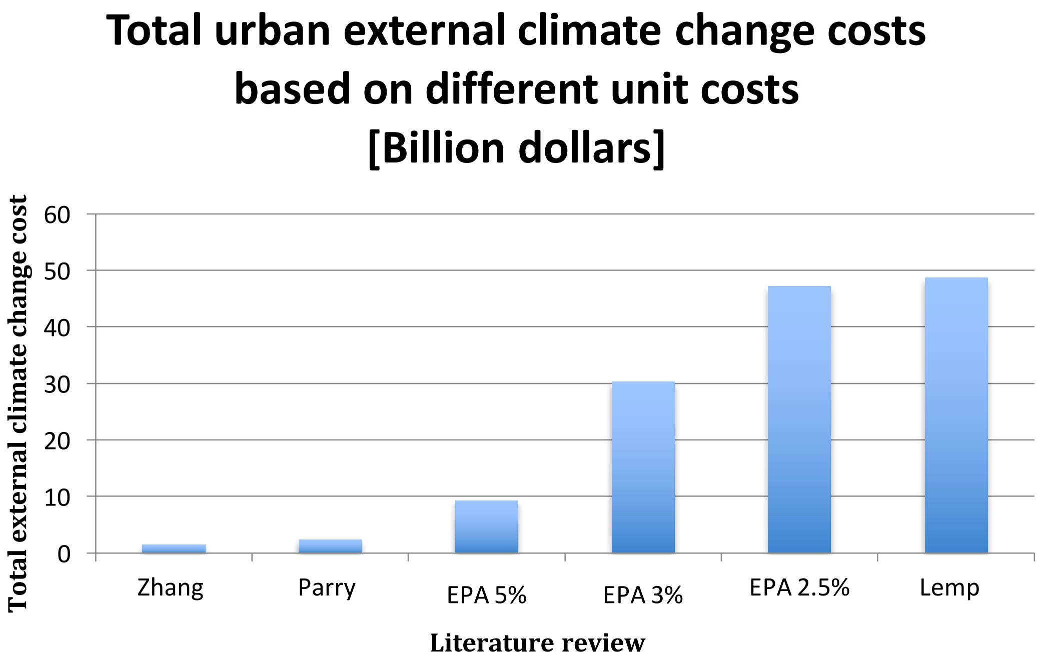


Figure 55. Total external climat change costs based on different unit costs

CHAPTER NINE

9. SUMMARIES AND CONCLUSIONS

The urban mobility demand is increasing rapidly. Researchers have proposed different sets of solutions that integrate alternative fuel technologies, self-driving technologies and mobility sharing models to address the challenge. The simulation results are promising. The social economic benefits that are brought by implementing new technologies or sets of technologies have not been quantified.

The purpose of the parametric study is to evaluate the social economic impact of different possible technology adoption pathways in the transition in urban mobility service sector before implementation.

The author believes that externality can be used as a leading indicator for disruptive technology adoption in Product-to-Service Transition in the automotive industry. The changes of externalities among scenarios indicate the possible economic outcomes by adopting different sets of technologies. Understanding the potential economic loss or gain at a mass-adoption level is the key to assist constructing the urban mobility marketplace for both market institutions and non-market institutions.

The analytical results can be applied to conduct future studies on the progress of technology adoption, consumer behavior shift, and regulation–making process in the mobility marketplace.

9.1 Identify the Product-to-Service Transition and dependent variables in the comparative study

9.1.1 The consequences of rapidly increasing mobility demands

By the year 2050, 70% of people will live in urban metro areas. The urban mobility demands will increase to 2.6 times the current level, faster than the growth rate of urban population. Current urban transportation systems fail to address the rapidly increasing urban mobility demands. The inefficient urban transportation systems have caused financial losses to individual users and society, especially in traffic congestion, human health and climate change categories.

9.1.2 The Product-to-Service Transition in the automotive industry

The current urban transportation pressure and emerging technology-driven trends will revolutionize how industry players respond to changing consumer behavior, develop partnerships, and drive transformational change. The Product-to-Service Transition (P2S) from current product-based competition to a marketplace focused on mobility services is unclear. The social economic benefits of adopting different sets of technologies in the transition have not been measured.

9.1.3 Identified inputs/variables in the research

A. Innovation inputs: Technology push in the transition

Traditional technical innovations in the automotive industry tend to focus on optimizing the performance of a vehicle as a product. The innovative parties are primarily tiered suppliers and original equipment manufacturers (OEM). The P2S transition in the automotive industry challenges the traditional innovation process due to technology complexity and new perspectives from nontraditional participants.

Electric vehicle and automated-driving technology have been reviewed in previous chapters, and adopted as technology input variables in the research.

B. Market pull – consumer mobility preference

Gen Y (those born from 1977 to 1994) is emerging as the largest segment influencing the automotive industry. Gen Y has grown up in a connected world that has changed how they interact with friends, family and the world around them. The needs to complete tasks that require access to a vehicle are being met by emerging transportation models such as car-and-ride-sharing, and improved public transportation. These multimodal systems are shifting preferences to vehicle access in contrast to vehicle ownership.

