Integrating Shared Autonomous Mobility into the U.S. Transportation System: An Equity, Economic, Ethical, and Environmental Assessment

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Abstract

The transportation sector will experience a significant shift with the advent of automated vehicles. As the new technology emerges, shared automated mobility is a potentialopportunity to improve equity, access, and sustainability at potentially lower costs. Automated vehicles and shuttles are agile for dynamic routing and can make use of the existing transportation infrastructure, but operating costs, environmental impacts, and social outcomes remain uncertain.

This dissertation advances the understanding of shared automated mobility when integrated with public transportation and when replacing regional air travel. The first study models unmet service need based on transit dependence and sociodemographic information to assess operation costs of shared autonomous vehicles (SAVs) and autonomous shuttles as a part of a public transit system in southwestern Pennsylvania. Analysis revealed SAVs having the lowest for cost per passenger-kilometer traveled (PKT) ranging from $0.77/PKT to $0.90/PKT. SAVs also had the lowest costs per vehicle kilometer traveled (VKT) with $/VKT between $2.15 and $2.28. Results suggest it is feasible to operate SAVs and shuttles into a public transit system at, on average, lower costs than buses. The tool developed in the first study is used in the second study for different-sized cities and transit systems across the United States to determine if there any unique characteristics of cities and public transportation infrastructure SAV public transportation integration and provided insight into service parameters that lead to the cost-efficient operation of shared automated mobility in different public transit systems. In New York City, there were ten Census Block Groups (CBGs) identified as locations for shuttle service. On average these CBGs experienced a 13% improvement in transit access and costs $1.1 million per CBG on average. In the second largest system, Chicago, two census block groups were most cost-efficiently served by shuttles with a mean cost of $869,000 per CBG for service. One of the mid-sized cities in this study, Minneapolis-St. Paul saw an 18% improvement in transit access for CBGs served by a small SAV fleet. On average adding SAV service in this city cost approximately $179,000 per CBG. Finally, Pittsburgh was compared to our other cities and had the greatest increase in transit coverage at 315% for SAV service in 4 CBGs. New service for

Pittsburgh cost approximately $168,000 per CBG. There are, however, certain conditions where it is still most cost-efficient to add transit access with more conventional modes like bus and rail. The third study assesses to operating costs for trips via shared autonomous electrics vehicles (SAEVs) compared to regional air travel. Ninety-seven of the most common regional aircraft routes were identified as prospective candidates representing approximately 1.2 million flights annually. When the levelized operating costs of SAEVs, privately owned vehicles are regional flights were compared, SAEVs were shown to be the most cost effective and emit the least CO_2. SAEVs were found to be less expensive than planes, costing $0.33 versus $12.22 per RKT. SAEVs displayed cost parity with privately owned vehicles while cutting emissions by 39% on average, signaling the prospect of achieving economic and environmental efficiency through intercity shared autonomous mobility services. The final study explores the ethical responsibilities of engineers that contribute to the development and deployment of AVs. While uncertainty surrounds the AV space as a result of technological novelty, engineering ethical canons provide guidelines for engineers to follow. In its totality, this dissertation improves our understanding of the cost, social, and ethical challenges associated with shared automated mobility in different use cases to better inform AV deployment policy and decision making.

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1 Introduction

1.1. Potential Social Benefits from Autonomous Mobility

Automated vehicles (AVs) shift the responsibilities of driving tasks from human drivers to machines. Commercialization of AVs has been considerably delayed due to technological challenges and policy stagnation. Despite the challenges, automakers and technology companies continued to research and pilot a variety of autonomous vehicles to develop commercial use cases and prepare for deployment (Coyner et al. 2021; Steckler et al. 2021). Once introduced to the passenger transportation sector, AVs could potentially result in many societal benefits. Early analyses suggest that the most considerable gains could be fewer crashes (Anderson et al. 2014; Fagnant and Kockelman 2018; Greenblatt and Saxena 2015; Harper et al. 2016; Khan et al. 2019; Metz and Metz 2018), less congestion (Fagnant and Kockelman 2018; Greenblatt and Saxena 2015; Metz and Metz 2018), reduced vehicle energy and emissions (Fagnant and Kockelman 2018; Greenblatt and Saxena 2015; Litman 2018a; Mersky and Samaras 2016; Taiebat et al. 2018; Vahidi and Sciarretta 2018), reduced urban parking requirements (Harper et al. 2018), and increased productivity (Fagnant and Kockelman 2018).

Improving access and mobility for those physically unable to drive is another substantial incentive for continuing to develop fully autonomous vehicles. Studies show that it is vital that seniors have access to transportation choices for their health and aging in place (Litman 2020; National Association of Area Agencies on Aging 2022; Pathak et al. 2011). The same is true for the six million differently-abled individuals in the US (Khan et al. 2019; Securing America's Future Energy et al. 2017). Many modes of transportation remain inaccessible, unreliable, or unsuitable for many disabled people. Transportation issues disproportionately affect this population, highlighting a systemic barrier that may contribute to lower rates of employment, education, and income. AVs are promising as they can provide independent mobility for these populations. There is an incredible opportunity to capture the positive social benefits of AVs. The equitable distribution of these benefits however depends on how AVs enter the market. AV technology without equity considerations threatens to exacerbate disparities.

Table 1.1: Summary Table for SAE's levels of automation.

SAE Levels of Automation	**Level 0 - Human Driving**	**Level 1 - Human Driving**	**Level 2 - Human Driving**	**Level 3 - Human/ Automated Driving**	**Level 4 - Automated Driving**	**Level 5 - Automated Driving**
Human Driver Responsibility	Human must steer, brake, or accelerate	Human must steer, brake, or accelerate	Human must steer, brake, or accelerate	When requested the human must steer, brake, or accelerate	Automated Driving under certain driving conditions	Automated Driving under all driving conditions

If Level 4 and Level 5 AVs (Level 4 vehicles can only function within a set operating range, whereas Level 5 vehicles can operate in any situation while adhering to ethical standards) enter the market as privately-owned vehicles for consumer purchase, the potential social benefits will be concentrated on the segments of society that can afford them. The owners of the first fully autonomous vehicles will likely be those with the means to purchase the vehicles. When safety, economic, and environmental benefits are skewed to only those with higher socioeconomic standing, inequities arise. If shared automobility is offered as a service, ensuring equitable service is still a concern. Shared autonomous mobility only available through private companies could potentially decrease transit ridership leading to reduced levels of service, which would impact transit-dependent riders acutely. Also, unlike public transit agencies, privately-owned companies are not mandated to operate equitably. If AV companies are not intentional about equity in choosing service areas and outcompete existing transit, zero-vehicle, low-income households will be excluded from social opportunities of all forms.

