Sustainability of Self-Driving Mobility: An Analysis of Carbon Emissions Between Autonomous Vehicles and Conventional Modes of Transportation

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Sustainability of Self-Driving Mobility: An Analysis of Carbon Emissions Between Autonomous Vehicles and Conventional Modes of Transportation

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Abstract

The primary contribution of this paper is to identify the potential variables through which vehicle automation may affect carbon emissions in the transportation sector, and compare modal shifts between conventional vehicles, public transportation, and pilot autonomous vehicles (AVs). AV programs that are rapidly emerging in cities, states, and nations across the globe mark the early stages of the next transportation revolution akin to the steam engine and assembly line. By safely allowing humans to take their hands off the steering wheel, autonomous technology could potential prevent 90% of car collisions every year, save hundreds of billions of dollars, and reduce carbon emissions. In order to examine how a modal shift to autonomous vehicles will impact carbon emissions specifically, I consolidated a literature review of AV factors that both help and hinder energy consumption and designed a carbon emissions model based on the United Nations (UN) Framework Convention on Climate Change.

I conducted various simulations to compare a modal shift away from public transit and toward AVs to address several research questions: Are AVs a viable mitigation strategy to reduce carbon emissions in the transportation sector? And will a modal shift to AV-based travel in urban areas produce more pounds of carbon per passenger mile than traditional modes of public transportation? Through these simulations, I examined two hypotheses. First, in the event that all public transportation passengers shift to traveling by AVs, carbon emissions in the transportation sector will increase compared to baseline

emissions. And second, modes of public transportation have a lower emissions rate (pounds of CO2 per passenger-mile) than AVs.

The scenarios modeled in this paper offer a glimpse into how AV technology might impact carbon emissions at a time when there are already early indicators of a transition to AVs. Based on these scenarios, it appears that Level 4 AVs would reduce emissions more than Level 3. Right-sizing, reduced engine performance, and platooning are AV factors that are available only in Level 4 vehicles and represent an 83.5% improvement in fuel economy. A modal shift to Level 4 AVs coupled with alternative fueled vehicles could substantially reduce carbon emissions. Specifically, emissions from conventional internal combustion engine cars were reduced by 50% as a result of a modal shift to hybrids, electrics, and CNG vehicles. However, a modal shift to public transportation coupled with a clean energy electrical grid reduced emissions by 91% compared to the baseline based on the model, 14% more than a complete modal shift to alternative energy Level 4 AVs.

Dedication

To my father, Dr. John F. McCarthy, III. Always has been, always will be, my hero.

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First, and foremost, thank you to my family for their bottomless love and endless support through the entirety of my program and this thesis. I could not of done it without you. You never stopped believing in me.

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Also, thank you to all the faculty and colleagues at Harvard Extension School for broadening my horizons and being thought-leaders in the field of education.

Last, but certainly not least, thank you to my wife. You lifted me when I was low and continue to push me to new heights. I am perpetually in awe of you and everything you do. OAO.

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Acronyms and Definition of Terms

AV: Autonomous Vehicles (also known as “driverless,” “self-driving,” “automated,” or “robocars”)

Bridj: Pop-up/On-demand public transportation company

CNG: Compressed Natural Gas

CAFE: Corporate Average Fuel Economy

Car-sharing: Programs in which cars are not privately owned but shared

Conventionals: Contemporary automobiles with internal combustion engines

DOT: US Department of Transportation

Eco-driving: Driving method to maximize energy efficiency

Engine Performance/Acceleration: De-emphasized engine performance to maximize energy efficiency

EPA: US Environmental Protection Agency

EV: Electric Vehicle

FTA: Federal Transit Administration

GHG: Greenhouse Gas

Google: The web-service company, specifically the self-driving car project (Waymo)

GPS: Global Positioning System

GREET: Greenhouse gases, Regulated Emissions, and Energy use in Transportation

HEV: Hybrid Electric Vehicle

HFC: Hydro fluorocarbons (air conditioning refrigerants)

Hypermiling: Maximizing the fuel economy of a vehicle

ICE: Internal Combustion Engine

Level 0: No-Automation. The driver is in complete and sole control of the primary vehicle controls – brake, steering, throttle, and motive power – at all times.

Level 1: Function-specific Automation. Automation at this level involves one or more specific control functions. Examples include electronic stability control or pre-charged brakes, where the vehicle automatically assists with braking to enable the driver to regain control of the vehicle or stop faster than possible by acting alone.

Level 2: Combined Function Automation. This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. An example of combined functions enabling a Level 2 system is adaptive cruise control in combination with lane centering.

Level 3: Limited Self-Driving Automation. Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. The Google car is an example of limited self-driving automation.

Level 4: Full Self-Driving Automation. The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles.

LIDAR: Light Detection and Ranging

MBTA (T): Massachusetts Bay Transit Association

MOVES: Motor Vehicle Emissions Simulator

MPG: Miles per Gallon (Fuel Economy)

NHTSA: US National Highway Traffic Safety Administration

New/Expanded User Groups: User population able to drive under Level 4 automation

New Feature/Content: Additional car features under Level 4 automation

NSPS: New Source Performance Standards

Paratransit: Mode of public transportation service for disabled persons

Platooning: Vehicle trains utilizing aerodynamics to improve energy efficiency

PTI: Planning Time Index

The RIDE: MBTA’s paratransit service

Right-sizing: Method of pairing passengers with the appropriate vehicle to maximize energy efficiency

Triple-Bottom-Line: Planet, people, profits with regards to sustainability

Uber: Ride-hailing company, specifically the autonomous car project

V2I: Vehicle to Infrastructure communication

V2V: Vehicle-to-Vehicle communication

VII: Vehicle Infrastructure Integration

VMT: Vehicle Miles Traveled

WTT: Well-to-Tank

WTW: Well-to-Wheel

Chapter I

Introduction

Across the globe, the automobile is a common, popular and sometimes essential mode of transportation; however, the US transit infrastructure is unique to the degree in which it is auto-dependent. Although the US represents less than 5% of the world's population, over a fifth of the total number vehicles on the planet are operated in the US (NASEM, 2016). Framed in other terms, in the US there is one car for every 2.2 people as opposed to global average where there is one car for every 7.6 people, Americans spend 4.8 billion hours a year driving, and US vehicles consume ¼ of the world's petroleum supply (World Bank, 2016; RITA, 2013; CAR, 2012).

The transportation industry is on the cusp of its next revolution, akin to the steam engine and the assembly line. Cities, states, and countries alike will be faced with a question of how they want their transportation networks to evolve as part of this revolution. What mode of transit best serves the public? Where should tax money be invested? How will the planet be impacted by these decisions?

Self-driving cars, or autonomous vehicles (AVs), that are able to safely and efficiently perform all driving functions with little to no input from a human driver have many visible advantages but, AVs could prove to be a hindrance to the planet as well. For example, AVs may continue to be powered by the finite supply of fossil fuels in the world. Currently the number of vehicles on the road is limited by the number of available drivers; however with autonomous cars, there is no limit to the number of vehicles on the road and as a result, the number of vehicle's on the road could increase with a commensurate in crease in emissions. Furthermore, the ease and convenience of autonomous cars could decrease the use of public transit, biking, and walking. These are some of the factors that could adversely impact the cumulative sustainability of AV technology.

Research Significance and Objectives

The rapid advances in AVs are poised to dramatically reshape many currently accepted societal practices and assumptions associated with transportation. Already there are early indicators that a modal shift to AVs is underway in the US. Semi-autonomous vehicle technology, such as adaptive cruise control, forward collision mitigation with brake support, blind spot information system, driver alert, cross traffic alert, and lane keeping aids have been available in 2013 vehicles that cost as little as $30,000 (Bishop, 2013). More recently, two counties in Florida have opted to subsidize Uber fares for passengers instead of extending public transportation routes (Shared-Use Mobility Center, 2016). This transition period presents an incredible opportunity to consider the various options that are available and help influence specific choices through education and economic incentives so as to maximize the benefits of this "transportation revolution."

This research investigates the nuances of a potential shift to AVs. In particular, I am interested in assessing whether AV technology is truly more sustainable than conventional modes (and fuels) of transportation. If AVs can reduce carbon emissions in the transportation sector, I aim to identify the tipping point of such a modal shift.

Background

In many ways, the futures of the US and the car industry as a whole are closely intertwined. Take for example the fact that 88% of the American workforce commutes via automobile and the US auto industry not only employs 1.7 million Americans but also pays $500 billion in compensation every year (CARS, 2012). For nearly a century, the automobile has been the standard by which Americans measure convenient and reliable transportation. Any substantial shift away from the automobile will have lasting repercussions for the US society, economy, and natural environment.

On the other hand, 1.3 million people die in car accidents annually, around the world (ASIRT, 2002-2016). It is a leading cause of death in America and is the number one cause of death for Americans between the ages of eight through 24 (NHTSA, 2015). On average, one American dies every 12 minutes from a motor vehicle accident (NHTSA, 2015).

From an economic standpoint, the millions of collisions in America also take a financial toll, estimated to cost $230.6 billion every year. This statistic includes economic factors such as lost workplace and household productivity, property damage, medical costs, and travel delay costs (Blincoe, Miller, Zaloshnja & Lawrence, 2015). As a result, the cost of motor vehicle crashes in the U.S. has reached 2.3 percent of the U.S. Gross Domestic Product (GDP) (Blincoe et al., 2015).

And finally, in terms of the natural environment, there are 1.1 billion cars running on fossil fuels operating worldwide (Navigant, 2015). Beyond carbon dioxide (CO2), vehicles also emit particulate matter, carbon monoxide, unburned hydrocarbons, and oxides of nitrogen– all of which reduce air quality, adversely impact health, and generate smog (NASEM, 2016). Over a quarter of the energy used in the US is for transportation purposes, 81% of which is consumed by cars (EIA, 2016).

The modern definition of sustainability is a triple-bottom-line of people, planet, and profit. To evaluate what is sustainable and what is not, one must quantify the impact on immediate stakeholders and society as a whole, measure the environmental effects, and calculate the financial implications. If there are benefits at the societal level, the environmental level, and the economic level then an activity can be properly deemed as "sustainable."

Public transit networks in America offer a good example of a sustainable triple-bottom-line. In terms of people, public transportation systems are designed for typically underserved populations. For example, nearly 90% of all transit stations in the US are handicap-accessible (RITA, 2016). And for the nearly one in ten households that cannot afford to own a car, public transportation is the only means by which these families can travel. Public transit systems also offer discounted fares for low-income residents, students, senior citizens, and people with disabilities (NRN, 2015). With regards to public safety, public transportation accounts for less than 1% of the fatalities and injuries that occur in the transportation sector (RITA, 2016). From an environmental standpoint, the combined reduction of cars, automobile congestion, and vehicle miles attributed to passengers riding public transit equals 37 million metric tons of CO2 emissions (APTA, 2015). What's more, public transportation systems make up only 0.6% of the total energy consumed in the transportation sector (RITA, 2016). Economically, it has been found that on average for every $1 billion spent by the public transportation sector, 21,700 permanent jobs are created, $3.0 billion is generated by sales, $1.8 billion in gross domestic product, $1.2 billion in labor income, and $429 million in tax revenue (APTA, 2015).

In comparison, given the aforementioned facts about the automobile industry, the future of motorized vehicles appears to have unsustainable triple-bottom-line. As the world population increases, so will the number of vehicles, the number of accidents, the energy demand, and in turn, the impact on the environment. Some reports indicate that the number of vehicles in the world could nearly double to 2 billion by 2035 (Navigant, 2015). However a confluence of emerging technologies, embodied by the autonomous car, does offer a potential remedy for an otherwise unsustainable relationship that has developed with the popularity and pervasiveness of automobiles around the world.

It has been determined that human error accounts for over 90% of automobile collisions in the US (Bainwol, 2013). Autonomous vehicle technology could dramatically reduce the number of collisions, and in turn the number of automobile injuries and fatalities on the road by safely allowing humans to take their hands off the steering wheel. Preventing 90% of car crashes every year would mean saving 34,470 lives and $207.54 billion (NHTSA, 2006; Blincoe et al., 2015).

Within the people, profits, planet framework, the potential health and financial benefits of a shift to autonomous vehicles (AVs) is compelling. The environmental impact of AVs however requires further evaluation. Essentially, the AV claim is this: Today’s car drives 12,500 miles per year on average and emits 464 pounds of CO2 per year; tomorrow’s vehicle, equipped with autonomous technology, will drive the same distance and pollute 80% less due to a wide range of energy gains (SARTRE, n.d.;

TAMU, 2013; BEES, 2013). The question that arises, and that my research aims to address, is, based on this claim, is it less polluting to make a modal shift to AVs or to public transportation?