Mobility sharing trend is identified as a dependent variable in the study.

9.2 Designed framework and scenarios to analyze the economical impact of different technology adoptions

There are a variety of possible technology adoption pathways in the P2S transition due to changing dynamics in both technology and the marketplace. The framework serves to capture the tendencies of pathways for further quantifying studies.

9.2.1 Resource-Demand view of mobility market and the framework for the P2S Transition

Resource-demand view helps understand the mobility marketplace due to the capability of recombining resources to offer different forms of services. In the P2S transition, innovative technologies are resources. Consumer demand (purchasing preference) is another important factor when designing a framework for the mobility service marketplace. Therefore, a resource-demand view of urban mobility service marketplace is described in Figure28.

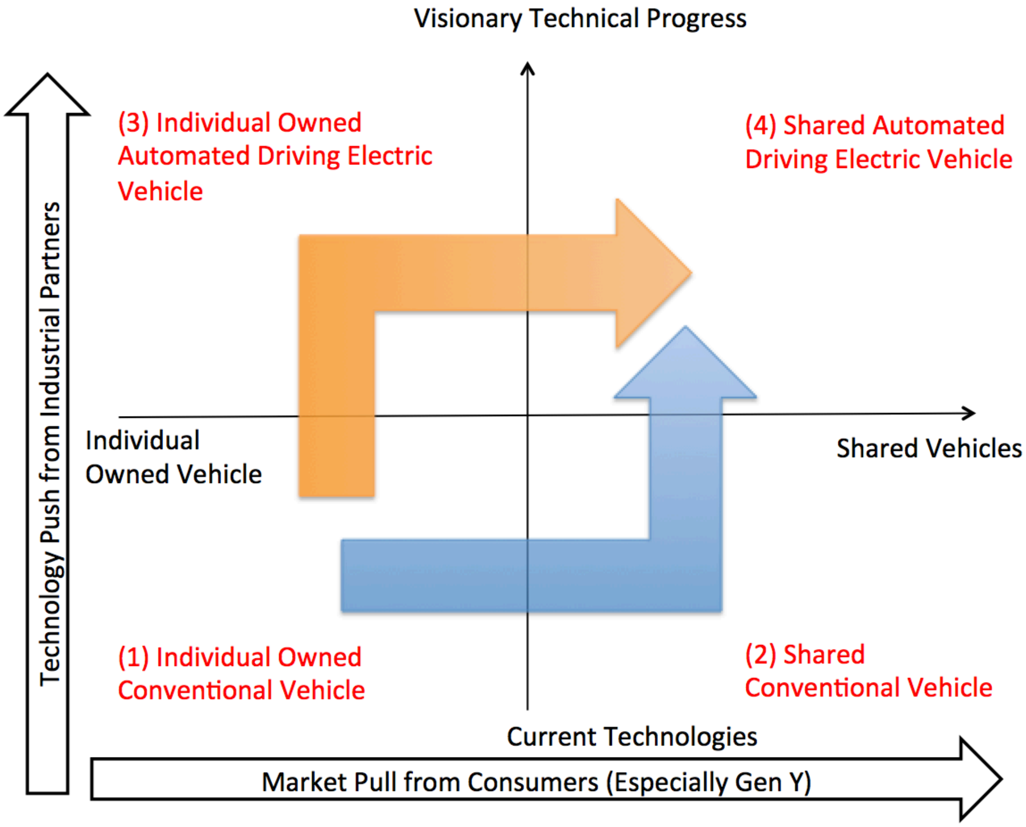


Figure 56: Framework to capture technology adoption pathways in the marketplace

9.2.2 Scenarios design

The scenario design serves the purpose of quantifying externalities in adoption pathways in mobility service transition.

Table 116: Designed scenarios

Urban Mobility Scenarios Study				
	ICE Vehicles	Electric Vehicles	Automated Driving Vehicles	Automated Driving Electric Vehicles
Individual Owned Fleet	Baseline Scenario **(1)**	Individual Owned EV Scenario **(2)**	Individual Owned AV Scenario **(3)**	Individual Owned EV+AV Scenario **(6)**
Mobility Sharing	Shared ICE Scenario **(4)**	Shared EV Fleet Scenario **(5)**	Shared AV Scenario	Shared EV+AV Scenario (Visionary Scenario) **(7)**

* Scenario 1 is the baseline scenario – transportation externalities in 2013 urban areas in the United States.

* Scenario 2, 3, 4 are single-technology integration scenarios. One dependent variable out of the chosen ones is integrated into the study.

* Scenario 5 and 6 are double-technology integration scenarios. Two dependent variables out of chosen ones are integrated into the study.

* Scenario 7 is the visionary scenario; all dependent variables are integrated in the study.

* Shared AV scenario is not analyzed in the research due to data availability.

9.3 Externality – the quantified leading indicator for technology adoption in mobility service sector

9.3.1 Internal cost and the tragedy of the commons

Internal costs refer to the direct monetized costs (planning, management, purchasing, maintenance, disposal) for a person or an entity undertaking an activity[77]. The most common term to describe the amount of money we exchange when buy or sell goods.