Various studies assess the positive impacts of shared AVs in a city and discovered road and economic efficiencies (Fagnant and Kockelman 2018; Spieser et al. 2014). These studies demonstrate that while the positive effects of AVs are feasible when they are shared, the replacement scenarios presented would necessitate rapid and significant regulatory and traveler behavior changes. Other studies have examined the first and last mile use cases of SAVs, in which they deliver or pick up customers at their residences and transport them to adjacent bus or rail terminals (Gurumurthy et al. 2020; Shan et al. 2021; Shen et al. 2017). Some reports examine low-speed autonomous electric shuttle service as a shared autonomous mobility solution (Berschet et al. 2017; Coyner et al. 2021; Smart Columbus 2021; U.S. Department of Transportation 2017). Several shuttle pilot schemes include first- and last-mile transportation access to the current public transit system (Smart Columbus 2021; The Swiss Transit Lab 2018). Other initiatives make use of shuttles to transport participants between university campuses and senior living homes. These studies and pilot programs reinforce the positive benefits of shared autonomous mobility solutions over privately owned vehicles. Further, these studies offer strategies available for introducing AVs and capturing the social benefits equitably. Public transit agencies can manage a fleet of SAVs or shuttles and consequently can provide an equitable level of access for choice and transit-dependent riders. While the first and last mile service and ridesharing are viable options, they are not the only opportunity to access the benefits of SAVs; long-distance trips may provide some environmental or economic benefits as well.

1.2. Economic Impact of Autonomous Mobility

Reducing vehicle crashes and injuries are the most lauded potential economic and social benefits of introducing AV technology (Bagloee et al. 2016; Crist and Voege 2018; Kalra 2017; Khan et al. 2019). In 2016, there were 7.3 million crashes and 37,461 fatalities in the United States (Khan et al. 2019; U.S. Department of Transportation 2018), totaling $242 billion in economic costs, growing to $836 billion when societal costs are included (U.S. Department of Transportation 2018). Collision avoidance technologies made available in early automated vehicles are expected to decrease crashes and fatalities (Anderson et al. 2016; Kalra 2017) with one study estimating 1.3 million fewer crashes annually (Harper et al. 2016). This reduction in crashes with currently available automated technologies equates to $202 billion in economic and societal benefits (Harper et al. 2016) if the entire U.S. vehicle fleet possessed these features, and they were always effective in avoiding crashes. Even if ten percent of vehicles on the roads were fully automated, an estimated 211,000 fewer crashes would result in $25.6 billion for economic and $38.1 billion for social and economic cost savings combined (Fagnant and Kockelman 2015). Reducing crashes also leads to less congestion due to crash clean-up, less emergency response activity from fewer crashes, reduced insurance costs, along with a reduction in the associated costs (Khan et al. 2019). Driver warning systems and partial automation can also be useful when coupled with vehicle connectivity to achieve crash reductions (Zhang and Cassandras 2018). The potential economic benefits of safety improvements provide a strong case for encouraging this technology.

AV companies like Waymo, Cruise, and Ford Motor Company are testing their vehicles in small fleets around the U.S. (Feigon et al. 2016; Krafcik 2018). In September 2016, Pittsburgh became the first city with partially automated vehicles provided through Uber (Bloomberg Philanthropies and Aspen Institute 2018). The fleet provided ride-hailing services by using their application to match riders with partially automated vehicles. In March 2022, Waymo and Cruise received permits to charge for trips served by their fully autonomous vehicles in San Francisco (Reuters 2022). The permits represent a positive move towards profitability for AV companies looking to enter the passenger travel market as they are ready for a return on investment. City commutes are more commonly used for analysis and piloting, however, there is a subset of literature that explores long-distance trips. Some domestic long-distance trips could experience up to a 50% shift from air travel to AVs once they are made widely available (Miller 2020).

Electric and autonomous shuttles are minibuses, one-third the size of conventional transit buses. The passenger capacity ranges from 12 to 15 total and typically has seating available with 4-6 standing passengers to reach maximum capacity. Shuttles operate at lower speeds and their predictability reduces risks that act as a barrier for private autonomous vehicles (Hunter 2018). More than one hundred testing deployments of autonomous shuttles have taken place globally as they are well-suited to provide first and last-mile service for short-distance tourist destinations and university campus transit routes (Berschet et al. 2017; Comfort 2018; Cregger et al. 2018; Moorthy et al. 2017). Some pilot programs for shuttles are including service to the existing public transit system in the form of first-mile, last-mile transit access. One of the first shuttle-public transit integration was located in Schaffhausen, Switzerland. They integrated an electric, autonomous shuttle fleet into the existing public transportation system (The Swiss Transit Lab

2018). The fleet uses its existing infrastructure, traveling on a planned route that is fully integrated into the local transit timetable (The Swiss Transit Lab 2018). This program demonstrates the feasibility of public transit agencies using shuttles for fixed-route service. In addition to testing pilots, studies assess factors like life cycle emissions, public perception (The Swiss Transit Lab 2018), congestion (Feigon et al. 2016), and economic activity (Zhang et al. 2018), but equity impacts have not been included at the time.

The cost associated with operating shared automated vehicles is an important factor in decision-making, regardless of private or public operation. To date, numerous studies have estimated operating costs for automated vehicles and shuttles in a variety of sharing scenarios. Automated taxis (Bauer et al. 2018; Bösch et al. 2018; Fagnant and Kockelman 2018) and AV ride-sharing (Fagnant and Kockelman 2018; Fulton et al. 2020; Narayanan et al. 2020) were more prominent scenarios in existing literature reporting a range from $0.11/km to $1.03/km. The discrepancy in results could be attributed to many studies not including overhead, parking, maintenance, and cleaning in the analysis, potentially overstating the benefits of SAVs (Narayanan et al. 2020). These findings are also limited since automated technology is still under development, so the associated costs vary between studies over time. There is a growing body of literature on integrating shared automated mobility into public transit. One study explored demand-responsive transit using SAVs reported costs between $0.19/km and $0.30/km (Litman 2018b). Another study found that using SAVs for first and last miles service for public transit costs $0.39/km (Moorthy et al. 2017). Shared automated mobility is still evolving to provide pragmatic information for future transportation policymaking but is still grappling with uncertain technology costs, fleet sizing, repositioning vehicles, and more.

The actions of autonomous vehicle manufacturers and related industrial partners, as well as the interest from policymakers and researchers, point towards the likely initial deployment of autonomous vehicles as shared autonomous mobility services as AV companies are ready for a return on investment. However, the variability in operating costs leads to uncertainty regarding the profitability of SAVs. Policymakers need pragmatic information to form AV policy but are still grappling with uncertain technology costs and operation costs, fleet sizing, and other factors (Narayanan et al. 2020).

Without policy in place, AV companies could develop business models that compete with existing transit and exclude low-income individuals from the benefits of the technology. For example, policymakers are concerned that SAVs may arrive on U.S. streets and leave an impact similar to Transportation Network Companies (TNCs) like Uber and Lyft. Some cities have embraced these companies' presence, finding that public transit ridership and access have improved (Ward et al. 2021). Other cities have experienced the complete opposite—declining ridership leading to shrinking budgets that ultimately diminish transit access for those with the greatest need. Since new mobility solutions from private companies are also not currently beholden to equity mandates like public transit agencies the concern about potential negative equity externalities is justified. However, profitability is paramount for AV companies that have invested billions in research and development of the technology and will guide decision-making in the absence of holistic public policy. If economic viability is not confirmed, AV companies could suspend the deployment effort and the potential lifesaving, access-improving, emissions-reducing benefits will not be achieved. Thus, uncovering the middle ground where social benefits are maximized, social costs minimized, and financial feasibility achieved, is of interest to both policymakers and AV companies.