Sustainability in the Transportation Sector

Any analysis of carbon emissions involves assessing how much and what types of greenhouse gases (GHGs) are emitted. GHGs are gases that prevent heat from naturally escaping the Earth's atmosphere and in turn contribute to a worldwide greenhouse effect (EPA, Fast Facts, 2015). With regards to transportation, fuel sources like gasoline, diesel, biodiesel, and natural gas produce various GHGs as a byproduct. Gases emitted from these energy sources, such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N20), all qualify as GHGs because they are heat-trapping and can remain in the atmosphere for a century or more (NASEM, 2016).

The unregulated release of GHGs disrupts the natural cycles that govern the planet and poses many risks to all forms of life (NASA, 2005). 35.6 million kilotons of CO2 are emitted across the world annually and cause irreversible damage to the Earth's climate (EPA, n.d.). The US accounts for 15% of the world's GHG emissions and is the second largest polluter following only China (EDGAR, 2014). Within the US, over a quarter of annual emissions are attributed to transportation, the vast majority of which, 84%, comes from road vehicles (EPA, 2015).

State of the Transportation Sector

Of the 260 million motor vehicles in the US, 99% are powered by internal combustion engines (ICE) (AFDC, 2015). The primary fuel sources for ICE vehicles are gasoline, diesel or compressed natural gas (CNG). Beyond the ICE, there are currently two major alternative automobile engines that comprise the remaining 1% of vehicles in the US: Hybrid-Electric Vehicles (HEVs) and Electric Vehicles (EVs).

HEVs essentially have two motors onboard, one is a conventional internal combustion engine powered by fossil fuels and the other is an electric motor with a battery that captures kinetic energy generated from braking (regenerative braking). The HEV alternates between these two motors as needed in order to power the vehicle. EVs on the other hand use only batteries to power the vehicle and typically need to be plugged into a source of electricity in order to charge the batteries (UCS, n.d.).

Other than automobiles, there are several other modes of transportation when assessing carbon emissions from passenger travel. Bicycling and walking are two that require very little energy and thereby have negligible carbon footprints; whereas subways (underground or elevated) and trollies (streetcars) require a substantial amount of energy and are hard-wired directly to a city’s electrical grid. Heavy railroad trains, such as commuter rails, which operate outside of city limits, are not typically powered by electricity but are instead driven by diesel/diesel electric-powered locomotives.

City buses can be powered by internal combustion engines as well as electric-hybrid engines. Predominantly, bus engines use diesel fuel and a fraction use bio-diesel, a cleaner-burning fuel manufactured from vegetable oils, animal fats, or recycled restaurant grease (AFDC, 2015). Trolley buses are a different mode of transportation in which standard buses are tethered to and powered by the electric grid. And some transit systems adjacent to large bodies of water utilize diesel-powered ferryboats as yet another mode of transportation. In addition to fixed-route transit (bus, subway, trolley) public transportation systems also have a fleet of paratransit vehicles dedicated to passengers with physical, cognitive, or mental disabilities in accordance with the Americans with Disabilities Act (ADA) (RITA, 2016). The fleet of paratransit vehicles is comprised of small buses and specialized personal vehicles, all of which primarily run on gasoline (MBTA, 2016).

For example, the Massachusetts Bay Transit Authority (MBTA) manages the city of Boston's public transit network. The MBTA's transportation system (also known as the T) consists of subways, trolleys, commuter rails, a variety of buses, ferryboats, and paratransit (also known as the RIDE). These modes of public transit operate in 175 cities and towns in Massachusetts and span 3,244 square miles (MBTA, 2011). Of the 6.5 million citizens within Massachusetts, 5 million have access to the T (MBTA, 2011). All told, the MBTA's transportation portfolio provides approximately 6.2 million trips to 1.35 million residents, students, commuters, and tourists annually (Mitchell, 2010; MBTA, 2011). It costs over $1.16 billion and requires over 435,000 megawatt-hours of electricity to operate (Davey, 2011; Moskowitz, 2011).

It is also of note that there are new public transit technologies on the rise, in particular the concept of pop-up public transportation. Boston and Kansas City are two test beds for a new company called Bridj, which uses complex algorithms to create efficient and flexible bus routes based on real-time passenger demand. Different than Uber, these fares are competitive with public transit. Furthermore, Bridj also claims that their routes are twice as fast than the same journey via public transit (Bridj, n.d.).

Systems like Bridj hold the potential to redefine public transportation networks and urban infrastructure as a whole.

Autonomous Vehicles (AVs)

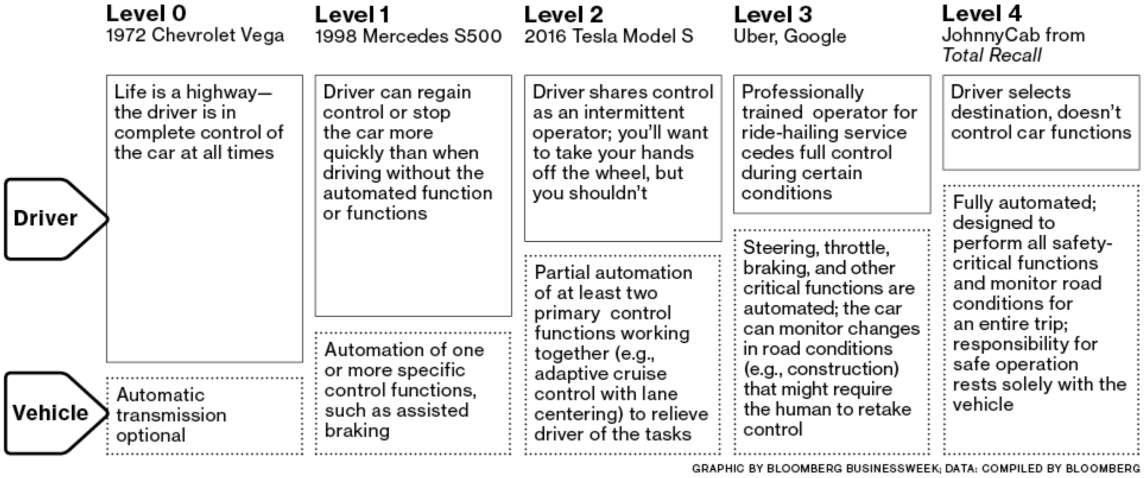
Another new and rapidly developing mode of transportation, and the focus of this thesis, is the autonomous vehicle (AV). AVs are essentially contemporary cars operated by computers with varying degrees of human input. These new automobiles are referred to be various terms, such as “driverless,” “self-driving,” “autonomous,” “automated,” and “robocars.” The National Highway and Traffic Safety Administration (NHTSA) outlines the five levels of vehicle autonomy as the industry currently understands them (Table 1):

- No-Automation (Level 0): The driver is in complete and sole control of the primary vehicle controls – brake, steering, throttle, and motive power – at all times.
- Function-specific Automation (Level 1): Automation at this level involves one or more specific control functions. Examples include electronic stability control or pre-charged brakes, where the vehicle automatically assists with braking to enable the driver to regain control of the vehicle or stop faster than possible by acting alone.
- Combined Function Automation (Level 2): This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. An example of combined functions enabling a Level 2 system is adaptive cruise control in combination with lane centering.
- Limited Self-Driving Automation (Level 3): Vehicles at this level of automation

enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. The Google car is an example of limited self-driving automation.

- Full Self-Driving Automation (Level 4): The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles.

Table 1. Level of vehicle autonomy (from NHTSA, 2016).



	Level 0 1972 Chevrolet Vega	**Level 1** 1998 Mercedes S500	**Level 2** 2016 Tesla Model S	**Level 3** Uber, Google	**Level 4** JohnnyCab from *Total Recall*
Driver	Life is a highway—the driver is in complete control of the car at all times	Driver can regain control or stop the car more quickly than when driving without the automated function or functions	Driver shares control as an intermittent operator; you'll want to take your hands off the wheel, but you shouldn't	Professionally trained operator for ride-hailing service cedes full control during certain conditions	Driver selects destination, doesn't control car functions
Vehicle	Automatic transmission optional	Automation of one or more specific control functions, such as assisted braking	Partial automation of at least two primary control functions working together (e.g., adaptive cruise control with lane centering) to relieve driver of the tasks	Steering, throttle, braking, and other critical functions are automated; the car can monitor changes in road conditions (e.g., construction) that might require the human to retake control	Fully automated; designed to perform all safety-critical functions and monitor road conditions for an entire trip; responsibility for safe operation rests solely with the vehicle

GRAPHIC BY BLOOMBERG BUSINESSWEEK; DATA: COMPILED BY BLOOMBERG

AVs are still in the experimental phase, however, already many cities, states, and nations allow these vehicles to drive on public roads. In the US for example, AVs can be seen on the roads of eight states, Nevada, California, Florida, Michigan, and Tennessee, Louisiana, Utah, and North Dakota, as well as the District of Columbia (Figure 1) (CIS, 2016). The United Kingdom, France, Germany, Spain and the Netherlands have also issued licenses for autonomous trials (Torbert & Herrschaft, 2013; MRG Oxford, 2013; Autonomous Labs, n.d.; SARTRE, n.d.).

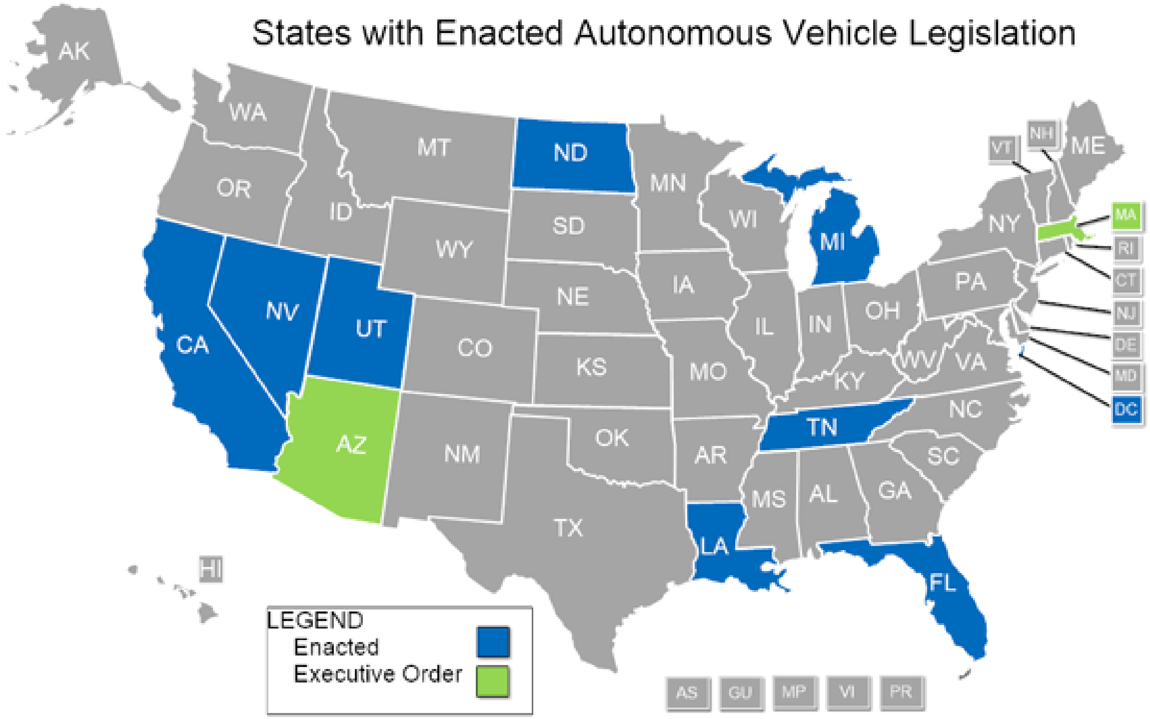


Figure 1. States with enacted autonomous vehicle legislation (from NCSL, 2016).

The rapid emergence of AVs can partially be attributed to the types of companies experimenting with autonomous technologies. Tesla Motors, Uber, Google, Toyota, BMW, Volvo, Nissan, Ford, General Motors, Mercedes-Benz, Audi, and Baidu represent the industry leaders planning to have fully autonomous vehicles available to the public by 2020 (Muoio, 2016). Google has been testing Level 3 self-driving cars on public streets since 2012 and is considered the leader of leaders within the industry. A close second to

Google is Tesla Motors, who introduced Autopilot technology, a Level 2 automation system that can be enabled only on highways. Google's and Tesla's autonomous vehicles have logged 1.5 and 47 million miles respectively as of early 2016 (Lambert, 2016). Uber, a relative newcomer to the field, has incorporated AVs into its taxi fleet in Pittsburgh and as a result has become the first company to bring a self-driving car-sharing service to market. Therefore Uber has "cross[ed] an important milestone that no automotive or technology company has yet achieved." (Chafkin, 2016).