At this point, people are under the impression that economists believe markets always result in efficient outcomes, and stay balance – with total surplus maximized when market operates without interference from other institutions [78]. If this statement were true, there would be no efficient role for non-market institutions, especially government. The only justification would lie in concerns about the distribution of surpluses. However, the tragedy of the commons phenomenon has proved that deadweight losses occur to non-decision makers in the supply-demand process.

Before get to the predictions of future market and technology adoption tends in certain industry, we need to first evaluate a set of conditions that lead to deadweight losses in the absences of instrumental institutions – even when markets are perfectly competitive. The conditions are called externalities.

9.3.2 Externality – the quantified leading indicator for disruptive innovation adoptions

Externalities arise when decisions of some parties in the market have a direct impact on others in ways that are not captured by prices. An externality is a discrepancy between social costs and private costs [79]. Therefore, externalities are a type of market failure. When an externality exists, the prices in a market do not reflect the true marginal costs or marginal benefits associated with the goods and services traded in the market[80]. In the presence of externalities, free market may fail to result in the best allocation of resources. In the transport sector, the externalities of traffic congestion, human health impact and air pollution have caused serious issues more than just inefficient market outcomes.

Previous researches in the transportation externality have successfully quantified the full set of external costs of certain transport mode under different road conditions, but fail to establish the connection between externality and technology adoption. In other words, previous researches focus on present impacts, rather than possible changes in the future by adopting new technologies.

Table 117: External cost categories and the causes of changes

	Congestion Cost	**Health Cost**	**Climate Change Cost**
Increased External Cost	Indicates increased total user value loss due to traffic congestion, could be caused by increased total VMT traveled, decreased traffic efficiency, or a combination of both.	Indicates increased user and social value loss due to increased total VMT travels or lack of alternative-energy adoption.	Indicates increased user and social value loss due to increased total VMT travels or lack of alternative-energy adoption.
Decreased External Cost	Indicates decreased total user value loss due to traffic congestion, could be caused by	Indicates decreased user and social value loss due to decreased creased total VMT	Indicates decreased user and social value loss due to decreased creased total VMT

	decreased total VMT traveled, increased traffic efficiency, or a combination of both.	travels or alternative-energy adoption.	travels or alternative-energy adoption.

The author believes that externality can be used as a leading indicator for disruptive technology adoption in Product-to-Service Transition in the automotive industry. The changes of externalities among scenarios indicate the possible economic outcomes by adopting different sets of technologies. Understanding the potential economic loss or gain at a mass-adoption level is the key to predict the technology adoption progress, consumer behavior shift, and regulation-making process in the mobility service marketplace.

9.4 Analytical results and conclusions - comparison of single technology adoption scenarios

Scenarios with single technology integration will be evaluated in this sub-chapter. The following questions will be addressed in each scenario analysis:

- Will the integration of certain technology increase or decrease the total external cost? by how much?
- Will the integration of certain technology increase or decrease each external cost category? Why?
- What are the observations?

9.4.1 Scenario 1 – Baseline scenario

The external costs in traffic congestion, air pollution and climate change are calculated in baseline scenario based on available open traffic data in 2013. Only light-duty vehicles (passenger vehicles) are considered in the research for comparison purpose due to data availability. The external costs of urban travel that are caused by heavy-duty vehicles were calculated and analyzed only in Chapter 4.

Table 118: Quantified transport externalities in baseline scenario

Baseline scenario	
Cost category	External cost [Billion dollars]
Congestion cost	185.59
Human health impact	36.70
Climate change	30.32
Total cost	252.61

9.4.2 Scenario 2 – Electric Vehicle adoption scenario

Electric vehicle technology is integrated into the baseline scenario at different penetration rates. Electric powered vehicles have relatively higher fuel-efficiency when compared to gasoline-powered vehicles. Electric vehicle emits no tailpipe pollutants in urban travel.

Table 119: Evaluated externalities in EV adoption scenario

Cost Category	Penetration Rate				
	0%	25%	50%	75%	100%
Con. Cost	185.59	185.59	185.59	185.59	185.59
	0%	0%	0%	0%	0%
HH Cost	36.70	27.53	18.35	9.18	0.00

	0.00%	-25.00%	-50.01%	-74.99%	-100.00%
Cli. Cost	30.32	22.74	15.16	7.58	0.00
	0.00%	-24.99%	-50.00%	-75.00%	-100.00%
Total Cost	252.61	235.86	219.10	202.35	185.59
	0.00%	-6.63%	-13.27%	-19.90%	-26.53%