1.3. Environmental Impact from AVs

AVs may not only improve the economy and society but also the environment, depending on technologies and policies. Changes in vehicle usage, vehicle design, and transportation systems can reduce energy consumption and GHG emissions (Anderson et al. 2016; Greenblatt and Saxena 2015; Harper et al. 2016; Wadud et al. 2016). Eco-driving and collision avoidance could save fuel usage by up to 25% (Chase et al. 2018; Mersky and Samaras 2016; Vasebi et al. 2018; Wadud 2014). Additionally, modifications in vehicle design, such as changes in vehicle size and electrification, could reduce GHG emissions (Greenblatt and Saxena 2015). Improved road capacity through platooning and more efficient driving patterns (Anderson et al. 2016; Fagnant and Kockelman 2015) are examples of transportation system modifications. Increased throughput allows for more efficient use of road space allowing for more pedestrians, cyclists, and public transportation (Rouse et al. 2018).

While the potential for energy savings for AVs is widely recognized even at Level 2 and Level 3 (Mersky and Samaras 2016; Vasebi et al. 2018), the future environmental consequences of a fully autonomous US vehicle fleet are unknown. The perceived economic and social costs of driving will diminish (Litman 2017), causing changes in travel behavior. Improved mobility for people unable to drive due to age or disability could result in a 14% rise in VMT and energy consumption (Harper et al. 2016; Trommer et al. 2016). More travel could reduce fuel savings and pollution. Several studies claim that even with increased VMT, total fuel savings could be realized (Anderson et al. 2016; Greenblatt and Saxena 2015). The influence of AV technology on energy use and emissions is one example of considerable uncertainty.

Transportation systems will likewise evolve, both positively and negatively. Changing roadway design and associated procurement and maintenance expenses will be required to connect vehicles to pedestrians, bicycles, public transit, emergency vehicles, and others (Hanna and Kimmel 2017; Kockelman et al. 2016). Also, as AV market share grows, parking demand is predicted to decrease, leaving 30% of Central Business District (CBD) property accessible for residential, commercial, or recreational development (Harper et al. 2018).

Transportation is the world's second-largest emitter of CO_2 (Baumeister 2019). While vehicle transport contributes the most to emissions, air travel contributes 12% and is expanding at 6% per year globally (Miller 2020). Like other modes of transport, aviation has enormous human and environmental externalities. With low passenger density, regional air travel is the worst emitter and decarbonization has become increasingly challenging (Baumeister 2019). Increasing environmental and airplane control in the early 2000s improved noise, local air quality, and ozone depletion. Regional airports are vital to transportation infrastructure (Gao and Sobieralski

2021), but some of these trips might be shared, automated, and electrified. However, the economic and environmental effects of a mode transition have not been extensively examined.

Over time, U.S. regional aviation has continued to grow and so has its impact on the U.S aviation sector. Total passenger capacity from regional aircraft increased 3% from 2009 to 2018, totaling 90 million available seat miles. Research shows that short-haul flights have the most inefficient fuel consumption per passenger (Chester and Ryerson 2013). Regional aviation undermines the aviation sector's fuel efficiency and CO_2 emissions reduction goals and mitigation efforts have the potential to markedly reduce aviation emissions in the U.S. and the world. Mounting environmental pressure on the aviation industry has prompted significant efforts to reduce emissions. International and federal governing bodies have established standards and regulations that promote new technologies, materials, and travel behavior as mitigation practices (Federal Aviation Administration 2005; Graham et al. 2014; Singh et al. 2018). But growing demand for air travel may outpace technological advances leaving emissions reductions goals unrealized.

Shifting passengers to a more sustainable mode can reduce air demand and contribute to reducing emissions. Regional flight is already competing with other modes but mounting pressure to decarbonize aviation along with the pending deployment of autonomous vehicles presents new competition. Further, positive environmental benefits can potentially be realized; Mackenzie et al. (2016) found a 20% reduction in emissions with a transition to shared autonomous electrified vehicles (SAEVs). Intercity travel with SAEVs is not currently being tested, but some studies suggest passengers are willing to pay for such a service (Gurumurthy and Kockelman 2020).

1.4. Ethics Of Autonomous Vehicle Mobility

Automated vehicles (AVs) also present a challenge for those responsible for developing, deploying, regulating, and using the technology. There are ethical concerns that require the participation of legislators, economics, automakers, and the general public, among others.

Engineers from a variety of disciplines contribute to or interact with AV technology, providing a unique chance to contribute meaningfully to the AV ethical discourse.

A well-publicized ethical challenge with autonomous vehicles revisited a thought experiment known as the "trolley problem" which examined the ethical dilemma of limiting injury to drivers or spectators when an accident is unavoidable (Thomson 1984). Concerns about the ethical implications of an AV's decision-making algorithm in the case of an accident have garnered widespread public and academic attention. Although the trolley dilemma is hypothetical, oversimplified, and overused, the activity surrounding it has benefits. AV ethical problems are now front and center creating an opportunity to broaden the conversation to include additional crucial ethical issues surrounding AV technology (Goodall 2016, 2017).

The fields of technology, transportation, and policy encompass the ethical dimensions of critical sociotechnical systems and their interaction with AV technology (Borenstein et al. 2017). Each area was chosen because it was a recurring theme in the current engineering ethics literature on AVs, which focuses on the most salient challenges surrounding this innovative technology. Technology is critical since it is concerned with the creation and implementation of software and hardware that allows the capabilities of AVs. The second domain, transportation systems, encompasses physical infrastructure like roadways, privately owned and shared modes of transit, and the subsequent consequences of AV deployment. Transportation systems raise significant ethical considerations since autonomous cars will be deployed on current transportation infrastructure and will affect future infrastructure decisions as AV technology spreads across the automobile industry. Finally, the policy domain is significant because it represents state and federal regulatory activities as well as the bidirectional effect of AV technology and policy. Policy considerations and actions alter the transportation and technology sectors, hence affecting the ethical concerns surrounding AVs that engineers may address. Examining ethical challenges within each domain identifies places where risk reduction efforts should be concentrated. More precisely, uncovering ethical issues in each domain allows for a clearer understanding of engineers' contributions to AV ethics.

1.5. Research Objectives

Self-driving vehicles offer the promise of significant benefits to society but raise several challenges. There is a growing body of literation on the ethical, environmental, equity, and economic dimensions of AVs but the literature requires constant updating due to technological advances, and many studies lack specificity regarding the equity outcomes from and across different AV use scenarios. This dissertation provides an update on the environmental and economic impacts of shared autonomous mobility across different use cases in different cities. There is a heavy emphasis on detailing potential equity outcomes and the associated social cost for the benefits.

In this dissertation, I will address the challenges outlined above by examining shared automated mobility in transportation systems. I will examine equity, ethics, environmental impacts, and cost-effectiveness through the following research projects:

1. Determine the feasibility of improving equitable transit access using autonomous technology as a part of a public transit system.

2. Analyze four different sized public transit systems across the United States to uncover any unique characteristics of systems that have the highest improvement in coverage at the lowest operating costs.