Regardless of the corporation, AVs primarily employee the same three pieces of technology, to varying degrees, in order to remove the human driver from the equation. Light Detection and Ranging (LIDAR) is a laser system capable of generating precise, three-dimensional maps of the Earth and its surface characteristics (NOAA, 2015). In the case of AVs, LIDAR is used to map the roadway around the vehicle. The second technology is an advanced camera system equipped with radar to provide a 360-degree view around the car in all weather conditions (Tesla Motors, 2016). GPS is the third technology that serves as a locator and navigator (Ackerman, 2016). These three components can be seen functioning in AVs today. However, there is a fourth form of technology that has yet to be fully deployed, and as described in detail below, has the potential to dramatically affect the use of the automobile as a far safer and more efficient conveyor of commuters.

The Vehicle Infrastructure Integration (VII) Initiative, founded in 2005 by the US, is a coordinated effort between Federal and State transportation departments as well as automobile manufactures to deploy a communications system that will improve safety and efficiency in the nation's road transportation system (NHTSA, 2013). The vision of this initiative is to establish two-way communication not only between vehicles and a city's infrastructure (V2I) but also between vehicles (V2V). Traffic flows could improve dramatically with the addition of V2I and V2V technology.

Climate Change and the Transportation Sector

With the state of technology in the transportation sector in mind, it's crucial to review the ways in which technologies in contemporary cars, public transit, and AVs currently impact climate change. Each mode has a different set of factors that significantly change the rate at which carbon is emitted. Critical to my analysis is to evaluate the variables that could most significantly impact carbon emission in the transportation sector, in particular with regards to AVs.

As previously mentioned, 99% of the vehicles currently in the US are powered by ICEs and the different fuel sources for these engines will impact the vehicle's carbon emissions. Gasoline is the predominant car fuel for in the US. Alternative fuels include hybrid, all-electric, compressed natural gas (CNG), and fuel cell. These alternative fuels are far less common but they emit less GHGs than gasoline and diesel (Table 2) (EPA, 2005). The fuel type also drives a vehicle's fuel economy (its miles per gallon).

Another determining factor for emissions associated with conventional automobile travel is occupancy rate. The primary means of transportation for 85.6% of the US population is by car and the majority of those trips are a person driving alone (US Census, 2015 ACS 1-year estimates); 1.67 passengers is the average occupancy rate for any given type of trip (commute, errands, recreational, etc.) in the US (FHWA, 2011). The fewer passengers per vehicle, the more vehicles are required to transport those passengers, and the more vehicles, the higher the emissions released. Only 11% of Americans carpool to work. Put another way, on average 113.6 million people drive to and from work by themselves every day (US Census Bureau, 2016).

Table 2. Fuel overview of conventional automobiles (from EIA, 2016; EPA, 2005; Pike, 2012; DOE, n.d.).

Fuel Source	**Vehicles in the US (%)**	**Emissions Factor (g CO2/km)**	**Average Miles per Gallon of 4-Door Sedan**
Gasoline	94%	186.8	24.3
Diesel	1%	233	24
Hybrid	5%	100.1	44.4
Electric	0.13%	136*	115**
CNG	0.091%	110	31**
Fuel Cell	0.0001%	155	49
TOTAL	**100%**	**-**	**-**
*Upstream emissions **Gallon gasoline equivalent			

The various types of journeys people make via automobile contribute to the total number of miles driven every year and the more GHG is emitted. The average trip distance by car in the US is 9.7 miles. The average distance to work is slightly further at 11.8 miles (RITA, 2015). When all the miles of all the trips are added up, the US Population drives 4 trillion miles per year, an average of 14,500 miles per person (BTS, n.d.).

The final emissions factor to take under consideration in the realm of conventional cars is time the amount of time a car's engine is running, in other words, the trip time. Planning Time Index (PTI) is a measure of how much extra time is needed to arrive at a destination on time. Today cities have a 4.26 PTI when traveling by car, meaning that it takes more than 2 hours to travel a half-hour distance (TAMU, 2013). The longer the trip duration, the more fuel is consumed by the engine, and therefore more carbon is emitted. This additional time on the road equates to 2.4 billion gallons of fuel being consumed unnecessarily (TAMU, 2013).

In the realm of public transit, energy sources and ridership are the two main factors that contribute to carbon emissions. Public transit networks are the largest consumers of electricity in most cities, which means the source of that electricity plays a major role in determining the carbon footprint of a city's public transportation system. Power grid carbon emissions are a function of the fuels, power plants, transmission and distribution networks, and local regulations. The amount of carbon produced varies depending on the region of the US. A cleaner, renewable energy such as hydro-power may be readily available in some regions while a higher emitting fossil fuel like coal may be the abundant primary source in other areas. Electrical generation and transmission is also highly inefficient. Around 75% of energy is lost between the point it is generated and the point at which it is consumed (EIA, 2016). Authorized by the Clean Air Act, the Environmental Protection Agency (EPA) has implemented New Source Performance Standards (NSPS) that are intended to regulate power plant emissions at the federal level (EPA, 2016). However state regulations controlling the amount of pollutants a power plant can emit still vary greatly across the US and in turn different regions have markedly different carbon emissions (EIA, 2016). All of the electric networks in the US fall within 10 geographic regions and 26 sub-regions that use different resource mixes to generate power. Boston's electric grid falls under the NPCC New England sub-region, and the source of power in that region is a mix of coal, nuclear, hydroelectric, and waste-burning facilities (EPA, 2016).

As with private vehicles, modes of public transit utilize a variety of engine types and fuel sources. Depending on the engine type, public transit buses are powered by diesel fuel, electricity, and/or compressed natural gas (CNG) and on average emit 0.64 lbs. of CO2/passenger-mile (FTA, 2010). Light rail pollutes 0.36 lbs. CO2/passenger-mile however this varies depending on the region of the US and how the electricity is generated. Heavy or commuter rail trains use diesel-powered locomotives and produce 0.33 lbs. of CO2/passenger-mile. Ferryboats represent a major source of carbon emissions, averaging 3.1 lbs. of CO2/passenger-mile. These boats are generally steam or diesel powered and are considered difficult to compare to other modes of transit "as ferries often carry automobiles as well as passengers and often allow for a much shorter route across a body of water rather than a circuitous route by land" (FTA, 2010).

Just as occupancy impacts automobile emissions, so does ridership on public transit. Again, using Boston as an example, a single passenger commuting to work via public transit for one year prevents an average of 5,000 pounds of GHG emissions (Rasmussen, 2008). In Boston, over 24% of riders rely solely on the T for transportation (Patrick, 2011).

Variables Affecting AV Carbon Emissions

Shifting now from public transit to AVs, there are 16 major variables stemming from AV technology that could impact carbon emissions. They are as follows:

1. V2V and V2I –Vehicle to vehicle (V2V) communication and vehicle to infrastructure (V2I) communication are the two major systems that will increase the reliability of the US transportation network (CAR, 2012). Individual autonomous

vehicles are already on the road, but as more autonomous vehicles are introduced, there is the potential for massive data exchanges between vehicles and transit infrastructure networks. This communication network maximizes the potential energy savings in AV factors such as traffic flow, eco-driving, and travel speeds, thereby contributing to reducing carbon emissions.

2. Traffic Flow/Congestion –Computer automated infrastructure is able to coordinate vehicles at intersections, which could eliminate traffics lights and stop signs (CAR, 2012). V2I could also reroute cars around roadwork or when an influx of traffic enters the transportation grid during rush hour or after a major sports event (RITA, n.d.). Furthermore, vehicles could be given preference in such as way that emergency responders and school buses could be given higher priority and faster routes (RITA, n.d.). As vehicles and infrastructure begin to cooperate through V2V and V2I communication, the capacity of existing roads and highways in the US has the potential to increase 500%, eliminating the waste and unnecessary pollution associated with the contemporary automobile grid (TAMU, 2013).

3. Safety Equipment –Annually, there are over 5.3 million traffic accidents and human error accounts for over 90% of them (RITA, 2013). As a result, contemporary vehicles are designed with crash worthiness in mind (NHTSA, 2013; Bainwol, 2013). Although autonomous cars will not bring the number of traffic accidents to zero, with sensors calculating, monitoring, and predicting its 360-degree environment 20 times per second, vehicles can begin to be designed with collision-free driving in mind (Vanderbilt, 2012; CAR, 2012). Safety measures such as structural steel and roll cages would be superfluous and in turn, vehicles will become much lighter (CAR, 2012). A 20%

reduction in weight corresponds to a 20% increase in fuel efficiency (CAR, 2012). Essentially, as vehicles become safer, they become lighter, and the lighter the vehicle, the more fuel-efficient it can be.

4. Fuel Type –All-electric vehicles are one of the least polluting automobiles on the road today but they only comprise 0.13% of the total vehicle population. The major challenges in the way of mass adoption of all-electric vehicles are the power, operational distance, and lack of recharging stations. The prevailing theory is that a widespread shift to AVs will unlock new opportunities for all-electric vehicles if cars are designed for two passengers and no longer require safety equipment. This would make the cars much lighter and thereby easier to be powered by batteries. Furthermore, if cars are able to operate with no driver (Level 4) then cars could independently travel to recharging stations (Mitchell, Borroni-Bird & Burns, 2010).

5. Eco-driving –Hypermiling, a term coined by driving enthusiasts who push the limits of their vehicles fuel economy (or miles per gallon), is a radical approach to driving, where speed, acceleration, braking, and approach to hills are dictated by fuel efficiency (Torbert & Herrschaft, 2013). Hypermilers, as these enthusiasts are called, are often able to improve their vehicle's EPA rated fuel economy by 175%. The same driving techniques exercised by hypermilers could be hardwired into the autonomous vehicle's computer programming to create an eco-drive mode, which would be further enhanced by V2V and V2I communication (Torbert & Herrschaft, 2013).

6. Platooning –Vehicle platooning utilizes the same aerodynamic principles employed by race car drivers, cyclists, and geese flying South to reduce drag. "The less force vehicles need to counteract, the less requirements on the engine and therefore fuel

consumption" (SARTRE, n.d.) and platooning allows autonomous cars to reduce drag by forming vehicle trains. The SARTRE project, a UN sponsored environmental program, found that platooning could reduce 2.85 tons of CO2 in a diesel truck and 0.1 tons of CO2 in a gasoline car every year (SARTRE, n.d.). There is an inverse relationship between the gap between cars and fuel savings. A 12 meter gap between vehicles produces an 8% savings in fuel, whereas a five meter gap produces 16% savings (SARTRE, n.d.). The optimal fuel savings platoon is 15 vehicles driving between 6-8 meters apart; a gap that is extremely unsafe in contemporary cars however is entirely within the capabilities of autonomous cars (SARTRE, n.d.).

7. Ridesharing/Carsharing –Similar to how ride-sharing programs like Zipcar have changed vehicle ownership, autonomous cars would prompt the next evolution in vehicle ownership. Contemporary vehicles are parked 90% of the time, which indicates not only that they are severely underutilized, they also occupy space and serve no purpose for 22 hours every day (IPI, 2013; CAR, 2013). What's more is the fact that automobiles are the 2nd biggest expense in US households (Thrun, 2012). Through ride-sharing programs, autonomous cars could boost utilization, reduce the amount of space they idly occupy, and still provide the convenience of vehicles on demand at people's doorsteps. Even during rush hour, "fewer than 12% of all personal vehicles are on the road," (CAR, 2012) which indicates it is possible to reduce the vehicle population by 88% and still meet peak demand through autonomous car ride sharing. For the 86.3% of Americans who commute to work by car, as autonomous cars are more readily available and convenient, private vehicle ownership would become obsolete and an unnecessary expense (CAR, 2012).

8. Right-sizing –The concept of right-sizing has to do with pairing passengers with the appropriate vehicle for the type of trip they're taking. Most cars today are designed to drive five passengers, with a full trunk, hundreds of miles on the highway without stopping to refuel. The reality is that these types of trips make up only 5% of the trips Americans take. 98% are single passengers driving 5.95 miles (FHWA, 2011). A fleet of shared AVs, or taxi-bot service mirroring Uber's business model, could feasibly supply the right-sized vehicle to match the passenger demand and avoid over-designed cars being under-utilized (OECD, 2015).

9. Parking –Based on studies at the Massachusetts Institute of Technology (MIT) Media Lab, nearly half of the gasoline consumed in urban areas is attributed to cars just trying to find a parking spot (Mitchell, n.d) This unnecessary pollution is further compounded by the fact that 30% of city traffic is caused by drivers looking for parking (Guccione & Holland, 2013). From a fuel efficiency standpoint, parking poses a double threat because a vehicle searching for a place to park consumes undue fuel but also increases traffic causing other vehicles to consume undue fuel. The congestion caused by parking increases pollution and consumes more fuel than necessary. V2I communication could direct cars efficiently to the nearest available parking spot. From an urban planning and resource allocation standpoint, having parking within city limits is an inefficient use of space. "Parking lots cover more than a third of the land area, becoming the single most salient landscape feature of our built environment," (CAR, 2012) and this massive land resource buried underneath pavement could be tapped into by engineering centralized parking locations adjacent to the city for autonomous vehicles. Instead of continued

urban sprawl, city developers would discover a blank canvas where parking areas once stood within existing city limits.