* Note that the decreased cost equals increased saving in the research

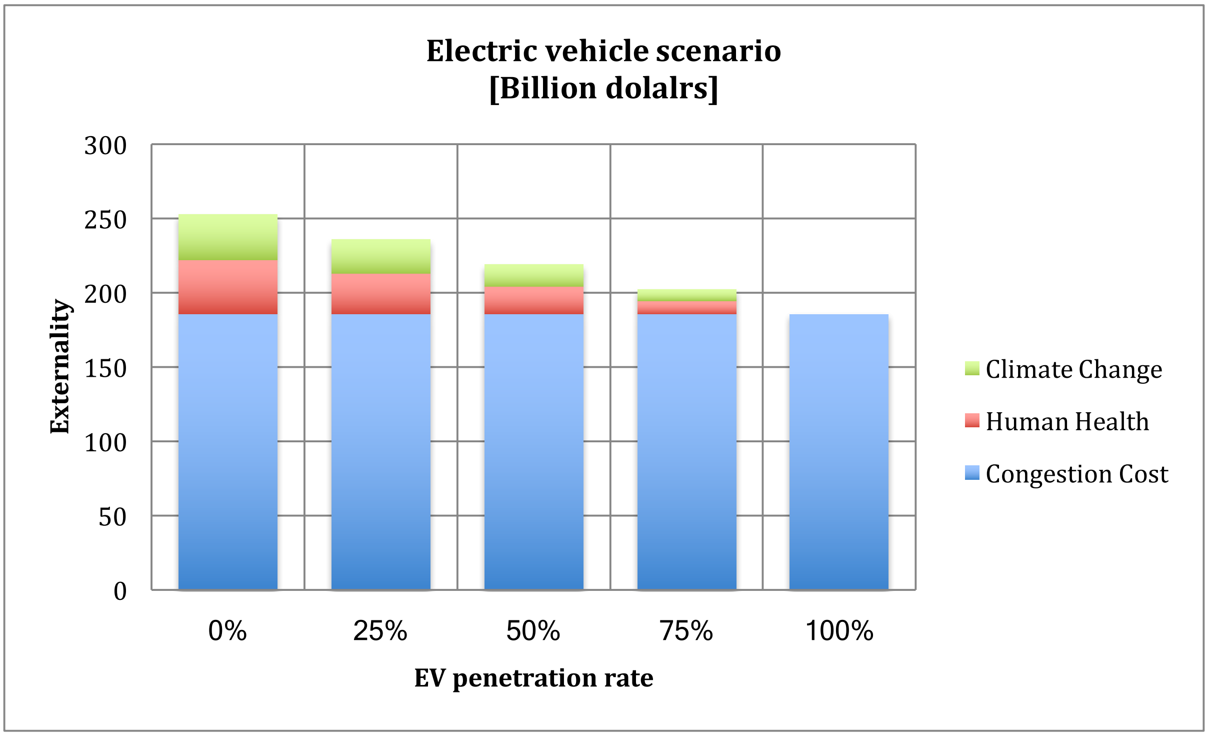


Figure 57: Evaluated externalities in EV scenario

Conclusions:

- The integration of electric vehicle technology at different penetration rates cause a decreased total external cost. The more electric vehicles in the traffic, the less total external cost. When 100% of vehicles in urban traffic are powered by electricity, the total external costs are reduced to 185.59 billion dollars - 73.47% of the baseline scenario.
- The integration of EV at any penetration rate does not generate differences in in traffic congestion cost. However, when the adoption at 100% rate, the

external costs of the human health and climate change are eliminated due to zero tailpipe pollutions.

- The adoption of electric vehicle technology effectively diminished the cost of health and environmental impacts, but does not affect congestion cost at all. The congestion cost is the largest cost among all current urban transport externalities. Therefore, the author suggests combining the adoption of EV technology with other technologies that are capable of improving traffic efficiency to release congesting cost.

9.4.3 Scenario 3 - Mobility sharing

Mobility sharing increases traffic efficiency and reduces unnecessary external costs. In 2013, the average vehicle occupancy rate in urban traffic is 1.6. Different vehicle occupancy rates (VOR) are integrated in Scenario 3 to seek potential impacts on urban transport externality.

Table 120: Evaluated externalities in mobility-sharing scenario

Cost Category	Vehicle Occupancy Rate				
	1.6	2	3	4	5
Con. Cost	185.59	43.53	3.12	0.48	0.09
	0%	-76.55%	-98.32%	-99.74%	-99.95%
HH Cost	36.70	29.36	19.58	14.68	11.75
	0.00%	-20.00%	-46.67%	-60.00%	-68.00%
Cli. Cost	30.32	24.25	16.16	12.13	9.70
	0.00%	-20.00%	-46.67%	-60.00%	-68.00%
Total Cost	252.61	97.15	38.86	27.29	21.54
	0.00%	-61.54%	-84.62%	-89.20%	-91.47%