3. Estimate emissions savings and operating costs for a mode shift from air travel to SAEVs for regional air travel in the United States.

4. Elucidate the ethical responsibilities of engineers that contribute to AV development and deployment within critical socio-technical domains.

1.6. Dissertation Structure

This dissertation consists of this introduction and four additional chapters, of which two have been published and the remaining two are undergoing preparation for submission to peer-reviewed journals. Cited publications are listed at the end of each chapter. Chapter 1, the introduction (and current chapter) provides background information and motivation for the research in this dissertation. Chapter 2, published in 2022 in Transportation Research Interdisciplinary Perspectives, explores the economic and equity impacts of SAVs and shuttles integrated with public transit in Pittsburgh, PA. Chapter 3 builds on the model built in Chapter 2 and investigates four urban transit systems of varying sizes and sociodemographic composition to determine the service metrics for equitable and economically viable SAV and shuttle service. Chapter 4 assesses the environmental and economic impacts of intercity shared autonomous mobility by looking at 97 city pairs as candidates for regional flight replaced with shared, electric autonomous vehicles. Chapter 5, published in 2022 in ASCE Journal of Transportation Engineering Part A: Systems, delineates the ethical responsibilities of engineering according to their professional engineering organization codes of ethics. Finally, Chapter 6 presents a summary and overall conclusions from the studies included in this dissertation and suggests areas for future work.

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2 Integrating Public Transportation and Shared Autonomous Mobility for Equitable Transit Coverage: A Cost-Efficiency Analysis [1]

2.1. Abstract

As automated transportation technology advances, public transit agencies could consider how integrating autonomous vehicles and shuttles into existing transit systems affects equity. Capital and operating costs for automated mobility modes managed by public transit agencies are uncertain since few deployments have occurred to date. Automated vehicles and shuttles are agile for dynamic routing and can make use of the existing transportation infrastructure, but operating costs remain uncertain. This study aims to characterize the economic feasibility of improving transit coverage and transit equity of public transportation with shared automated mobility. Cost efficiency analysis compares direct operating costs of shared autonomous vehicles (SAVs) and autonomous shuttles to a conventional transit bus. Using Allegheny County, Pennsylvania as a case study, the analysis considers potentially adding shuttle or SAV service to expand service for the existing public transit system. The results suggest it is feasible to improve transit equity with shared AVs and shuttles at lower costs than buses on average. Revenue kilometers traveled, fleet size, and operating hours are the most important parameters that determine cost-efficiency. Transit planners and policymakers can use this analysis to inform shared autonomous mobility operation guidelines to ensure emerging technology services remain a complement to existing transit.

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2.2. Introduction

U.S. public transportation agencies are responsible for enabling mobility within their service area by providing transit services. In their role, agencies uniquely serve the transit-dependent population, which relies more heavily on mass transit for social, leisure, and economic opportunities (Litman, 2018a). Transit-dependent populations often overlap with populations that are economically, physically, and socially disadvantaged (Jiao and Dillivan, 2013). So, transit agencies are responsible for maintaining equitable levels of transit service for both choice riders and transit-dependent riders. This requirement for equity in service was formalized in Title VI of the Civil Rights Act of 1964 and now equity analysis is conventional for public transit agencies, although each agency is left to determine its method of analysis. As a result, there are variations in equity analysis from one transit agency to another (Welch and Mishra, 2013). Subsequently, analyses may not completely capture the transit-dependent population. Transit equity analysis is also routinely overlooked in conventional transportation economic evaluation (Litman, 2018b) as it is generally analyzed separately from another measure, transit coverage. Transit coverage analysis serves as an informative indicator of transit service for public transit agencies when making changes to a system (Kittelson & Associates, Inc. et al., 2013). Transit coverage analysis is typically achieved spatially, temporally, or both, which can satisfy different transit agency service objectives. Both analyses are important for agencies in ensuring equitable coverage of transit.

Concurrently, advanced mobility solutions are emerging and expanding the suite of options for transit agencies to enhance services. The timeline for autonomous vehicle (AV) deployment and market acceptance is uncertain; however, shared autonomous vehicles (SAVs), are being deployed in small fleets by private companies (Fagnant and Kockelman, 2018; Feigon et al., 2016; Krafcik, 2018). Also, electric autonomous shuttles are being deployed as a transit solution and hold a larger passenger capacity than traditional cars or SUVs (Polzin, 2016; U.S. Department of Transportation, 2017). Operating SAVs and shuttles in public transit systems is uncertain, with few analyses exploring operating costs compared to other forms of mobility.

Furthermore, the existing literature has not evaluated how SAVs, or shuttles can affect transit access and equity for transit-dependent populations.

The aim of this study is to characterize the economic feasibility of improving transit coverage and transit equity of public transportation with shared automated mobility. More specifically, this paper attempts to answer the following questions using the Port Authority of Allegheny County transit system:

1. What is the socio-demographic profile of the transit-dependent population in Allegheny County?
2. How much does it potentially cost for SAVs and autonomous shuttles to improve public transit access for transit-dependent travelers?
3. Which service parameters are most important for shared automated mobility-public transportation integration to remain complementary?

Transit gap analysis tools that combine transit coverage and equity analysis identify priority services areas in a transit system based on transit dependency. The priority service areas have both unmet transit needs and equity challenges according to the sociodemographic characteristics of a census block group. Then, the priority service areas are used to perform a cost-based analysis for operating shared autonomous vehicles or electric autonomous shuttles as part of a public transit system. This paper makes a contribution to the literature by evaluating the economic and equity outcomes of shared automated mobility vehicles and shuttles operating as a part of an existing public transit system. By prioritizing transit dependent riders, this study also furthers the conversation regarding equity of autonomous vehicle technology. The scenarios presented in this analysis present a path towards AV deployment that furthers transit equity and preserves existing public transportation.

2.3. Literature Review

2.3.1. Transit Equity

Transit equity refers to the distribution of service from public transportation agencies across different populations (Jiao and Dillivan, 2013; Wei et al., 2018). Equity analysis aims to understand whether transit system services are provided in a nondiscriminatory manner (U.S. Department of Transportation, 1964) so that non-white and low-income populations are not worse off than the general public (U.S. Environmental Protection Agency, 2016). Another population of concern in transportation planning, termed transit-dependent, can overlap with populations that are prioritized in equity analysis (Wei et al., 2018). Transit-dependent populations are defined by the American Public Transit Association (APTA) as populations ages 65 or older, children between ages 6 and 12, households without a car, and the population physically unable to drive. Other definitions expand the groups considered transit-dependent, explicitly including populations below the poverty level and non-white populations (Feigon et al., 2016). APTA surveyed transit riders and found that 21.6% of respondents were transit-dependent (Neff and Pham, 2007). The survey results highlight the need for equitable access to public transportation by this subset of riders as respondents reported that they would lose their access to mobility if public transit were no longer available (Chowdhury et al., 2016; Neff and Pham, 2007).