10. Travel Time –Travel time is a determining factor when it comes to making travel plans, choosing the mode of transit, and perceived costs. The total amount of time spent traveling from door to door via automobile adds up to 472 million additional hours on the road and $10.1 billion due to delays (TAMU, 2013). Moreover, that is 472 million hours of additional engine runtime and emissions. The optimistic scenario of a modal shift to AVs envisions improved traffic flow, increased road capacity, and fewer cars on the road as a whole that will in turn better align the Planning Time Index with the amount of travel time it would take with no traffic (Porter, Brown, DeFlorio, McKenzie, Tao & Vimmerstedt, 2013).

11. Trip Distance –In a future where AVs are conveniently available and affordable, it's expected that the average mileage will increase 8-24% from its current average of 5.95 miles (Childress, Nichols, Charlton & Coe, 2015). This would come mainly as a result of a new era of suburban sprawl. With driving no longer an obstacle, people will opt to live farther away from their place of work and also urban centers.

12. Travel Speed –Keeping in mind the degree to which 360-degree lasers, cameras, and GPS sensors onboard AVs will be able to navigate and react faster than human drivers, it follows that AVs will be able to operate cars safely at faster speeds than human drivers. This coupled with V2V and V2I networks, which seamlessly communicate charted courses, enables speed limits to be increased on high-speed roadways (Porter et al., 2013). As seen on Germany's Autobahn, where there is no speed limit, the average travel speed is 88 miles per hour (mph) (Wadud, MacKenzie & Leiby,

2015). Speed limits in America were initially introduced to create and maintain a safe driving environment (accounting for operator reaction time, vehicle design and roadway limitations). In the early 1970's they were modified at the federal level and used to reduce fuel consumption (Guccione & Holland, 2013). Therefore if speed limits are increased across the country due to AVs, fuel consumption is expected to increase as well (Wadud et al, 2015).

13. Engine Performance/Acceleration –A selling point for vehicles today is how quickly it can accelerate from 0 to 60 mph. Although this sporty performance may be fun for a human driver, hard acceleration under a highly efficient and reactive computer driven vehicle "may become more a source of discomfort than of visceral satisfaction." (Wadud et al, 2015). In turn, engine performance in AVs is expected to be de-emphasized. From a carbon emissions standpoint, higher performance has a direct relationship with energy consumption. Reverting back to engines with slower acceleration speeds but that are still powerful enough to maintain highway speeds in excess of 100 mph would decrease energy consumption and carbon emissions (MacKenzie, Wadud & Leiby, 2014).

14. New/Expanded User Groups –In the event that AVs are able to attain Level 4 autonomy, where no human driver input is ever needed, then regulatory agencies will be faced with permitting groups of people on the road that previously were unable to be behind the wheel of conventional vehicles. For example, one new group would be children under the legal driving age. Examples of expanded user groups include the legally handicapped, such as the blind or deaf population, and the elderly who have given up driving (MacKenzie et al., 2014). The anticipated 2-10% expansion of the population

legally allowed to be behind the wheel of AVs is expected to increase the number of vehicles on the road and GHG emissions would increase as a result (Wadud, 2015).

15. New Feature/Content –Although autonomous technologies may make it possible to eliminate unnecessary components and ultimately reduce the mass of vehicles, AVs may also spur an array of new car features and content that will in fact add superfluous weight to cars. Hypothetically, there could be a consumer demand for everything from a fully reclining seat to fully equipped workstations in AVs. This additional weight will negatively impact carbon emissions in AVs (Wadud et al., 2015).

16. Efficient Routing –In some ways, efficient routing is already a reality with the popularity of GPS navigation tools used in conventional cars. However this is a one-way communication, where the GPS is informing the vehicle of the current fastest route. The next evolution of GPS navigation, which is made possible by AVs, is two-way communication, where a city's infrastructure is able to receive data from vehicles, anticipate traffic flows, and route vehicles most efficiently (Porter et al., 2013).

With all of this background information in mind, what remains to be seen is a comparison between the emissions per mile of conventional vehicles, public transportation, and AVs. It is commonly accepted that it is greener to travel by public transportation than it is to travel alone in a car. But is it still greener if that car is an AV?

There is a breadth of futurist literature on how disruptive AVs will be for society as a whole however only several works attempt to quantify the carbon implications of such a modal shift. The Union of Concerned Scientists (2008), for example, provides a framework for comparing the carbon emissions per passenger of different modes of transportation (air, automobile, rail, bus, etc.) however AVs are missing from this model as the work predates the introduction of AVs on the world stage. Mitchell et al (2010) work depicts the art of the possible after a sweeping adoption of AVs which results in a complete re-design of the automobile as it is known today into an all-electric, ultra compact, lightweight, two-passenger vehicle. MacKenzie et al. (2014) provides a first order of magnitude of AVs on energy consumption in the US, concluding that some AV factors would increase energy consumption but overall offers significant potential for energy and carbon emission reduction. Childress et al. (2015) modeled the impact of AVs on vehicle miles travels (VMT) and inferred from their findings that VMT, and thereby GHG emissions, increased in all but the most optimistic AV scenario. DuPuis et al. of the National League of Cities (2015) is one of the few publications that forecasts how a city's public transportation network will be impacted by AVs and highlights how only 6% of cities have plans in place that take autonomous technology into consideration. Wadud et al. (2015) determined 12 AV variables and used a simple framework to measure the impact on energy consumption in personal vehicle travel.

Research Questions and Hypotheses

Are AVs a viable mitigation strategy to reduce carbon emissions in the transportation sector? How do the emission rates of AVs compare to conventional modes of transit? Will a modal shift to AV-based travel in urban areas produce more pounds of carbon per passenger mile than traditional modes of public transportation? In order to address these questions, I conducted various simulations to compare a modal shift away from public transit and toward AVs.

I examined the following hypotheses through these simulations:

1. In the event that all public transportation passengers shift to traveling by AVs, carbon emissions in the transportation sector will increase compared to baseline emissions.
2. Modes of public transportation have a lower emissions rate (pounds of CO2 per passenger-mile) than AVs.

The data for this analysis is based on one city, Boston, which already has a relatively balanced modal split between public transit and private vehicles. The data are also specific to the miles driven while commuting to and from work, which comprise the majority of miles driven by a vehicle (FHWA, 2011).

Chapter II

Methods

To examine my research questions and hypotheses, I need to identify the potential variables through which vehicle automation may affect carbon emissions in the transportation sector and compare modal shifts between conventional vehicles, public transportation, and AVs. In order to do so, I have consolidated a literature review of AV factors that could impact energy consumption and, using them as inputs, designed a carbon emissions model based on the United Nations (UN) Framework Convention on Climate Change (UN, 2014).

Before arriving at the UN Framework as being the most appropriate for this analysis, other GHG evaluation tools were also considered as the best means for assessing the impact of a modal shift to AVs. Life Cycle Assessments (LCA) are effective at comparing the environmental impact of a product, such as an automobile, during its usable life spanning the impacts of the raw materials used to build the car through to how the materials biodegrade in landfills (Chester & Horvath, 2009). LCAs incorporate all environmental impacts of a given product, not just carbon emissions, and were determined to be too broad for the purposes of this research. Another option was to conduct a GHG Emissions Inventory in which direct and indirect emissions of carbon dioxide (CO2), methane (CH4), nitrous oxide (N20), and air conditioning refrigerants (hydro fluorocarbons (HFC)) were accounted for. Unfortunately, literature is sparse on how AVs will impact GHGs beyond CO2 whereas GHG data on conventional car emissions is abundant down to the micro-level (EPA, 2008; EPA, 2015). A Well-to-Wheel (WTW) or Well-to-Tank (WTT) analysis is a tool used for accounting how much GHGs an automobile produces, starting with the emissions associated with fuel production (the Well) all the way to its distribution at petroleum stations (the Tank) and finally the tailpipe emissions (the Wheel) (Edwards, Larivé & Beziat, 2011). Although this tool is comprehensive for automobiles, it is not applicable to analyzing modes of public transit. Finally, there are several GHG emission modeling tools such as Motor Vehicle Emission Simulator (MOVES) and the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model available through the EPA. This software is powerful but many of the variables, such as emissions factors, were static and therefore unable to meet the needs of this paper (EPA MOVES, 2016).

Ultimately, I utilized the formulas found within the UN Framework Convention on Climate Change to develop a model. This framework was originally developed by the UN in order to provide city planners with a means of projecting emissions after a modal shift, such as converting a percentage of a public bus fleet from diesel to hybrid (UNFCCC, 2015). By following this framework, a baseline amount of emissions that reflects specific modal splits across automobiles and public transportation could be established. The primary inputs are total number of passengers per year, average trip distance, share of passengers by mode of transit, and CO2 emissions per passenger mile. After establishing the baseline, different scenarios were created to isolate variables and allow for comparison. This required building the model from the ground up in order to be able to compare the impact of different AV factors, primarily on fuel economy.

There are strengths and weaknesses to using the UN Framework approach. The major advantage is that it was designed to compare major modal shifts. Furthermore, the same formula is used for all modes of transit, whether it is automobiles, commuter rails, or bicycles. In turn, all modes of transit can be compared in units of pounds CO2 per passenger mile. On the other hand, the UN Framework is not well suited to generate a comprehensive carbon footprint for the transportations sector as it uses some general inputs. It is a tool for comparison purposes only. As such, the framework only calculates CO2 GHG emissions; it does not take into account CH4 or N2O.

Model Formulation

The first phase of the model was to establish the baseline. This was comprised of the following five steps:

Step 1: Determine what modes of transit are most popular amongst commuters. They include: Car, Bus, Trolley, Subway, Railroad, Ferry, Taxi, Paratransit, Motorcycle, Bicycle, Walk, Work at home (None).

Step 2: Gather model inputs for each mode, including:

- Total Number of Vehicles by Mode (N_i)
- Share of Vehicles by Fuel-Type ($N_{i,n}$)
- Specific Electric Consumptions (SEC) in kilowatt-hours per mile (kWh/mi)
- Specific Fuel Consumption (SFC) in gallons per miles (gal/mi)
- Electric Emissions Factor (EF_{Elec}) in pounds of CO2 per kilowatt-hour (lb. CO2/kWh)

- Fuel Emissions Factor (EF_{Fuel}) in pounds of CO2 per British Thermal Unit (lb. CO2/BTU)
- Net Calorific Value (NCV) in British Thermal Unit per gallon (BTU/gal)

Step 3: Determine baseline emissions using UN Framework Convention on Climate Change. The electrical emissions factor per mile for each relevant vehicle category (Eq. 1) was calculated as:

Emissions Factor per Mile [Electric] ($EF_{mi,i}$) = $SEC_i \times EF_{Elec} \times (N_{i,n}/N_i)$

where:

- i = Vehicle category (bus, motorcycle, etc.…)
- n = Fuel types used by vehicle category i

The fuel emissions factor per mile for each relevant vehicle category (Eq. 2) was calculated as:

Emissions Factor per Mile [Fuel] ($EF_{mi,i}$) = $SFC_{i,n} \times NCV_{i,n} \times EF_{i,n} \times (N_{i,n}/N_i)$

where:

- i = Vehicle category (bus, motorcycle, etc.…)
- n = Fuel types used by vehicle category i

The total emissions factor per mile for each relevant vehicle category (Eq. 3) was calculated as:

Emissions Factor per Mile ($EF_{mi,i}$) = $\sum[(SEC_i \times EF_{Elec} + SFC_{i,n} \times NCV_{i,n} \times EF_{i,n}) \times (N_{i,n}/N_i)]$

where:

- i = Vehicle category (bus, motorcycle, etc.…)

- n = Fuel types used by vehicle category i

The emissions factor per passenger-mile for each vehicle category (Eq. 4) was calculated as:

Emissions Factor per Passenger-Mile ($EF_{pmi,i}$) = $EF_{mi,i}/OC_i$

where:

- i = Vehicle category (bus, motorcycle, etc.…)
- OC = Average occupancy rate (passengers)

The baseline emissions for all modes of transit (Eq. 5) was calculated as:

Baseline Emissions [All modes] (BE) = $P \times BTDP \times MS_i \times EF_{pmi,i}$

where:

- P = Total number of passengers transported annually
- BTDP = Average trip distance of the passenger
- MS_i = Share of passengers by transport mode i
- $EF_{pmi,\ i}$ = CO2 emissions factor per passenger for transport mode i
- i = Vehicle category (bus, motorcycle, etc.…)

Step 4

- Identify AV factors that could impact carbon emissions (Table 3)
- Establish a multiplier for each AV factor (Table 3). A multiplier increases or decreases a variable within the model by a certain percentage
- Determine to which model variables the multiplier should be applied (Table 3)

Table 3. AV factors for model.