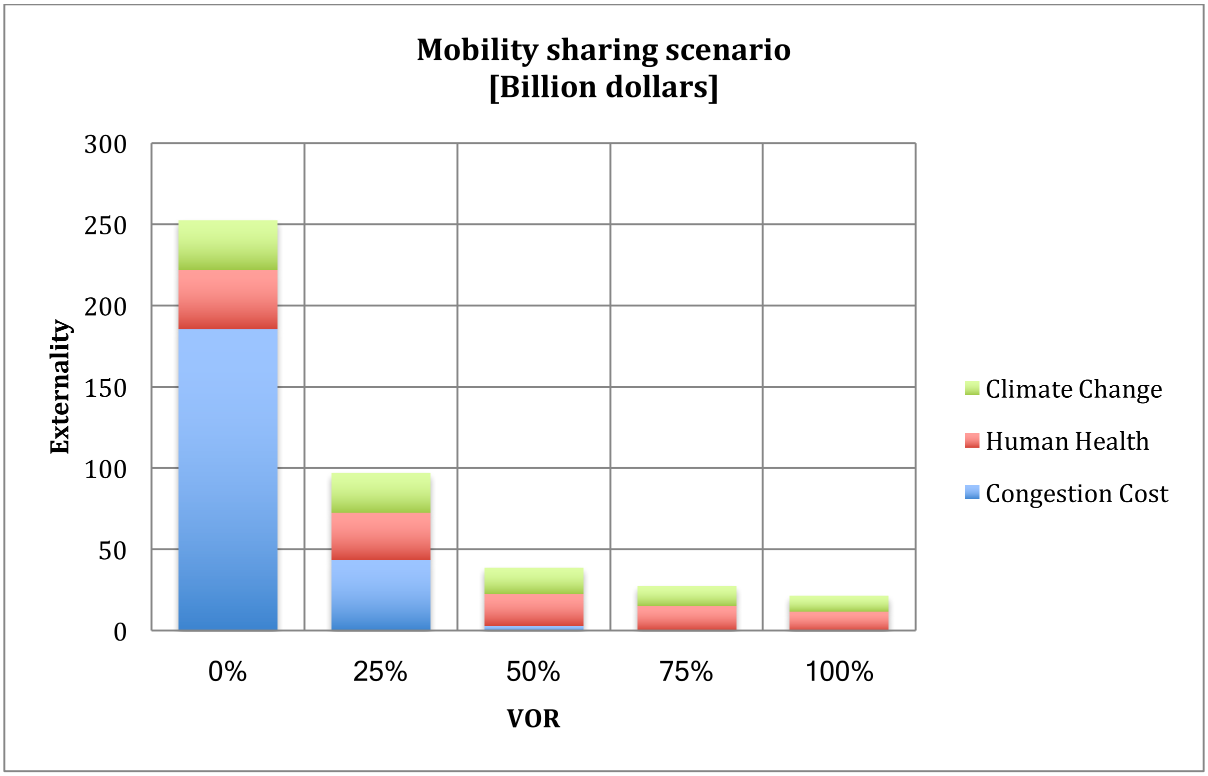


Figure 58: Evaluated externalities in mobility-sharing scenario

Conclusions:

- The integration of mobility sharing at different VOR rates causes a significantly decreased total external cost. The more occupants per vehicle, the less externality. When vehicles in urban traffic with full capacity (5 occupants include driver), the total external costs are reduced to 21.54 billion dollars – 8.53% of the baseline scenario.
- The integration of mobility sharing diminishes external costs in all cost categories due to the decreased vehicle-miles traveled. The most significant cost change happens when the author increased the VOR rate from 1.6 (baseline) to 2.
- The adoption of mobility sharing effectively eliminated the external cost of traffic congestion. No congestions occur when average vehicle occupancy

rate reaches three; urban traffic flows freely due to the decreased numbers of vehicle per mile per lane.

- The externals costs of human health and climate change will not be prevented by adoption mobility sharing only. The author suggests combining the adoption of mobility sharing with alternative fuel technology to address the human health and climate change costs.

9.4.4 Scenario 4 – Automated-driving technology

Automated-driving technology is integrated into the baseline scenario at different penetration rates. An automated-driving system is a complex combination of various components that can be defined as systems where perception, decision-making, and operation of the automobile are performed by electronics and machinery instead of human drive. Previous studies have indicated that the adoption of automated-driving system can increase traffic efficiency and lower congestion.

A number of complex factors will affect changes to travel behavior patterns, resulting in an increase in total vehicle-miles traveled (VMT) when adopting automated-driving technologies. The positive impacts on flow stability and capacity are achieved only when fleet penetration rate of vehicles with automated-driving technology exceeds 40%.

Table 121: Evaluated externalities in automated-driving scenario

Cost Category	Automated-driving Technology Penetration Rate				
	0%	25%	50%	75%	100%
Con. Cost	185.59	194.87	94.65	23.95	5.28
	0%	+5.00%	-49.00%	-87.10%	-97.16%
HH Cost	36.70	38.53	40.37	44.05	47.72
	0.00%	+5.00%	+10.00%	+20.00%	+30.00%
Cli. Cost	30.32	31.83	33.35	36.38	39.41
	0.00%	+5.00%	+10.00%	+20.00%	+30.00%
Total Cost	252.61	265.24	168.37	104.37	92.40
	0.00%	+5.00%	-33.35%	-58.68%	-63.42%