Transit planning has responded and organized operations around the commuting population at the expense of transit dependent riders who rely on public transport to meet multiple needs on a daily basis (Jiao and Wang, 2021; Lubitow et al., 2017). The assumption about mobility patterns in tangent with the promotion of and investment in private vehicle ownership has resulted in declining public transit service and access for transit dependent riders. Studies also suggest transit systems that are planned around commuter or choice riders contribute to the social exclusion of transit dependent riders who may be a part of low-income, disabled or racial minority populations (Chen et al., 2021; Lubitow et al., 2017; Merlin et al., 2021).

Transport equity analysis is challenging because there are several types of equity issues, with varying impacts to consider and several ways to measure those impacts (Twaddell et al., 2019). Some approaches are customized to identify areas with a high concentration of multiple types of underserved populations (Feitelson, 2002; Twaddell et al., 2019), like those of interest in this study. Several qualitative studies assess the implications of changes to transit service on the mobility of the transit-dependent population (Fagnant and Kockelman, 2018; Wei et al., 2018). Alternatively, quantitative studies have performed transit equity analysis via transit coverage (Litman, 2018b; S. A. Mamun and Lownes, 2011) as well as the costs of achieving social equity from both the agency and rider perspective (Carleton and Porter, 2018; Feitelson, 2002, 2002; Garrett and Taylor, 1999; Wei et al., 2018). These studies examine the status quo modes of public transportation: rail, bus, rapid service. As new technology emerges in the transportation sector, achieving or improving equity in access is still important to consider. Changes to transit will occur as more systems implement advanced mobility solutions like shared autonomous vehicles and electric autonomous shuttles.

2.3.2. Transit Coverage

Transit coverage is a level-of-service measure that evaluates spatial transit availability across a large-scale network (Ding et al., 2018; Fayyaz et al., 2017). Coverage measures are especially useful for revealing latent or unmet transit needs in a transit system (Kittelson & Associates, Inc. et al., 2013). Transit coverage analysis output is the percentage of a population that can potentially be served by the transit system (Fayyaz et al., 2017; Jiao and Dillivan, 2013). For example, systems might provide service to 80% of the service area or 65% of the population. Evaluating transit coverage typically requires spatial or temporal data to indicate service coverage across a system, satisfying different transit agency service objectives. Transit planning and service analysis typically include a coverage service objective for trips such as short passenger wait times, which is evaluated using temporal data (Fayyaz et al., 2017; Kittelson & Associates, Inc. et al., 2013). Alternatively, spatial and population data can be used to establish the percentage of the area that can access a transit stop (Fadaei and Cats, 2016).

Time-of-Day, Local Index of Transit Availability (LITA), and the Transit Capacity and Quality of Service Method (TCQSM) are three conventional approaches used for evaluating system-level coverage (Carleton and Porter, 2018; M. Mamun and Lownes, 2011). The Time-of-Day approach is an evaluation tool that uses a relative value of transit service across time in a day (S. A. Mamun and Lownes, 2011), producing a score for level-of-service during peak and off-peak hours. The Time-of-Day tool uses temporal transit demand data to make clear where transit demand is unmet, which can lead to changes in frequency or transit capacity to meet the demand (Ibarra-Rojas et al., 2015; Polzin et al., 2002). While adjusting transit service based on the temporal need will improve the riding experience, studies that only employ temporal analysis evaluate service for the population currently with transit access instead of the population that may still require service. Spatial methods for evaluating transit coverage are more robust in that they can capture the demographic information (Jiao and Dillivan, 2013), although the emphasized indicators can still vary.

The Local Index of Transit Availability (LITA) approach measures the service intensity based on the capacity, frequency, and service coverage of a system (Rood, 1999). The service intensity is related to the population of smaller areas of measures such as traffic analysis zones or census block groups which yield scores for the system (S. A. Mamun and Lownes, 2011; Rood, 1999). The LITA scores combine spatial and temporal coverage, unlike the Time-of-Day tool which only examines the temporal coverage of a transit system. This approach also uniquely evaluates passenger comfort and convenience by incorporating transit vehicle capacity (Rood and Sprowls, 1998). Although developed by transit planners Rood and Sprowls (Rood and Sprowls, 1998), this tool is better suited for use in coordinated land use and transit planning, or transit-oriented land development, rather than solely transit planning (M. Mamun and Lownes, 2011).

The Transit Capacity and Quality of Service Manual (TCQSM) uses temporal and spatial data to determine system coverage (Ding et al., 2018; Kittelson & Associates, Inc. et al., 2013; Wei et al., 2018). The systematic approach measures temporal accessibility at transit stops with various temporal measures such as dwell time, speed, and reliability (Kittelson & Associates, Inc. et al., 2013). This method also evaluates spatial service coverage in an area using proximity-based analysis. Areas with population density sufficient for hourly transit service are emphasized so the more a system provides service to high-density areas, the higher transit coverage it has according to the TCQSM. The TCQSM approach is useful; however, the focus on high-density areas does not necessarily capture a high density of demand by the transit-dependent population (Jiao and Dillivan, 2013). The TCQSM approach is used in this study, refocusing coverage analysis on the transit-dependent population specifically.

2.3.3. Shared Autonomous Mobility

Emerging mobility solutions seek to use automated technology to transition from a human-driven vehicle ecosystem to a computer-driven environment (Litman, 2018b). Previous studies note an array of potential societal benefits like fewer crashes (Anderson et al., 2014; Fagnant and Kockelman, 2018; Greenblatt and Saxena, 2015; Harper et al., 2016; Khan et al., 2019; Metz and Metz, 2018) less congestion (Fagnant and Kockelman, 2018; Greenblatt and Saxena, 2015; Metz and Metz, 2018) reduced vehicle energy and emissions (Fagnant and Kockelman, 2018; Greenblatt and Saxena, 2015; Litman, 2018b; Mersky and Samaras, 2016; Taiebat et al., 2018; Vahidi and Sciarretta, 2018), reduced urban parking requirements (Harper et al., 2018), and increased productivity (Fagnant and Kockelman, 2018) although the magnitude and even the sign of these impacts depend on assumptions, technologies, and policies (Anderson et al., 2014; Taiebat et al., 2018; Wadud et al., 2016). Auto manufacturers are increasingly adding partially automated features to their vehicles and policymakers are outlining regulations anticipating the deployment of highly automated vehicles. Yet, full-scale deployment of privately-owned AVs brings about a new set of risks, creating barriers to adoption (Bezai et al., 2020). Evaluating risks using on-road testing could take up to hundreds of years to reach a level of certainty equivalent to conventional vehicle safety tests (Kalra, 2017). Postponing deployment to accumulate the hundreds of millions of miles is not considered prudent because avoidable vehicle fatalities would continue in the meantime (Kalra, 2017). As a result, policymakers are working to develop a flexible regulatory framework to work around these risks to facilitate the successful adoption of the technology. Testing deployments have occurred with and without the shared use of autonomous technology in the U.S. and throughout the world (U.S. Department of Transportation, 2017).