	Factor	**Multiplier**	**Model Variable**	**Model Variable Abbreviation**
1	Fuel Type	Various	Emission Factor per Mile	EFMi
2	Source of Electricity	Various	Electric Emissions Factor	EFELEC
3a	Right-sizing (Short-term)	-21.0%	Specific Fuel Consumption Specific Electric Consumption	SFC SEC
3b	Right-sizing (Long-term)	-45.0%	Specific Fuel Consumption Specific Electric Consumption	SFC SEC
4a	Car-sharing (Short-term)	-8.8%	Number of vehicles	N
4b	Car-sharing (Long-term)	+10.0%	Average Commute Distance	BTDP
5	Ride-sharing/Carpooling	-5.0%	Number of vehicles	N
6a	Platooning (Short-term)	-3.0%	Specific Fuel Consumption Specific Electric Consumption	SFC SEC
6b	Platooning (Long-term)	-15.5%	Specific Fuel Consumption Specific Electric Consumption	SFC SEC
7	Trip Distance	+14.0%	Average Commute Distance	BTDP
8a	Travel Speed (Short-term)	+22.0%	Specific Fuel Consumption Specific Electric Consumption	SFC SEC
8b	Travel Speed (Long-term)	+7.0%	Specific Fuel Consumption Specific Electric Consumption	SFC SEC
9a	Eco-driving (short-term)	-20.0%	Specific Fuel Consumption Specific Electric Consumption	SFC SEC

	Factor	**Multiplier**	**Model Variable**	**Model Variable Abbreviation**
9b	Eco-driving (long-term)	-5.0%	Specific Fuel Consumption Specific Electric Consumption	SFC SEC
10	Traffic Flow	-2.0%	Specific Fuel Consumption Specific Electric Consumption	SFC SEC
11	Removal of Safety Equipment	-5.5%	Specific Fuel Consumption Specific Electric Consumption	SFC SEC
12a	Performance/ Acceleration/ Engine Power	-5.0%	Specific Fuel Consumption Specific Electric Consumption	SFC SEC
12b	Performance/ Acceleration/ Engine Power	-23.0%	Specific Fuel Consumption Specific Electric Consumption	SFC SEC
13	New/Expanded User Groups	+6.0%	Number of Commuter Passengers	BTDP
14	New Feature Content	+11.0%	Specific Fuel Consumption Specific Electric Consumption	SFC SEC

Step 5: Generate data using the model under different scenarios. Over the course of this process, there were several assumptions, conversions, and decisions made in order to create the model. First and foremost, there were a variety of sources used to compile the inputs for Step 2 and it is assumed that the margin of error is the same across these sources. It is also assumed that the mode of transit for each passenger was absolute, based off of US Census data. Although commuters may take public transportation in the summertime and drive a car in the wintertime, whichever mode was provided to the US Census was the one accounted for the whole year of commuting.

After compiling the sources of data, a series of conversions was necessary. A list of those conversion factors can be found in the Appendix. Regarding Step 4, after researching AV mechanisms, it was decided that most, but not all, of the AV factors listed are independent of one another. There are several AV factors that could potentially impact carbon emissions, but in order to avoid overlapping or compounded effects, these factors were intentionally excluded from the model: Parking, Travel Time, Available Seats, and Efficient Routing. To the extent possible, there are no overlapping or compounded effects within the associated multipliers (Wadud et al., 2015).

Chapter III

Results

The model was used to generate the following data based on various scenarios in which different modal shifts occurred. A narrative is associated with each hypothetical scenario in order to provide appropriate context for comparison. The percent of the commuting population divided by mode of transit (conventional car, public transit, and AV) accompanies each of the transportation categories impacted by the scenario. A table of all the AV factors and whether or not they apply to the scenario is also provided. And finally, a summary table of the findings from the emissions model is presented at the end of each scenario. A brief interpretation of the results follows the presentation of each individual scenario data.

Scenario 1: Business as Usual

This scenario (Table 4) determines the current amount of carbon generated by commuters in Boston and establishes the baseline. Modes of transportation are based on actual commuting statistics for the city of Boston in which 44.7% of commuters use conventional cars and a further 33.4% of the population uses public transportation. Zero percent use AVs and in turn, no AV factors impact the scenario. There is no change to the ratios of modes of transportation, fuel types, or commuters.

Table 4. AV factors used in scenario 1.

	Factor	Applicable (Y/N)	Comments/Assumptions
1	Fuel Type	No	
2	Source of Electricity	No	
3	Right-sizing	No	
4	Car-sharing	No	
5	Ridesharing/Carsharing	No	
6	Platooning	No	
7	Trip Distance	No	
8	Travel Speed	No	
9	Eco-driving	No	
10	Traffic Flow/Congestion	No	
11	Safety Equipment	No	
12	Engine Performance /Acceleration	No	
13	New/Expanded User Groups	No	
14	New Feature/Content	No	

In this scenario (Table 5), conventional cars produce the most CO2, with single-passenger vehicle travel as the single most carbon emitting mode of transit. Public transit produces almost a quarter of emissions, with bus travel producing the majority in that sector. Other modes of transit contribute only 1% of total emissions, with taxicabs and motorcycles being the highest emitters. Conventional cars occupied by one passenger transport the majority of commuters overall. Among the other modes of transit, walking and subways are most popular. Ferryboats have the highest rate of CO2 emissions per passenger mile, followed by paratransit, and then one-passenger conventional cars.

Table 5. Results of scenario 1 model.

Model Input	*% of Total Emissions*	*Scenario 1 Emissions*	*Number of Passengers per Year*	*Avg Trip Distance (Round trip)*	*Share of Commuters by Mode*	*Emissions Factor per Passenger Mile*
Model Abbreviation	*-*	*S1E*	*P*	*BTDP*	*MS*	*EFPM*
Units	*%*	*lb CO2/year*	*Passenger/Yr*	*Miles*	*%*	*lb CO2/passenger-mi*
Car (alone)	69.7%	617,979,824	94,027,077	23.6	38.6%	0.721
Car (carpool 2-people)	4.1%	36,022,140			4.5%	0.361
Car (Carpool 3-people)	0.5%	4,802,952			0.9%	0.240
Car (Carpool 4-or-more)	0.3%	2,801,722			0.7%	0.180
Car Total	**74.6%**	**661,606,638**			**44.7%**	-
Bus	10.6%	94,176,227			9.5%	0.445
Trolley Bus	0.2%	1,759,812			0.3%	0.289
Streetcar or Trolley car	3.4%	30,446,792			6.2%	0.222
Subway or elevated	5.2%	46,131,226			14.1%	0.147
Railroad	3.2%	28,536,830			3.0%	0.426
Ferryboat	1.1%	10,088,134			0.1%	4.247
Paratransit	0.7%	5,844,303			0.2%	1.470
T Total	**24.5%**	**216,983,324**			**33.4%**	-
Taxicab	0.4%	3,860,441			0.5%	0.387
Motorcycle	0.4%	3,553,174			0.5%	0.356
Bicycle	<0.0%	336,187			1.9%	0.008
Walk	<0.0%	246,894			15.0%	0.001
Work at home	0.0%	-			3.6%	0.000
Other Total	**1%**	**7,996,696**			**21.4%**	-
TOTAL	**100%**	**886,586,658**	**-**	**-**	**100%**	-

Scenario 2: Greenest T

In this scenario (Table 6), public transportation switches to alternative energies and electrical grid switches to renewable energy. The city of Boston invests heavily in its existing electrical grid and public transportation system. The goal is to achieve maximum GHG reduction in the public sector. Sources of electricity are all from renewable energy sources (primarily wind turbines along the coast, biomass-fired power plants, solar arrays and hydroelectric power plants) as well as nuclear power. Boston's coal, oil, and gas-fired power plants are all de-commissioned. Fossil fuel engines used by the bus, ferry, and paratransit fleets are replaced with electric and cleaner fuel sources.

Table 6. AV factors used in scenario 2.

	Factor	Applicable (Y/N)	Comments/Assumptions
1	Fuel Type	Yes	Bus: 100% shift to CNG Heavy Rail: Shift to 50% more efficient MPG Ferry: Shift from 0.18 MPG to 0.46 MPG Paratransit: 100% shift to CNG
2	Source of Electricity	Yes	kWh: Average wind/solar/hydro emissions = 0.114 lb/kWh
3	Right-sizing	No	
4	Car-sharing	No	
5	Ridesharing/Carsharing	No	
6	Platooning	No	
7	Trip Distance	No	
8	Travel Speed	No	
9	Eco-driving	No	
10	Traffic Flow/Congestion	No	
11	Safety Equipment	No	
12	Engine Performance /Acceleration	No	
13	New/Expanded User Groups	No	
14	New Feature/Content	No	

The ratio of commuters by modes of transportation remains the same with 44.7% driving conventional cars and 33.4% using public transportation (0% using AVs).

In this model (Table 7), carbon emissions were reduced 21% from baseline overall. Public transit emissions were reduced by over 80%. Conventional cars emit nearly all of the carbon, with public transit and other modes representing only 6% of total emissions. Single-passenger vehicle travel remains the single most carbon-emitting mode of transit, followed by 2-passenger vehicles, followed by railroads. Conventional cars occupied by one passenger transport the majority of commuters overall. Among the other modes of transit, walking and subways are most popular. Ferryboats have the highest rate of CO2 emissions per passenger mile, followed by one-passenger conventional cars.

Table 7. Results of scenario 2 model.

Model Input	*% of Total Emissions*	*Scenario 2 Emissions*	*Number of Passengers per Year*	*Avg Trip Distance (Round trip)*	*Share of Commuters by Mode*	*Emissions Factor per Passenger Mile*
Model Abbreviation	-	*S2E*	*P*	*BTDP*	*MS*	*EFPM*
Units	%	*lb CO2/year*	*Passenger/Yr*	*Miles*	%	*lb CO2/passenger-mi*
Car (alone)	88.1%	617,793,374	94,027,077	23.6	38.6%	0.7213
Car (carpool 2-people)	5.1%	36,011,272			4.5%	0.3606
Car (Carpool 3-people)	0.7%	4,801,503			0.9%	0.2404
Car (Carpool 4-or-more)	0.4%	2,800,877			0.7%	0.1803
Car Total	**94.3%**	**661,407,025**			**44.7%**	**-**
Bus	<0.0%	273,235			9.5%	0.0013
Trolley Bus	<0.0%	316,265			0.3%	0.0519
Streetcar or Trolley car	0.8%	5,471,747			6.2%	0.0400
Subway or elevated	1.2%	8,290,476			14.1%	0.0264
Railroad	2.0%	14,268,415			3.0%	0.2131
Ferryboat	0.6%	3,947,531			0.1%	1.6617
Paratransit	<0.0%	1,204			0.2%	0.0003
T Total	**4.6%**	**32,568,873**			**33.4%**	**-**
Taxicab	0.6%	3,860,441			0.5%	0.3866
Motorcycle	0.5%	3,553,174			0.5%	0.3558
Bicycle	<0.0%	60,418			1.9%	0.0014
Walk	<0.0%	44,371			15.0%	0.0001
Work at home	0.0%	-			3.6%	0.0000
Other Total	**1.1%**	**7,518,404**	**-**	**-**	**21.4%**	**-**
TOTAL	**100%**	**701,494,302**	**-**	**-**	**100%**	**-**

Scenario 3: Cash for Clunkers

In this scenario (Table 8), commuters trade-in conventional cars for alternative (cleaner) energy cars. The city of Boston rolls out a sweeping ‘cash for clunkers’ program and all gasoline-powered privately owned vehicles are replaced with cleaner energy vehicles. Privately owned cars, paratransit vehicles, and taxis are all impacted. At the same time, the city invests heavily in its existing electrical grid, as well as incentivizing car-sharing and carpooling. Primary sources of electricity are from renewable energy sources. This impacts subways, trolleys, and electrical-buses, otherwise the public transit system remains the same. The ratio of commuters by modes of

Table 8. AV Factors used in scenario 3.

	Factor	Applicable (Y/N)	Comments/Assumptions
1	Fuel Type	Yes	All diesel and gasoline vehicles eliminated and converted to Electric, Hybrid, and CNG.
2	Source of Electricity	Yes	kWh: Average wind/solar/hydro emissions = 0.114 lb/kWh
3	Right-sizing	No	
4	Car-sharing	Yes	Total number of vehicles reduced by 8.8%
5	Ridesharing/Carsharing	No	
6	Platooning	No	
7	Trip Distance	No	
8	Travel Speed	No	
9	Eco-driving	No	
10	Traffic Flow/Congestion	No	
11	Safety Equipment	No	
12	Engine Performance /Acceleration	No	
13	New/Expanded User Groups	No	
14	New Feature/Content	No	

transportation remains the same with 44.7% driving conventional cars and 33.4% using public transportation (0% using AVs).