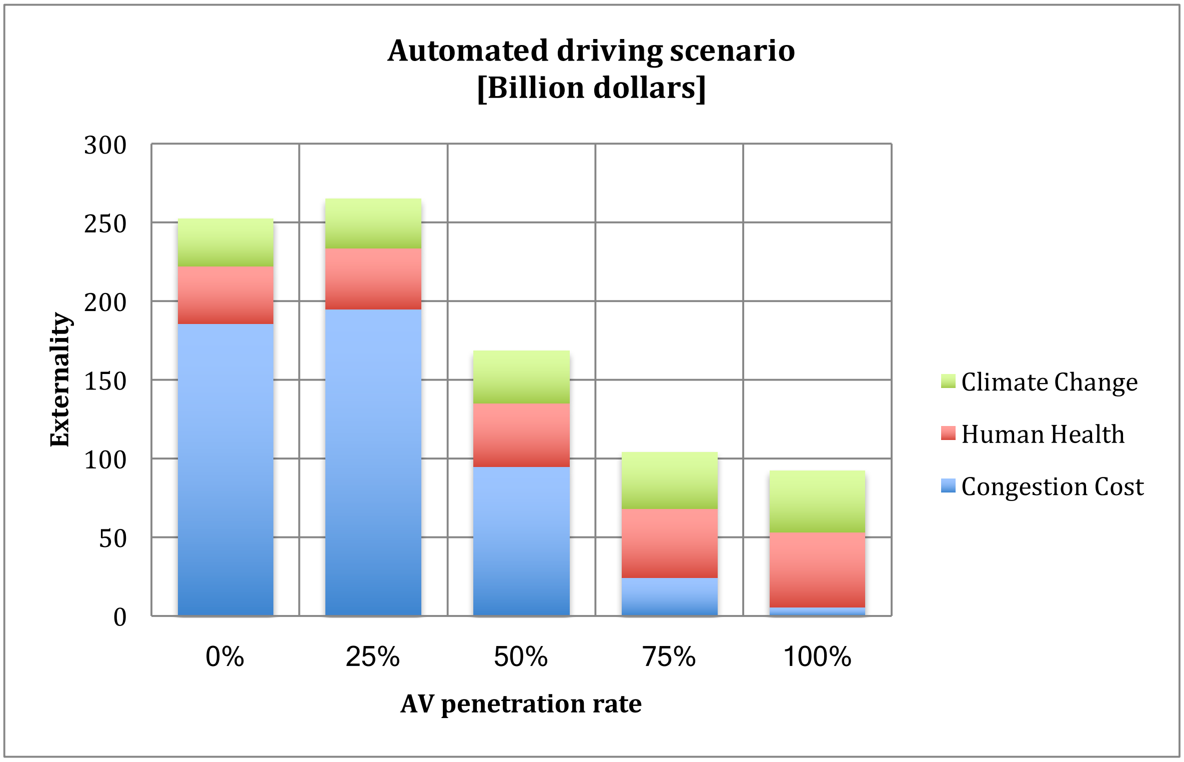


Figure 59: Evaluated externalities in automated-driving scenario

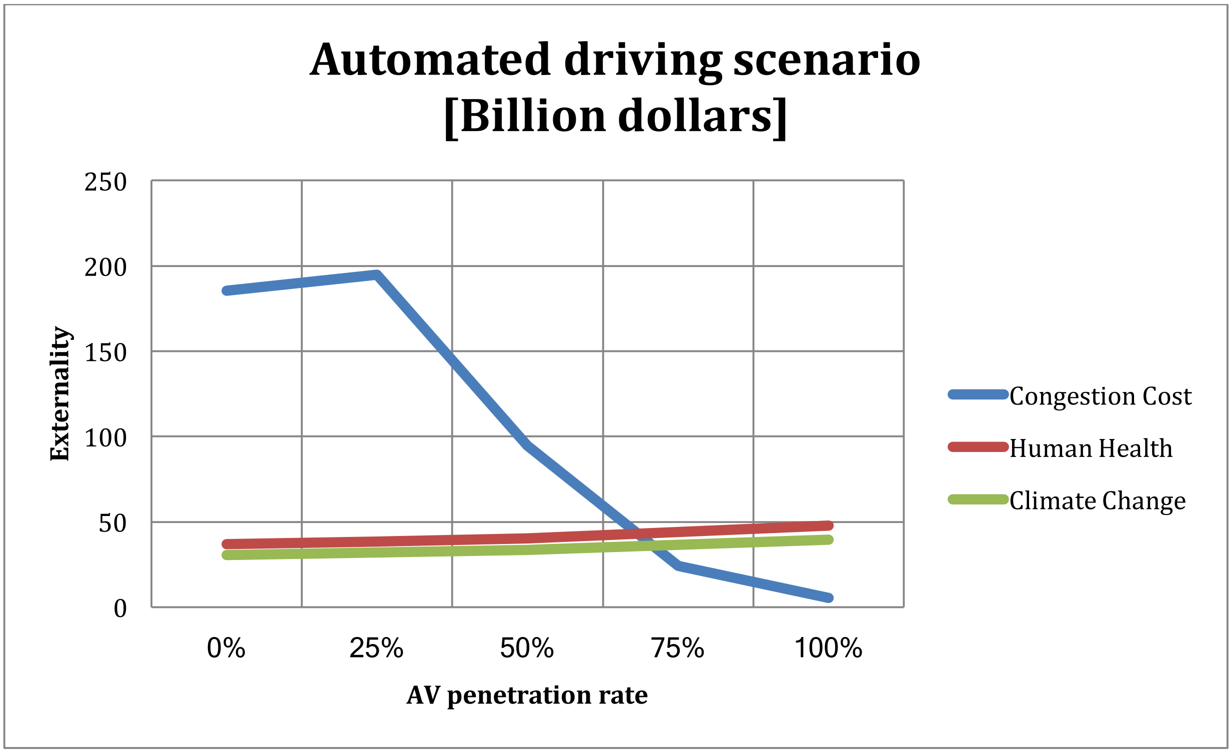


Figure 60: Comparison of different external costs in automated-driving scenario

Conclusions:

- The integration of automated-driving at 25% penetration rate increases the total external cost. When the adoption of automated-driving system in traffic reaches and exceeds 40%, the total external cost drops down significantly. The abnormal cost increase at 25% penetration rate is caused by the total increased VMT and maintained unit cost in all categories.
- The integration of automated-driving technology causes increased total VMT, and improved traffic efficiency (only when the penetration rate exceeds 40%). The integration at any penetration rates introduces more external cost (linear) in human health and climate change when compare to baseline scenario.

- The adoption of automated-driving technology impacts on traffic congestion positively only when the penetration rate exceeds 40%. The related congestion externality starts to decrease at 40% penetration rate and can be eliminated at 100%.
- The adoption of automated-driving technology is more complicated than the other two technology integrations. When the adoption rate is below 40%, the total external cost increases in all categories, which indicates less efficient urban transport system. The author suggests combining the adoption of automated-driving with other technologies during the transition when the adoption rate is low.

9.5 Discussion of double and triple technology adoption scenarios

The purpose of this research is to evaluate external transportation costs as indicators during technology transitions in the automotive industry. The previous scenarios have proven that the economic differences can be demonstrated at different technology adoption rates.

The double or triple technology adoption scenarios are demonstrated in the research to provide insights on the possible impacts of adopting different sets of technologies in the P2S transition. The costs of all scenarios in the research are listed in Table below.

Table 122. Results of all scenarios

Scenarios	Technology	25%	50%	75%	100%

Single-technology adoption	EV	6.63%	13.27%	19.90%	26.33%
	Sharing	61.54%	84.62%	89.20%	91.47%
	AV	-5.55%	33.35%	58.68%	63.42%
Double-technology adoption	EV + AV	2.85%	48.56%	82.90%	97.91%
	EV + Sharing	67.53%	91.99%	97.27%	99.96%
Visionary scenario	EV + S +AV	65.90%	81.99%	95.44%	99.78%