To date, numerous studies have estimated costs for automated vehicles and shuttles in a variety of sharing scenarios. The cost associated with operating shared automated vehicles is an important factor in decision-making, regardless of private or public operation management. All dollar values of past studies are converted into $2019 for comparison, using the Consumer Price Index. Automated taxis (Bauer et al., 2018; Bösch et al., 2018; Fagnant and Kockelman, 2018) and AV ridesharing (Fagnant and Kockelman, 2018; Fulton et al., 2020; Narayanan et al., 2020; Turoń and Kubik, 2020) were more prominent scenarios in existing literature, reporting a range of operating costs from $0.11/km to $1.02/km. The range of results could be attributed to some studies omitting overhead, parking, maintenance, and cleaning in cost analysis, which may overstate the cost benefits of SAVs (Narayanan et al., 2020). Also, because automated technology is still under development, the associated costs vary between studies over time while deployments provide pragmatic acquisition and operational costs for AVs and shuttles. Many studies explore costs associated with AVs used for ride-hailing and as taxis, resulting in a gap in the literature on costs for integrating shared automated mobility into public transit (Golbabaei et al., 2020).

Although automated vehicle-public transit operational feasibility is being established (Levin et al., 2019; Mo et al., 2021; Pinto et al., 2020; Wei et al., 2018), cost analysis studies have reported costs between $0.19/km and $0.30/km and up to $0.39/km for SAVs providing first and last-mile service in a public transit system (Moorthy et al., 2017). Shared automated mobility is still evolving to provide pragmatic information for future transportation policymaking but is still grappling with uncertain technology costs, fleet sizing, regulatory requirements, and other factors (Narayanan et al., 2020). Meanwhile, more than one hundred testing deployments of autonomous shuttles have taken place globally as they are well-suited to provide service for short-distance trips like tourist destinations and university campus transit routes (Iclodean et al., 2020; Smith, 2014). Shuttles operate at lower speeds and their predictability reduces risks that act as a barrier for private autonomous vehicles (Hunter, 2018). Some pilot programs for shuttles include service to the existing public transit system (Smart Columbus, 2021; The Swiss Transit Lab, 2018) in the form of first-mile, last-mile transit access.

Cities that tested AV technology have found that publicly-led testing and pilots provide the best opportunity to shape local AV deployment (Chatman and Moran, 2019), incentivizing transit agencies to provide shared autonomous mobility. If shared autonomous mobility is only available through private companies, the potential decline in transit ridership could lead to reduced levels of service (Litman, 2020), which would affect transit-dependent riders acutely. Also, ensuring equitable service from mobility-as-a-service companies is an ongoing concern. Unlike public transit agencies, privately-owned companies are not mandated to operate equitably at this time. However, public transit agencies can expand their transit services by managing or contracting a fleet of SAVs or shuttles and subsequently provide an equitable level of access for choice and transit-dependent riders (Mo et al., 2021; Narayanan et al., 2020).

2.4. Data & Methods

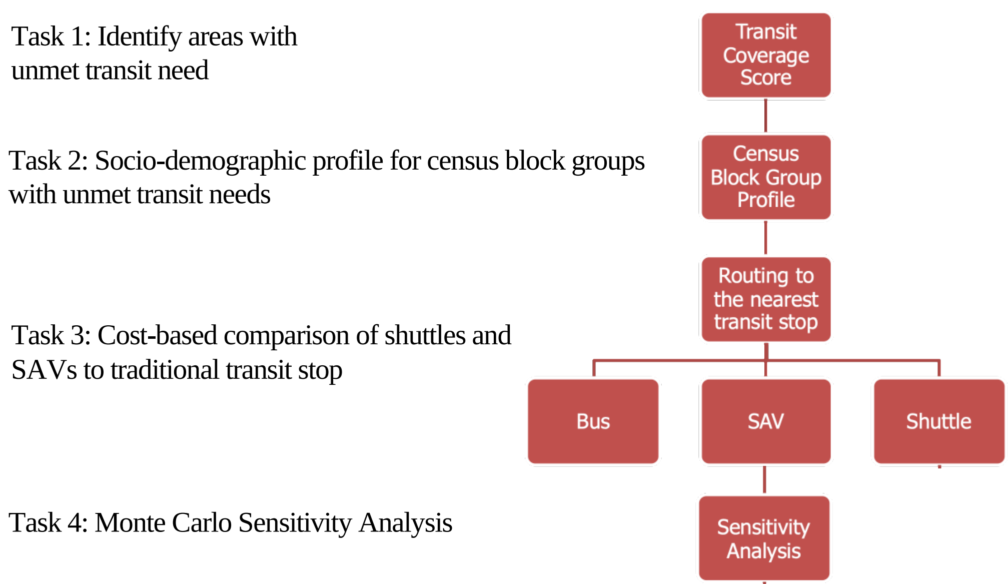

Figure 2.1: Graphical Summary of the study methods.

Multiple methods and datasets for assessing operating costs and equity outcomes of shared automated vehicles and shuttles integrated into a public transit system. Census and EPA data provided demographic details to represent the transit-dependent, low-income, and minority populations in each census block group and determine transit needs. We used multiple methods and datasets for assessing operating costs and equity outcomes of shared automated vehicles and shuttles integrated into a public transit system. Census and EPA data provided demographic details to represent the transit-dependent, low-income, and minority populations in each census block group and determine transit needs. Census block groups (CBG) are divisions of census tracts generally covering a continuous area, and typically contain between 600 to 3000 people (U.S. Census Bureau, n.d.) CBG level data is used throughout the study because smaller, low-income or minoritized communities are overlooked at more aggregate levels of geographic analysis (U. S. Environmental Protection Agency, 2016). The study area is shown in Figure 2.2 and Figure 2.3. Then, the transit supply score was determined using transit stops, routes, and service frequency data from the Port Authority of Allegheny County's General Transit Feed Specification. The transit supply score and transit need scores for each census block group determine transit coverage, revealing how the system is currently serving the transit-dependent population. By identifying the census block groups with the lowest transit coverage score and greater than average low-income or minority population, a set of census block groups are prioritized for service improvement. These priority CBGs are used as origin points for calculating route distances to and from the nearest bus stop with adequate transit service, then used as inputs for cost analysis. Each priority census block group was assessed for cost efficiency of adding either shuttle, SAV, or bus service for these route distances. Cost analysis considers a variety of factors, like capital costs, fuel, insurance, wages, and is provided in more detail in section 2.3. Finally, levelized cost per vehicle kilometer traveled and levelized cost per passenger-kilometer traveled for are derived for all three modes. Levelized costs for operating SAVs as shuttles in Allegheny County, PA are estimated across multiple scenarios to provide insight into the cost efficiency of different transit planning futures. Due to the uncertainty of shared autonomous mobility, sensitivity analysis is performed over a range of AV operating costs and uncovers the most important parameters influencing shared automated mobility operational feasibility.

2.4.1. Transit Coverage Analysis

To effectively identify areas with unmet transit access needs in the case study county, a transit coverage score must be calculated. The transit coverage score is a measurement found in the Transit Capacity and Quality of Service Method (Kittelson & Associates, Inc. et al., 2013). This method was used because it allowed for analysis with our census block groups that properly capture smaller, low-income, or minoritized communities that are overlooked at more aggregate levels of geographic analysis (U.S. Environmental Protection Agency, 2016). The measures of interest for this analysis included: transit-dependent population, transit stops, the number of routes, the frequency of service for each stop per weekday, and a final transit coverage score.