In this model (Table 9), carbon emissions were reduced 42% from baseline. Vehicle emissions were reduced by nearly 50% and public transit emissions by over 30% compared to the baseline. Conventional cars emit nearly ¾ of the carbon. Single-passenger vehicle travel remains the single most carbon-emitting mode of transit, followed by city buses and commuter rails. Conventional cars occupied by one passenger transport the majority of commuters overall. Among the other modes of transit, walking and subways are most popular. While ferryboats remain as the mode with the highest rate of CO2 emissions per passenger mile, buses and railroads now have higher rates than passenger cars.

Table 9. Results of scenario 3 model.

Model Input	*% of Total Emissions*	*Scenario 3 Emissions*	*Number of Passengers per Year*	*Avg Trip Distance (Round trip)*	*Share of Commuters by Mode*	*Emissions Factor per Passenger Mile*
Model Abbreviation	-	*S3E*	*P*	*BTDP*	*MS*	*EFPM*
Units	%	*lb CO2/year*	*Passenger/Yr*	*Miles*	%	*lb CO2/passenger-mi*
Car (alone)	65.3%	333,534,756	94,027,077	23.6	38.6%	0.3894
Car (carpool 2-people)	3.8%	19,441,793			4.5%	0.1947
Car (Carpool 3-people)	0.5%	2,592,239			0.9%	0.1298
Car (Carpool 4-or-more)	0.3%	1,512,139			0.7%	0.0973
Car Total	**69.9%**	**357,080,928**			**44.7%**	**-**
Bus	18.3%	93,535,972			9.5%	0.4416
Trolley Bus	0.1%	316,265			0.3%	0.0519
Streetcar or Trolley car	1.1%	5,471,747			6.2%	0.0400
Subway or elevated	1.6%	8,290,476			14.1%	0.0264
Railroad	5.6%	28,536,830			3.0%	0.4262
Ferryboat	2.0%	10,088,134			0.1%	4.2466
Paratransit	0.2%	1,012,223			0.2%	0.2546
T Total	**28.8%**	**147,251,646**			**33.4%**	**-**
Taxicab	0.6%	3,102,308			0.5%	0.3107
Motorcycle	0.7%	3,553,174			0.5%	0.3558
Bicycle	<0.0%	60,418			1.9%	0.0014
Walk	<0.0%	44,371			15.0%	0.0001
Work at home	0.0%	-			3.6%	0.0000
Other Total	**1.3%**	**6,760,270**	**-**	**-**	**21.4%**	**-**
TOTAL	**100%**	**511,092,844**	**-**	**-**	**100%**	**-**

Scenario 4: Computers for Clunkers

In this scenario (Table 10), the existing private vehicle fleet is retrofitted with Level 3 automation technology. The city of Boston rolls out a sweeping 'computers for clunkers' program in which all privately owned (and MBTA paratransit and taxi) vehicles are retrofitted with an AV computer thereby achieving widespread Level III automation. V2V and V2I also become widespread, enabling right-sizing, car-sharing, ride-sharing, platooning, eco-driving, better traffic flow, and efficient routing. Commuting travel

Table 10. AV factors used in scenario 4.

	Factor	Applicable (Y/N)	Comments/Assumptions
1	Fuel Type	No	
2	Source of Electricity	No	
3	Right-sizing	Yes	Emissions Factor reduction only in 1- and 2-person cars
4	Car-sharing	Yes	Total number of vehicles see a 8.8% reduction (1, 2, 3, 4 person cars)
5	Ridesharing/Carsharing	Yes	Total number of vehicles sees a 5% reduction of 1-person cars and a 5% increase of carpool cars
6	Platooning	Yes	Emission Factor sees 3% reduction
7	Trip Distance	Yes	Average Commute Distance sees 14% increase for cars only
8	Travel Speed	Yes	Emission Factor sees 22% **increase**
9	Eco-driving	Yes	Emission Factor sees 20% reduction
10	Traffic Flow/Congestion	Yes	Emission Factor sees 2% reduction
11	Safety Equipment	No	
12	Engine Performance /Acceleration	Yes	Emission Factor sees 5% reduction
13	New/Expanded User Groups	No	
14	New Feature/Content	No	

distance increases and vehicle weight increases from new feature content. At Level 3, safety equipment cannot be removed and new/expanded user groups are not possible. And as existing vehicles are retrofitted, the engine power remains the same. The city's source of electricity remains the same. The public transit system remains the same. The ratio of commuters by modes of transportation remains the same with 44.7% driving conventional cars and 33.4% using public transportation (0% using AVs).

In this model (Table 11), carbon emissions were reduced by only 14% from baseline (Table 11). Vehicle emissions were reduced by less than 20% and all other modes had little to no change from the base case. Conventional cars emit just over 70% of the carbon. Single-passenger vehicle travel remains the single most carbon-emitting mode of transit, followed by city buses and subways. Conventional cars occupied by one passenger transport the majority of commuters overall. Among the other modes of transit, walking and subways are most popular. Ferryboats are by far the mode with the highest rate of CO2 emissions per passenger mile. Vehicle emissions rates are more in line with railroads, buses, and trolleys.

Table 11. Results of scenario 4 model.

Model Input	*% of Total Emissions*	*Scenario 4 Emissions*	*Number of Passengers per Year*	*Avg Trip Distance (Round trip)*	*Share of Commuters by Mode*	*Emissions Factor per Passenger Mile*
Model Abbreviation	-	*S4E*	*P*	*BTDP*	*MS*	*EFPM*
Units	%	*lb CO2/year*	*Passenger/Yr*	*Miles*	%	*lb CO2/passenger-mi*
Car (alone)	65.7%	500,192,869	94,027,077	26.904	38.6%	0.512
Car (carpool 2-people)	3.8%	29,156,320			4.5%	0.256
Car (Carpool 3-people)	0.7%	5,037,336			0.9%	0.221
Car (Carpool 4-or-more)	0.4%	2,938,446			0.7%	0.166
Car Total	**70.5%**	**537,324,972**			**44.7%**	
Bus	12.4%	94,176,227		23.6	9.5%	0.445
Trolley Bus	0.2%	1,759,812			0.3%	0.289
Streetcar or Trolley car	4.0%	30,446,792			6.2%	0.222
Subway or elevated	6.1%	46,131,226			14.1%	0.147
Railroad	3.7%	28,536,830			3.0%	0.426
Ferryboat	1.3%	10,088,134			0.1%	4.247
Paratransit	0.7%	5,493,644			0.2%	1.382
T Total	**28.4%**	**216,632,666**			**33.4%**	
Taxicab	0.5%	3,628,815			0.5%	0.363
Motorcycle	0.5%	3,553,174			0.5%	0.356
Bicycle	<0.0%	336,187			1.9%	0.008
Walk	<0.0%	246,894			15.0%	0.001
Work at home	0.0%	-			3.6%	0.000
Other Total	**1.0%**	**7,765,070**			**21.4%**	
TOTAL	**100%**	**761,722,707**	**-**	**-**	**100%**	**-**

Scenario 5: Cash for Conventionals

In this scenario (Table 12), all conventional vehicles are traded in for new cars with Level 4 automation. The city of Boston rolls out a sweeping ‘cash for conventionals’ program in which all privately owned conventional (and MBTA paratransit and taxi) vehicles are replaced with new, fully autonomous, alternative energy vehicles thereby

Table 12. AV factors used in scenario 5.

	Factor	Applicable (Y/N)	Comments/Assumptions
1	Fuel Type	Yes	All diesel and gasoline vehicles are converted to Electric, Hybrid, and CNG
2	Source of Electricity	No	
3	Right-sizing	Yes	Emission Factor sees a 45% reduction only for 1- and 2-person cars
4	Car-sharing	Yes	Total number of vehicles sees a 8.8% reduction AND Average Distance sees a 10% **increase**
5	Ridesharing/Carsharing	Yes	Total number of vehicles sees a 5% reduction of 1-person vehicles and a 5% increase of carpool vehicles
6	Platooning	Yes	Emission Factor sees 15.5% reduction
7	Trip Distance	Yes	Average Commute Distance sees 14% **increase** for cars only
8	Travel Speed	Yes	Emission Factor sees 7% **increase**
9	Eco-driving	Yes	Emission Factor sees 5% reduction
10	Traffic Flow/Congestion	Yes	Emission Factor sees 2% reduction
11	Safety Equipment	Yes	Emission Factor sees 5.5% reduction
12	Engine Performance /Acceleration	Yes	Emission Factor sees 23% reduction
13	New/Expanded User Groups	Yes	Number of Commuter Passengers per Year sees 6% **increase**
14	New Feature/Content	Yes	Emission Factor sees 11% **increase**

achieving widespread Level 4 automation. V2V and V2I also become widespread, enabling right-sizing, car-sharing, ride-sharing, platooning, eco-driving, better traffic flow, and efficient routing. Commuting travel distance increases and vehicle weight increases from new feature content. At Level 4, safety equipment can be removed, new/expanded user groups can also access the vehicles, and the engine power is reduced. The city's source of electricity, public transit system, and ratio of commuters by modes of transportation remains the same with 44.7% driving conventional cars and 33.4% using public transportation (0% using AVs).

In this model (Table 13), carbon emissions were reduced by 60% from baseline. Vehicle emissions were reduced by over 80% despite experiencing an increase in the trip distance. Public transportation emissions, on the other hand, actually increased as a result of the increase in commuter population. At 66%, public transportation now emits the majority of carbon. In turn, single-passenger vehicle travel and bus travel are the modes that account for most of the carbon emissions, followed by subways and trolleys. Conventional cars occupied by one passenger transport the majority of commuters overall. Among the other modes of transit, walking and subways are most popular. AVs have the lowest rate of CO2 emissions per passenger mile other than bicycling, walking, and working from home. All modes of public transit are among the highest vehicle emissions rates.

Table 13. Results of scenario 5 model.

Model Input	*% of Total Emissions*	*Scenario 5 Emissions*	*Number of Passengers per Year*	*Avg Trip Distance (Round trip)*	*Share of Commuters by Mode*	*Emissions Factor per Passenger Mile*
Model Abbreviation	-	*S5E*	*P*	*BTDP*	*MS*	*EFPM*
Units	*%*	*lb CO2/year*	*Passenger/Yr*	*Miles*	*%*	*lb CO2/passenger-mi*
Car (alone)	29.1%	102,807,363	103,993,947	29.5944	38.6%	0.087
Car (carpool 2-people)	1.7%	5,992,657			4.5%	0.043
Car (Carpool 3-people)	0.7%	2,433,382			0.9%	0.088
Car (Carpool 4-or-more)	0.4%	1,419,473			0.7%	0.066
Car Total	**31.8%**	**112,652,875**			**44.7%**	
Bus	29.4%	104,158,908		23.6	9.5%	0.445
Trolley Bus	0.6%	1,946,352			0.3%	0.289
Streetcar or Trolley car	9.5%	33,674,152			6.2%	0.222
Subway or elevated	14.4%	51,021,136			14.1%	0.147
Railroad	8.9%	31,561,734			3.0%	0.426
Ferryboat	3.2%	11,157,476			0.1%	4.247
Paratransit	0.2%	748,433			0.2%	0.170
T Total	**66.2%**	**234,268,191**			**33.4%**	
Taxicab	0.6%	2,298,872			0.5%	0.208
Motorcycle	1.1%	3,929,810			0.5%	0.356
Bicycle	0.1%	371,823			1.9%	0.008
Walk	0.1%	273,065			15.0%	0.001
Work at home	0.0%	-			3.6%	0.000
Other Total	**1.9%**	**6,873,570**			**21.4%**	
TOTAL	**100%**	**353,794,636**	**-**	**-**	**100%**	**-**

Scenario 6: T Outmoded by Computerized Conventionals

In this scenario (Table 14), public transit is replaced with a massive fleet of cars retrofitted with Level 3 automation technology. Uber makes an offer Boston cannot refuse – to retrofit all conventional cars with Level 3 automation. In return, Uber is awarded the MBTA contract. As a result, the public transportation system is replaced with a dedicated network of conventional Uber cars containing Level 3 automation. Buses, trolleys, subways, railroads, ferryboats, and paratransit become non-factors. The same characteristics as Scenario 4 apply. In addition, all commuters from public transit migrate over to driving AVs, totaling 78.1% of the commuter population.

Table 14. AV factors used in scenario 6.