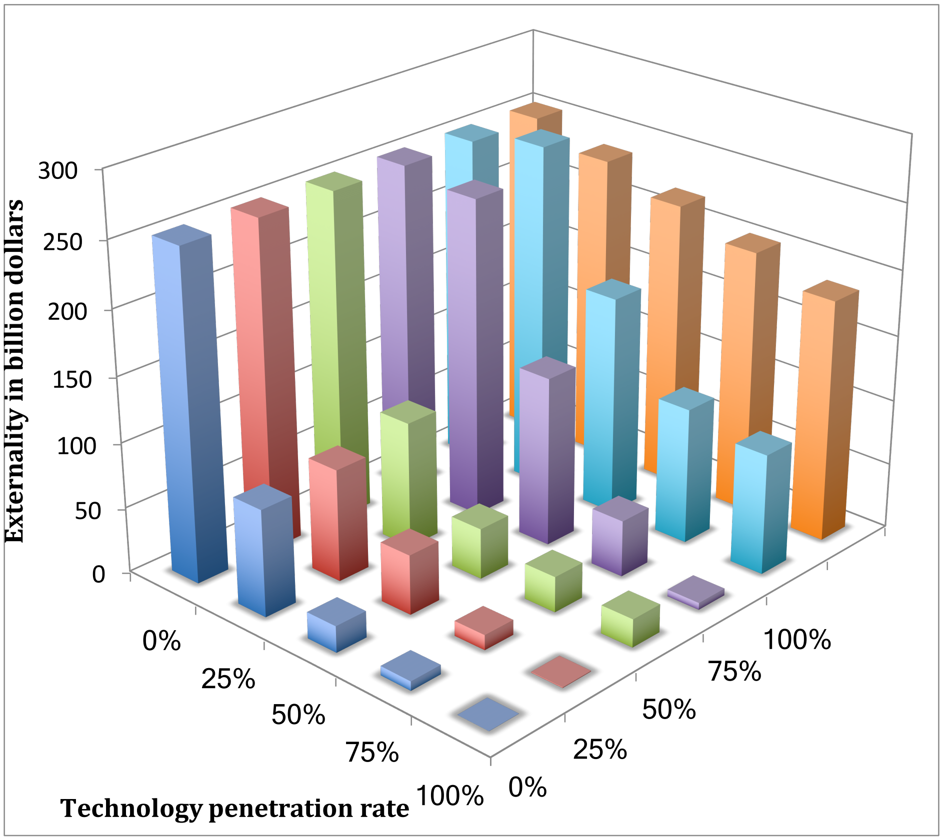


Figure 61. Results of all scenarios in the study

Conclusions for single-technology adoption scenarios

- The EV trend is an on-going adoption process. The increased penetration rate of EV in all vehicle types eliminates the external costs in human health impacts and climate change. However, the technology fails to address the enormous economic loss in congested traffic. Even if all vehicles were electric, the total transportation externality would still be 75.5% of the current value. This improvement is not significant when compared to other technology adoption scenarios.
- Sharing mobility services is the most efficient single technology to adopt in order to decrease the total external cost at all penetration rates. The most significant drop is observed when VOR increased to from the current average of 1.6 to 2 occupants per vehicle.
- Adopting automated driving technology at 25% penetration rate causes an increase in total externalities due to the increased VMT (see Chp. 6 for details). However, the traffic efficiency is not improved until 40% of vehicles in the traffic flow are equipped with CACC systems. Once the penetration rate of CACC driving systems reaches 50% or more, the total external cost is decreased due to less traffic congestion. However, the total VMT increases linearly with the adoption rates due to changes in consumer demands and behaviors.

Conclusions for double-technology adoption scenarios

Shared EV scenario

- If 25% of vehicles in traffic flow are electric vehicles with an average of 2 people per vehicle, the total externality is reduced to 32.5% of the current value. This is equivalent to the performance of 75% of vehicles in traffic being automated-driving vehicles.

- If 50% of vehicles in traffic flow are electric vehicles with an average of 3 people per vehicle per trip, the total externality is reduced to 8% of the current scenario. This is a better result than any single-technology adoption scenario at 100% adoption rate.
- The total externality is close to being eliminated when two or more technology adoption rates are beyond 75%.
- VMT is a dependent variable that changes with vehicle occupancy rates, impacting total external costs in all cost categories (details in Cha. 5)

Electric automated-driving vehicle scenario

- If 25% of vehicles in traffic flow are electric automated-driving vehicles, the total externality is only decreased by 2.85%.
- If 50% of vehicles in traffic flow are electric automated-driving vehicles, the total externality is reduced by almost 50%. The savings are significant, but less cost efficient when compared to the shared EV scenario.
- If 75% of vehicles in traffic flow are electric automated-driving vehicles, the total externality is reduced to almost 17% of the current scenario. The difference between double-technology adoption scenarios at 75% is insignificant.
- If 100% of vehicles in traffic flow are electric automated-driving vehicles, the total externality is eliminated

- The adoption of automated-driving technology impacts the total VMT due to the to travel demands and driving behaviors. The more vehicles in traffic are automated, the higher total VMT is expected. VMT is the dependent variable in the scenario that changes with the automated-driving adoption rate, also impacts on total external costs in all categories.

Triple technology adoption scenario

- If 25% vehicles in traffic are electric, automated and shared (VOR at 2), the total external cost is reduced by 65%. The performance is similar to the shared EV scenario at 25% penetration rate. The automated driving adoption offset the performance due to the increased total VMT.
- If 50% vehicles in traffic are electric, automated and shared (VOR at 3), the total external cost is reduced by 82%, less than the external cost in the shared EV scenario at 50% penetration rate. The automated driving adoption offsets the performance even more.
- When the all technology adoption rate are at or beyond 75%, the total externality can be eliminated.
- The author did not observe significant improvements when comparing the triple-technology adoption scenario to double technology adoption scenario (shared EV) or even single technology scenario (sharing). Sharing is the most efficient method of all technology adoptions.

9.6 Future work

This research has proven that externalities in congestion costs, human health impacts and climate change can be used as indicators during technology transitions in the automotive industry. Changes to externalities indicate social economic gains or losses from adopting new technologies.

This research demonstrated eight possible technology adoption scenarios in the P2S transition。 Electric vehicles, mobility sharing and automated driving technology are technology inputs (innovation push) that have revolutionized mobility services. Below are some suggestions for future research topics for doctoral candidates with business, policy or transportation economics focus.

9.6.1 Business

All we have learned about the innovation ecosystems in the mobility marketplaces are that they are open-architecture, and lead by variety of entities. A couple of examples were analyzed in Chapter 3 and Chapter 4. The forming of such an innovation ecosystem is still an on-going process. The author suggests that future researchers analyze the final innovation ecosystem when the mobility marketplace is mature, and learn what factors lead to success (transformation of current entity, or entrepreneurial business) in the marketplace.

9.6.2 Policy

The predictive economic results by adopting different sets of technologies are analyzed in the research. The author suggests future researchers observe policy trends in mobility sharing and automated driving technologies; validate the model by comparing gains from new policies to the expected gain from Sun's study

9.6.3 Transportation economics

Transportation externalities are calculated or simulated to demonstrate the current efficiency of different transportation modes in certain regions. Sun's research focuses on the changes of transportation externalities by technology adoption. The changes indicate possible economic outputs before implementation and provide insights on technology adoption when there are multiple possible adoption pathways. For future research topics in transportation economics:

- Apply external congestion cost models to different regions (especially in Asia), and analyze the comparative results of all regions.
- Build simulations that consider local travel patterns to monitor how pollutants in the transportation sector affect on human health.
- Build economic models to analyze the well-to-wheel emission impacts on human health and climate change.

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