First, the transit-dependent population was derived from data provided in the 2016 American Community Survey (U.S. Census Bureau, 2016). Age and vehicle ownership data were aggregated to obtain the transit-dependent population by CBG. The driving eligible population was aggregated for every census block group in Allegheny County. The legal driving age in the U.S. is, on average, 15 years old, and literature shows that driving ends around 70 years old (Foley et al., 2002), which was used as a conservative input to estimate the driving eligible population in each census block group. Vehicle ownership data from the American Community Survey includes zero-vehicle households which represent the transit-dependent population in this study. Although the transit-dependent population consists of many types of riders: zero-vehicle households, those who are unable to drive due to physical limitations, and specific age groups, the zero-vehicles households are a sufficient proxy to estimate the population. The transit-dependent population density per CBG was determined by dividing the population by the net land area in Allegheny County CBG shapefiles, then normalized to ensure a direct comparison between transit-dependent population and the transit supply found in the next step.

The determinants for transit service, outlined by Jiao et al. (Jiao and Dillivan, 2013) and the TCQSM (Kittelson & Associates, Inc. et al., 2013) are (1) number of transit stops in each block group, (2) average frequency of weekday service in each block group, and (3) number of routes serving each block group (Fayyaz et al., 2017; Jiao and Dillivan, 2013). Since riders do not consider CBG borders to access a transit stop, stops near a CBG boundary are included in transit service analysis. This was accounted for by adding a 0.4 km or quarter-mile buffer around each CBG to give a count of transit stops that can potentially serve the population (Fayyaz et al., 2017; Jiao and Dillivan, 2013). The transit stop aggregate value was converted to a transit stop density per net area then normalized. The transit routes within a 0.40-km buffer of each census block group were counted for each CBG. Routes passing through a CBG without a transit stop were assigned a value of zero since service is not accessible. Like the transit stop counts, the route count output was converted to a route density by dividing by the net area for each CBG and normalized. Transit service frequency was determined using general transit specification feed (GTSF) processed data from Carnegie Mellon University's Mobility Data Analytics Center (Qian, 2018) which provided the bus frequency by the hour for each road segment in Allegheny County. The resulting value was divided by the net area then normalized. If this information is not available at the high resolution used in this study, GTSF data is sufficient for calculating the average number of buses per hour in a CBG, as used by Jiao et al. (Jiao and Dillivan, 2013). These three transit supply values–transit stops, routes, and frequency–were aggregated into a transit supply score for each CBG. The transit supply was calculated as

$$S_i = \frac{\sum t_i}{a_i} + \frac{\sum r_i}{a_i} + f_i \quad (1)$$

where S_i is the supply score for any CBG i, t_i is the total number of transit stops, a_i was the net area, r_i was the total number of routes, and f_i was the frequency of service or average bus per hour. The supply inputs were not weighted because any configuration of transit supply can satisfy the specific needs of a CBG. Finally, the transit coverage scores for each census block group i (C_i) based on the transit-dependent population, P, was

$$C_I = S_i - P \qquad (2)$$

(Jiao and Dillivan, 2013; Kittelson & Associates, Inc. et al., 2013). There are various approaches for measuring transit level of service; however, a standard coverage threshold was not found in previous studies. The CBGs within the bottom five percent of all transit coverage scores were considered low transit coverage block groups. This threshold systematically captures the most extreme cases of low transit coverage and, accordingly, transit-dependent populations with the lowest transit supply in Allegheny County.

2.4.2. Transit Equity Analysis

Sociodemographic profiles of CBGs provide pertinent information for analyzing transit equity. EJSCREEN, the EPA's environmental justice screening tool, provides sociodemographic data by CBG (U.S. Environmental Protection Agency, 2014). The groups of interest included in EJSCREEN data are low-income and minority households. Minority households are defined by the EPA as the percent or number of minority individuals that are non-white, including multiracial individuals, in a census block group (U.S. Department of Transportation, 1964). Households are designated as low-income when the household income is less than or equal to twice the federal poverty level (U.S. Environmental Protection Agency, 2014). Data aggregated by ethnicity and income were appended to spatial data to identify CBGs with greater than average low-income or minority populations. If the minority population within a block group was greater than the county average of 23.1%, it was denoted as an equity designated CBG. When the low-income population in a CBG was greater than the county average, it was denoted as an equity designated CBG. The final step in equity analysis was assigning priority to the CBGs that had both an equity designation and low transit coverage. The priority CBGs were used for calculating operational costs for the three mobility solutions.

2.4.3. Direct Cost Analysis of Autonomous Mobility Solutions

Estimating operating costs required framing the problem to allow for equal comparison across modes of interest in the study. Calculating the levelized cost of driving (LCOD) is based on the calculations developed by the U.S. Department of Energy's Office of Energy Efficiency and

Renewable Energy (Nealer et al., 2018). LCOD highlights the effects of advances in vehicle technology which supports the aims of this study.

Three transit modes were considered for the cost analysis to improve transit coverage

1. Bus: The base-case mode adds a transit stop in a priority CBG centroid which is served by at least one conventional diesel bus connecting a priority CBG to an established transit stop. The study assumes a 40-foot bus with an average bus capacity of 40 passengers.
2. Shared Autonomous Vehicles (SAVs): The first alternative mode operates as at least one autonomous vehicle traveling from the priority CBG to the nearest existing transit stop. Sedans and minivans are the standard vehicles used in AV testing, so this study used four-passenger gasoline SAVs to serve each priority CBG.
3. Electric Autonomous Shuttles: The second alternative mode uses electric shuttles to serve priority CBGs with service to the nearest existing transit stop. Capital and operating costs were used to compute separate estimates of direct costs for the implementation of a 12-passenger electric autonomous shuttle.

All three modes were evaluated for the exact same service. For each priority census block group the route distance between the centroid and nearest transit stop was determined using Open Source Routing Machine's ("Open Source Routing Machine," 2019) Table service. The frequency of service was determined using the average frequency of census block groups adjacent to priority census block groups. Each transit mode was evaluated for cost efficiency using levelized cost per vehicle kilometer traveled ($/VKT) and levelized cost per passenger-kilometer traveled ($/PKT).

Cost Per Vehicle Kilometer Traveled Calculation. The following equation calculates the levelized costs for each mode

$$\text{Levelized Cost per Vehicle Kilometer Traveled} = \frac{\sum c_c + \sum c_o}{d} + c_e \qquad (4)$$