	Factor	Applicable (Y/N)	Comments/Assumptions
1	Fuel Type	No	
2	Source of Electricity	No	
3	Right-sizing	Yes	Emission Factor sees 21% reduction, only 1- and 2-person cars
4	Car-sharing	Yes	Total number of vehicles sees a 8.8% reduction
5	Ridesharing/Carsharing	Yes	Total number of vehicles sees a 5% reduction of 1-person percentage and a 5% increase of carpool percentage
6	Platooning	Yes	Emission Factor sees 3% reduction
7	Trip Distance	Yes	Average Commute Distance sees 14% increase for cars only
8	Travel Speed	Yes	Emission Factor sees 22% **increase**
9	Eco-driving	Yes	Emission Factor sees 20% reduction
10	Traffic Flow/Congestion	Yes	Emission Factor sees 2% reduction
11	Safety Equipment	No	
12	Engine Performance /Acceleration	Yes	Emission Factor sees 5% reduction
13	New/Expanded User Groups	No	
14	New Feature/Content	No	

Public transportation is a non-factor in this model (Table 15) due to the modal shift to AVs. This is the only scenario in which carbon emissions increased compared to the baseline. Vehicle emissions increased by over 40% as a result of the modal shift from public transportation. AVs occupied by one passenger transport the majority of commuters overall. Among the other modes of transit, walking and bicycling are most popular. Single-passenger AVs have the highest rate of CO2 emissions per passenger mile.

Table 15. Results of scenario 6 model.

Model Input	*% of Total Emissions*	*Scenario 6 Emissions*	*Number of Passengers per Year*	*Avg Trip Distance (Round trip)*	*Share of Commuters by Mode*	*Emissions Factor per Passenger Mile*
Model Abbreviation	-	*S6E*	*P*	*BTDP*	*MS*	*EFPM*
Units	*%*	*lb CO2/year*	*Passenger/Yr*	*Miles*	*%*	*lb CO2/passenger-mi*
Car (alone)	92.3%	874,149,189	94,027,077	26.904	67.5%	0.512
Car (carpool 2-people)	5.4%	50,954,292			7.9%	0.256
Car (Carpool 3-people)	0.9%	8,803,371			1.6%	0.221
Car (Carpool 4-or-more)	0.5%	5,135,300			1.2%	0.166
Car Total	**99.2%**	**939,042,151**			**78.1%**	-
Bus	0.0%	-		23.6	0.0%	0.445
Trolley Bus	0.0%	-			0.0%	0.289
Streetcar or Trolley car	0.0%	-			0.0%	0.222
Subway or elevated	0.0%	-			0.0%	0.147
Railroad	0.0%	-			0.0%	0.426
Ferryboat	0.0%	-			0.0%	4.247
Paratransit	0.0%	-			0.0%	1.470
T Total	**0.0%**	**-**			**0.0%**	-
Taxicab	0.4%	3,551,606			0.5%	0.356
Motorcycle	0.4%	3,553,174			0.5%	0.356
Bicycle	<0.0%	336,187			1.9%	0.008
Walk	<0.0%	246,894			15.0%	0.001
Work at home	0.0%	-			3.6%	0.000
Other Total	**0.8%**	**7,687,861**	-	-	**21.4%**	-
TOTAL	**100%**	**946,730,012**	**-**	**-**	**100%**	**-**

Scenario 7: T Outmoded by Computers

In this scenario (Table 16), public transit is replaced with a fleet of publicly available Level 4 automated vehicles. Google makes an offer the city of Boston cannot refuse—to replace all conventional cars with brand new fully-automated Google cars. In return, Google is awarded the MBTA contract. As a result, the public transportation

Table 16. AV factors used in scenario 7.

	Factor	Applicable (Y/N)	Comments/Assumptions
1	Fuel Type	Yes	All diesel and gasoline vehicles eliminated and converted to Electric, Hybrid, and CNG
2	Source of Electricity	No	
3	Right-sizing	Yes	Emissions Factor sees 45% reduction only in 1- and 2-person cars
4	Car-sharing	Yes	Total Vehicles see 8.8% reduction AND Average Commute Distance sees 10% **increase**
5	Ridesharing/Carsharing	Yes	Total Vehicles see 5% reduction of 1-person percentage and 5% increase of carpool percentage
6	Platooning	Yes	Emission Factor sees 15.5% reduction
7	Trip Distance	Yes	Average Commute Distance sees 14% **increase** (Cars only)
8	Travel Speed	Yes	Emissions Factor sees 7% **increase**
9	Eco-driving	Yes	Emissions Factor sees 5% reduction
10	Traffic Flow/Congestion	Yes	Emissions Factor sees 2% reduction
11	Safety Equipment	Yes	Emissions Factor sees 5.5% reduction
12	Engine Performance /Acceleration	Yes	Emissions Factor sees 23% reduction
13	New/Expanded User Groups	Yes	Number of Commuter Passengers per year see 6% **increase**
14	New Feature/Content	Yes	Emissions Factor sees 11% **increase**

system is replaced with a dedicated network of Google cars. Buses, trolleys, subways, railroads, ferryboats, and paratransit become non-factors. The same characteristics as Scenario 5 apply. In addition, all commuters from public transit migrate over to riding in AVs, totaling 78.1% of the commuter population.

Public transportation is a non-factor in this model (Table 17) due to the modal shift to AVs. At 77% less carbon than baseline, this scenario produces the second greatest overall reduction in carbon emissions. Despite the modal shift from public transportation to AVs, vehicle emissions decreased by 30%. AVs occupied by one passenger transport the majority of commuters overall. Among the other modes of transit, walking and bicycling are most popular. Single-passenger AVs have the highest rate of CO2 emissions per passenger mile only to bicycling and walking.

Table 17. Results of scenario 7 model.

Model Input	*% of Total Emissions*	*Scenario 7 Emissions*	*Number of Passengers per Year*	*Avg Trip Distance (Round trip)*	*Share of Commuters by Mode*	*Emissions Factor per Passenger Mile*
Model Abbreviation	-	*S7E*	*P*	*BTDP*	*MS*	*EFPM*
Units	*%*	*lb CO2/year*	*Passenger/Yr*	*Miles*	*%*	*lb CO2/passenger-mi*
Car (alone)	88.2%	179,668,641	103,993,947	29.5944	67.5%	0.087
Car (carpool 2-people)	5.1%	10,472,913			7.9%	0.043
Car (Carpool 3-people)	2.1%	4,252,637			1.6%	0.088
Car (Carpool 4-or-more)	1.2%	2,480,705			1.2%	0.066
Car Total	**96.6%**	**196,874,897**		**-**	**78.1%**	**-**
Bus	0.0%	-		23.6	0.0%	0.445
Trolley Bus	0.0%	-			0.0%	0.289
Streetcar or Trolley car	0.0%	-			0.0%	0.222
Subway or elevated	0.0%	-			0.0%	0.147
Railroad	0.0%	-			0.0%	0.426
Ferryboat	0.0%	-			0.0%	4.247
Paratransit	0.0%	-			0.0%	0.255
T Total	**0.0%**	**-**			**0.0%**	**-**
Taxicab	1.1%	2,298,872			0.5%	0.208
Motorcycle	1.9%	3,929,810			0.5%	0.356
Bicycle	0.2%	371,823			1.9%	0.008
Walk	0.1%	273,065			15.0%	0.001
Work at home	0.0%	-			3.6%	0.000
Total Other	**3.4%**	**6,873,570**	**-**	**-**	**21.4%**	**-**
TOTAL	**100%**	**203,748,467**	**-**	**-**	**100%**	**-**

Scenario 8: Cars Outmoded by T

This scenario (Table 18) models the most popular and greenest public transit option. Bridj makes an offer the city of Boston cannot refuse—to fully fund replacing the existing electric grid with renewable energy sources. In return, Bridj is awarded the MBTA contract. Bridj creates a state-of-the-art, on-demand, fuel-efficient transportation network that is so reliable, extensive, and affordable that commuting with a private car becomes obsolete. The same characteristics as Scenario 2 apply. In addition, all commuters from private vehicles migrate over to public transit, totaling 78.1% of the commuter population.

Table 18. AV factors used in scenario 8.

	Factor	Applicable (Y/N)	Comments/Assumptions
1	Fuel Type	Yes	Bus: 100% shift to CNG Heavy Rail: Shift to 50% more efficient MPG Ferry: Shift from 0.18 MPG to 0.46 MPG Paratransit: 100% shift to CNG
2	Source of Electricity	Yes	kWh: Average wind/solar/hydro emissions 0.114 lb/kWh
3	Right-sizing	No	
4	Car-sharing	No	
5	Ridesharing/Carsharing	No	
6	Platooning	No	
7	Trip Distance	No	
8	Travel Speed	No	
9	Eco-driving	No	
10	Traffic Flow/Congestion	No	
11	Safety Equipment	No	
12	Engine Performance /Acceleration	No	
13	New/Expanded User Groups	No	
14	New Feature/Content	No	

Cars are non-factors in this model (Table 19) due to the modal shift to public transit. This scenario appears to have the greatest reduction in emissions, 91% compared to baseline. Even with the influx of passengers as a result of the modal shift, public transit emissions decreased by 35%. Commuter rails account for the majority of emissions. Subways transport the majority of commuters overall, followed by buses and then trolleys. Other than ferryboats, railroads have the highest rate of CO2 emissions per passenger mile.

Table 19. Results of scenario 8 model.

Model Input	*% of Total Emissions*	*Scenario 8 Emissions*	*Number of Passengers per Year*	*Avg Trip Distance (Round trip)*	*Share of Commuters by Mode*	*Emissions Factor per Passenger Mile*
Model Abbreviation	-	*S8E*	*P*	*BTDP*	*MS*	*EFPM*
Units	*%*	*lb CO2/year*	*Passenger/Yr*	*Miles*	*%*	*lb CO2/passenger-mi*
Car (alone)	0.0%	-	94,027,077	23.6	0.0%	0.7213
Car (carpool 2-people)	0.0%	-			0.0%	0.3606
Car (Carpool 3-people)	0.0%	-			0.0%	0.2404
Car (Carpool 4-or-more)	0.0%	-			0.0%	0.1803
Car Total	**0.0%**	**0**			**0.0%**	**-**
Bus	0.8%	638,706			22.3%	0.0013
Trolley Bus	0.9%	739,291			0.6%	0.0519
Streetcar or Trolley car	15.3%	12,790,594			14.4%	0.0400
Subway or elevated	23.2%	19,379,571			33.0%	0.0264
Railroad	39.9%	33,353,423			7.1%	0.2131
Ferryboat	11.0%	9,227,631			0.3%	1.6617
Paratransit	0.0%	2,814			0.4%	0.0003
T Total	**91.0%**	**76,132,030**			**78.1%**	**-**
Taxicab	4.6%	3,860,441			0.5%	0.3866
Motorcycle	4.2%	3,553,174			0.5%	0.3558
Bicycle	0.1%	60,418			1.9%	0.0014
Walk	0.1%	44,371			15.0%	0.0001
Work at home	0.0%	-			3.6%	0.0000
Other Total	**9.0%**	**7,518,404**			**21.4%**	**-**
TOTAL	**100%**	**83,650,434**	**-**	**-**	**100%**	**-**

Comparison of Scenario Results

Ultimately, by following this process and adhering to the UN Framework, this thesis was able to produce relevant outcomes by using eight well-defined scenarios to isolate various AV factor's impact on baseline emissions. Among the scenarios in which AV factors that were manipulated, Scenario 7 (T Outmoded by Computers) and Scenario 5 (Cash for Conventionals) respectively saw the greatest reduction in carbon emissions compared to the baseline (Figure 2). Both of these scenarios involved Level 4 (full self-driving automation) technology. Right-sizing, reduced engine performance, and platooning are AV factors that are available only in Level 4 vehicles and that also represent substantial improvements in fuel economy and in turn reductions in carbon emissions (Table 20). Right-sizing has the greatest potential, in which fuel economy could increase by 45% with the introduction of new 2-passenger vehicles (Table 20). Reducing engine performance could also reduce fuel consumption by 23% and platooning at Level 4 could reduce fuel consumption a further 15.5% (Table 20).

Beyond AV factors, the other vital component to the reduced emissions exhibited in Scenarios 5 and 7 is a shift to alternative fuel vehicles. Scenario 3 (Cash for Clunkers), in which the only variables were cleaner fuels and cleaner electricity, saw a 42% reduction overall (Figure 2). Specifically, emissions from cars were reduced by 50% compared to the baseline as a result of trading out ICE vehicles for ones powered by hybrid, electric, and CNG engines (Figure 3).

In contrast, Scenarios 4 (Computers for Clunkers) and 6 (T Outmoded by Computerized Conventionals), which both introduced Level 3 AVs, exhibited the least improvement compared to baseline emissions (Figure 2). These scenarios both modeled seven AV factors available on in Level 3 (limited self-driving automation) vehicles that reduced energy consumption. The sum of these factors improved fuel economy by 51%. Despite this, Scenario 4's emissions decreased by only 14% and emissions in Scenario 6 actually increased by 7% (Table 20). It appears that the lack of improvement in carbon emissions in both scenarios stems from the fact that ICE vehicles remained on the roads. Although AV technology offers substantial energy savings, it is not enough to overcome the high emission rates of the conventional car engine.

Scenarios 3 through 7 modeled variables in cars whereas Scenarios 2 (Greenest T) and 8 (Cars Outmoded by T) solely modeled potential changes in public transportation. Although Scenario 2 had a modest 21% reduction, the greatest reduction out of all the scenarios modeled was the outcome of Scenario 8 (Figure 3). A modal shift of all passengers from cars to public transportation reduced emissions by 91% compared to the baseline, 14% more than a complete modal shift to Level 4 AVs (Figure 3).

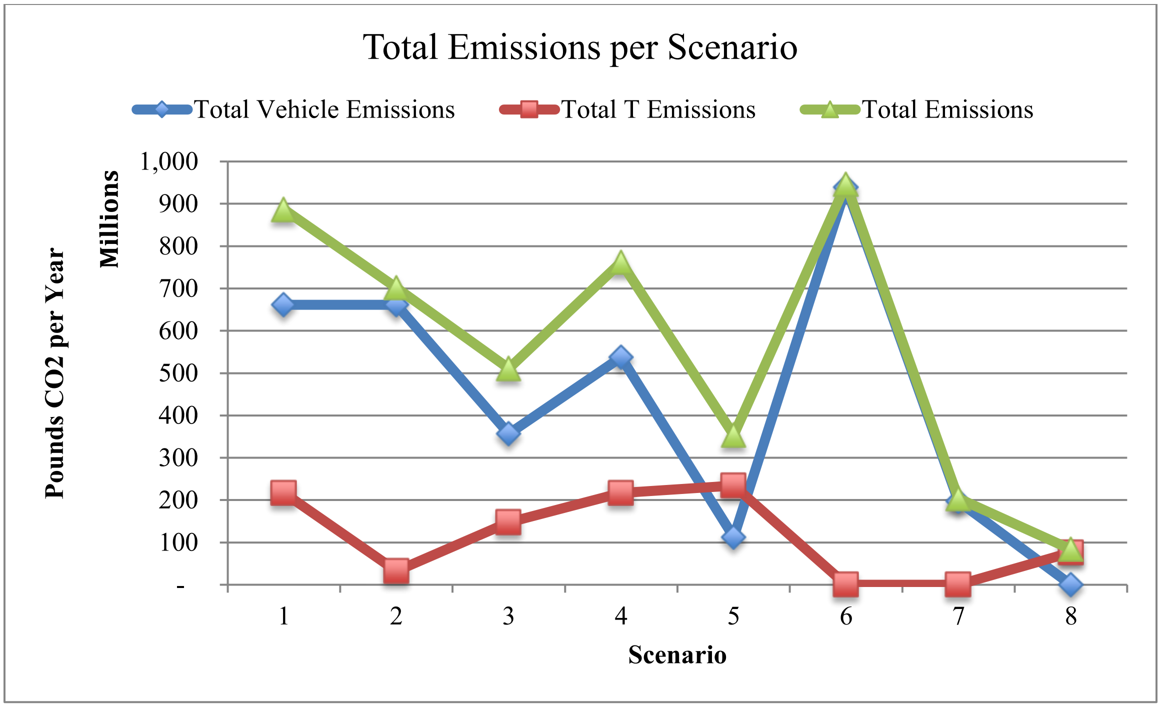


Figure 2. Total emissions in each scenario.

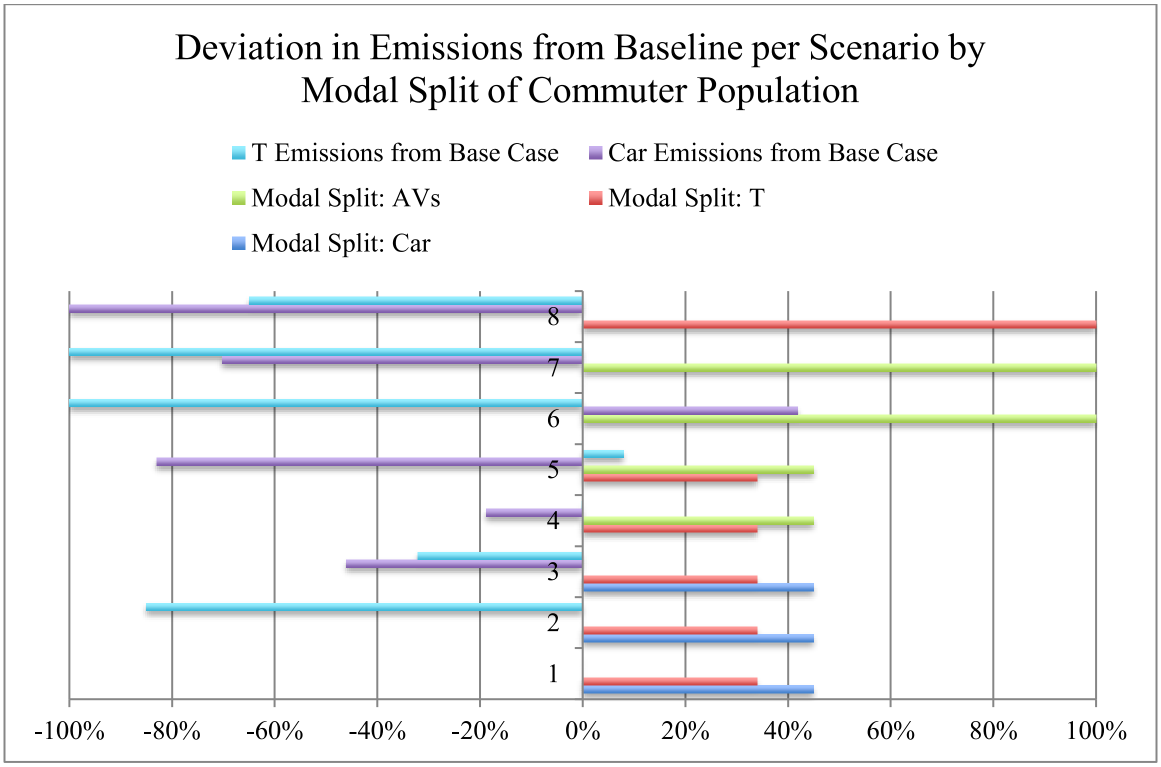


Figure 3. Emissions by cars, public transportation, and public transportation compared to baseline.

Table 20. Summary of pounds CO2 per passenger-mile by mode per scenario.

🟩	Low (<0.1 lb CO2/passenger-mi)	🟨	Medium (0.1-0.3 lb CO2/passenger-mi)	🟧	Med.-High (0.3-0.7 lb CO2/passenger-mi)	🟥	High (>0.7 lb CO2/passenger-mi)

Mode	*Scenario 1*	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Scenario 5*	*Scenario 6*	*Scenario 7*	*Scenario 8*
Car (alone)	0.7215	0.7213	0.3894	0.5122	0.0865	0.5122	0.0865	0.7213
Car (carpool 2-people)	0.3607	0.3606	0.1947	0.2561	0.0433	0.2561	0.0433	0.3606
Car (Carpool 3-people)	0.2405	0.2404	0.1298	0.2213	0.0879	0.2213	0.0879	0.2404
Car (Carpool 4-or-more)	0.1804	0.1803	0.0973	0.1659	0.0659	0.1659	0.0659	0.1803
Car Total	**0.3758**	**0.3757**	**0.2028**	**0.2889**	**0.0709**	**0.2889**	**0.0709**	**0.3757**
Bus	0.4446	0.0013	0.4416	0.4446	0.4446	0.4446	0.4446	0.0013
Trolley Bus	0.2886	0.0519	0.0519	0.2886	0.2886	0.2886	0.2886	0.0519
Streetcar or Trolley car	0.2224	0.0400	0.0400	0.2224	0.2224	0.2224	0.2224	0.0400
Subway or elevated	0.1472	0.0264	0.0264	0.1472	0.1472	0.1472	0.1472	0.0264
Railroad	0.4262	0.2131	0.4262	0.4262	0.4262	0.4262	0.4262	0.2131
Ferryboat	4.2466	1.6617	4.2466	4.2466	4.2466	4.2466	4.2466	1.6617
Paratransit	1.4698	0.0003	0.2546	1.3816	0.1702	1.4698	0.2546	0.0003
T Total	**1.0351**	**0.2850**	**0.7839**	**1.0225**	**0.8494**	**1.0351**	**0.8615**	**0.2850**
Taxicab	0.3866	0.3866	0.3107	0.3634	0.2082	0.3557	0.2082	0.3866
Motorcycle	0.3558	0.3558	0.3558	0.3558	0.3558	0.3558	0.3558	0.3558
Bicycle	0.0080	0.0014	0.0014	0.0080	0.0080	0.0080	0.0080	0.0014
Walk	0.0007	0.0001	0.0001	0.0007	0.0007	0.0007	0.0007	0.0001
Work at home	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Other Total	**0.0029**	**0.0005**	**0.0005**	**0.0029**	**0.0029**	**0.0029**	**0.0029**	**0.0005**
TOTAL	**1.4137**	**0.6611**	**0.9872**	**1.3143**	**0.9232**	**1.3269**	**0.9352**	**0.6611**

Chapter IV

Discussion

Although the widespread adoption of AVs will have many advantages, ranging from increased passenger safety to reducing commuting times, the intent of this analysis was to focus on how the modeling of modal shifts in transportation can help predict reductions in carbon emissions. This model can also be used to complement an evaluation of the overall societal and economic impacts of AVs. Using reductions in green house gas emissions as the key outcome, the benefits associated with various AV factors were effectively categorized, evaluated, and modeled in order to offer insights into how AV technology might impact carbon emissions in the US.

In terms of AV factors, it appears that Level 4 AVs reduce emissions more than Level 3. However Level 4 AV factors coupled with alternative fueled vehicles offers further opportunity for carbon reductions while keeping cars on the road. Strictly from a carbon emissions standpoint, the greatest carbon mitigation strategy is to get cars off the road, regardless of fuel or AV factor, and transport commuters by means of public transportation. With that said, barring any significant external events, such as an economic depression or an oil embargo, it is more likely that the US will see a gradual shift to AVs. Therefore scenarios in which passengers were spread across different modes of transit are more realistic. And of those more realistic scenarios, Scenario 5, where conventional cars were traded in for Level 4 AVs, produced the greatest carbon reduction.

It is important to note that the predicted GHG emissions for each scenario are not exact. The AV variables used for the model were based on theoretical constructs obtained from primary sources and extremely small sample sizes, not real-world or particularly robust data sets. When accounting for carbon emissions, it is also difficult to generate comprehensive findings because a carbon footprint can vary greatly depending on how far upstream or downstream the accounting goes. Here, the model was designed to account for on-road emissions only and therefore should be directionally correct but not necessarily precise in the absolute magnitude between the different scenarios. The model also did not account for commuters that use services like Uber and/or ZipCar to commute and data from these companies were not available to strengthen the AV factors. These startup companies are also good examples of the changing landscapes in the transportation, energy, and business sectors, which make it difficult to precisely model transportation trends.

The model provided in this thesis is a good starting point for further research and analysis of the impact of various mixes of AV modes on delivering specific benefits to consumers and effecting sustainability outcomes. There are several AV factors that were not included in the model that provide additional meaningful societal benefits, such as parking, travel time, efficient routing, and available seats that could be the subjects for further fruitful research. For example, parking is one such opportunity where AVs will have a substantial and beneficial effect on traffic flow, land utilization, and passenger-less miles. The model could also be expanded to take into account additional societal and/or economic impacts, such as people's commute times and/or the cost of replacing functional ICE vehicles with newer, more efficient models. There is also an opportunity to use this same model to compare cities with different modal splits. Journey types other than commuting, such as leisure or travel, could also be analyzed using the model.

Ultimately, approaching AVs from a sustainability standpoint, where people, planet, and profits are equal stakeholders, will help direct this next transportation revolution in the most effective direction. Developing programs that satisfy all these stakeholders is not easy due to the many, often conflicting, factors that must be considered. However, pressure is already mounting on cities and states to accommodate AVs and a systematic approach to evaluate such modal shifts must be implemented to reduce short term thinking and eliminate introduction of ill considered stop gap measures. Public policy demands that a well considered strategy be flexible, sustainable, and based on solid data. Such an approach will enable cities and states to capitalize on the significant opportunities being presented in the transportation sector through the advent of autonomous vehicles.

Appendix

Conversions

1 Calorie (Cal) = 0.0012 kilowatt hours (kWh)

1 Gram (g) = 0.0022 Pounds (lbs.)

High Heating Value (HHV) x 0.90 = Lower Heating Value (LHV)

1 Kilogram (kg) = 2.2046 Pounds (lbs.)

1 Kilometer (km) = 0.62137 Miles (mi)

1 Liter (L) = 0.26417 Gallons (gal)

1 / Miles per gallon = Gallons per Mile

1 Megajoule (MJ) = 0.2778 kilowatt hours (kWh)

1 Million British Thermal Units (MMBTU) = 1,000,000 British Thermal Units (BTU)

1 Megawatt Hour (MWh) = 1,000 kilowatt hours (kWh)

1 Gallon of Gasoline Equivalent (GGE) = 126.67 Standard Cubic Feet (SCF) of Natural Gas

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