where c_c is the total annualized capital cost to acquire the shuttle, SAV, or bus. The summation for c_c accounts for the cost of the shuttle and charger for the shuttle mode scenario. Annualized costs were calculated using a 6% discount rate from the state of Pennsylvania Department of Transportation bond rate (Port Authority of Allegheny County, 2016), and an estimated ten years of use based on the average ten years of use for transit vehicles (Hughes-Cromwick et al., 2017). Capital purchase costs of electric autonomous shuttles (Local Motors, 2018), gasoline SAVs (Chen et al., 2016), and conventional diesel buses (Colorado Department of Transportation, 2018) were annualized. The cost of wireless electric chargers for autonomous shuttle charging was also annualized (Nicholas, 2019; Sierra Club, 2016). Operating costs or c_o, comprises of the annual operator wages, fringe benefits, insurance, and annualized maintenance costs. Operator hourly pay for the conventional diesel bus was determined by the annual salary and revenue hours for operators reported by the PAAC (Port Authority of Allegheny County, 2016). Operator hourly pay is reduced by 60% for electric autonomous shuttles and SAVs to account for the potential operational cost savings (Wadud, 2017). Fringe benefits represent the employee benefits package of health, retirement, and other benefits offered to Port Authority of Allegheny County employees which are roughly 33% of their annual salary (Port Authority of Allegheny County, 2016). Insurance costs per mile for electric autonomous shuttles and SAVs were drawn from APTA's breakdown of operation expenses by function (Hughes-Cromwick et al., 2017). Liability and casualty costs are 2% of operating expenses and the 2016 financial performance report from PAAC detailed operating expenses, which was used to derive the insurance cost per kilometer for shuttles (similar to demand response costs) and buses (Port Authority of Allegheny County, 2016). This value was used to determine the insurance cost per kilometer for electric autonomous shuttles, as they would be categorized as a form of shared ride transit service. The American Automobile Association (AAA) reported insurance costs of $0.20/km for vehicles that were used for SAVs. Maintenance costs for electric autonomous shuttles came from a report by the Sierra Club (Sierra Club, 2016) and the SAV maintenance cost per kilometer was estimated in a study by Fagnant and Kockelman (Chen et al., 2016). The route annual revenue kilometers were captured in d, and c_e was the energy cost per kilometer for each mode of transportation. Parameter values are shown in Table 2.1 and Table 2.2. Energy costs to propel the various vehicles were based on 2019 data from the Energy Information Administration (EIA) (U.S. Energy Information Administration, 2019). Gasoline fuel efficiency of 14.87 kilometers per liter (km/L) and a national average of $0.59 per liter for SAVs was used. The EIA reported average diesel costs at $0.56/liter in 2019, so the median diesel price per kilometer was derived from a 1.69 km/L fuel efficiency for diesel buses (U.S. Department of Energy, 2018). Table 2.2 details these point estimates for capital costs, energy costs, and operator pay.

Cost Per Passenger-Kilometer. Next, the cost per passenger kilometer traveled was calculated for each mode using

$$\text{Levelized Cost per Passenger-Kilometer Traveled} = \frac{C_0 + c_c + d(C_e)}{p} \quad (5)$$

where *p* represents annual passenger-kilometers as detailed in Table 2.1 and Table 2.2.

This study used three analyses for levelized cost analysis to offer a variety of ways to analyze the results and provide insight about operating shared autonomous mobility integrated with an existing public transit system. First, baseline levelized costs were determined using U.S. transit system average values to determine $/VKT and $/PKT. Since shuttles, SAVs, and buses in this study are being used solely for first- and last-mile service, national averages of demand response transit in the U.S were used as parameter values (American Public Transit Association et al., 2017) for the baseline analysis. Second, CBG-level analysis considers the ridership demand of an individual CBG and provides a higher resolution of levelized costs to uncover the most cost-effective routes. Lastly, Monte Carlo simulation considers the uncertainty of each parameter in the model to estimate levelized $/VKT and $/PKT across a range of feasible scenarios.

Table 2.1: Point estimate inputs for calculating $/VKT and $/PKT for baseline cost analysis and CBG-level cost analysis.

Parameters	Baseline Analysis (Average U.S. Transit System)	CBG level Analysis (mean)
Annual Distance (km)	71,500	68,872
Annual Passenger-KM	51,000	200,763

Operator Vehicle Hours	1,700	2,871

Table 2.2: Point estimate inputs for calculating $/VKT and $/PKT by transit mode. All values are $2019 and used for transit standard cost analysis and CBG-level cost analysis.

	Mode of Transit			
Parameters	Shuttle	SAV	Bus	Reference
Operator Wages ($/hour)	10.20	10.20	25.51	(Port Authority of Allegheny County, 2016; Wadud, 2017)
Fringe Benefits ($/hour)	3.36	3.36	8.41	(Port Authority of Allegheny County, 2016; Wadud, 2017)
Insurance ($/km)	0.10	0.20	0.18	(Port Authority of Allegheny County, 2016; American Auto Association, 2017; American Public Transit Association, 2020)
Maintenance Cost ($/km)	0.39	0.32	0.89	(Fagnant and Kockelman, 2015; Sierra Club, 2016)
Energy Cost ($/km)	0.04	0.08	0.33	
Acquisition (Capital) Costs ($)	238, 095	70,000	300,000	(Chen et al., 2016; Colorado Department of Transportation, 2018; Local Motors, 2018)
Annualized Acquisition Cost ($/year)	32,349	10,130	43,417	(Hughes-Cromwick et al., 2017; Port Authority of Allegheny County, 2016)
Annualized Charger Acquisition Cost	24,796	--	--	(Nicholas, 2019; Sierra Club, 2016)

Monte Carlo simulation presents a probabilistic representation of operating cost outputs under the uncertainty of costs associated with shuttles and SAVs, and with the choices in the mode scenarios. The simulation model used the parametrized inputs in Table 2.1and Table 2.1, with ranges of values shown in Table 2.3. Probability distributions capture the optimistic and pessimistic ranges of levelized cost parameters. Using a triangular distribution of capital and energy costs accounts for optimistic cost savings or pessimistic increases in costs in the future. The annual distance was based on the range of annual distances found in CBG level analysis and parameterized as shown in Table 2.3 to have best- and worst-case scenarios. Annual passenger-km was similarly derived from CBG-level analysis. Lower annual passenger-km, annual distance, and operating hours are included in the pessimistic scenario because it would increase costs per kilometer and per passenger-kilometer. Conversely, a greater annual distance, annual passenger-km, capital costs, and energy costs drive down operating costs, resulting in a best-case scenario for analysis. Base values for annual distance, annual passenger-km, and operator hours are derived from the mode of the priority CBGs. Base values for capital and energy costs come from the point estimates detailed in Table 2.1 and Table 2.2. Sensitivity analysis was performed using Sobol's sequence in the SALib Python package (Herman and Usher, 2017) to estimate the main and total effects for each parameter.

Table 2.3: Monte Carlo Simulation Parameters

Parameters	Probability Distribution	Pessimistic	Base	Optimistic
Annual Distance	Uniform	18,000	71,000	111,000
Annual Passenger-KM	Triangular	131,000	160,000	317,000
Annual operating hours	Uniform	1,700	3,000	5,000
Electric Charger ($/year)	Triangular	40,000	14,000	9,5000
Bus Fuel Costs-Diesel ($/kilometer)	Triangular	0.35	0.33	0.3
SAV Fuel Costs-Gasoline ($/kilometer)	Triangular	0.1	0.07	0.05
Shuttle Electricity costs ($/kilometer)	Triangular	0.07	0.05	0.02
Shuttle Capital Cost ($/year)	Triangular	39,000	32,000	26,000
SAV Capital Cost ($/year)	Triangular	12,000	10,000	8,000
Bus Capital Cost ($/year)	Triangular	52,000	43,000	35,000

2.5. Results & Discussion

2.5.1. Allegheny County

The Port Authority of Allegheny County (PAAC) is the public transit system that serves Pittsburgh, PA, and surrounding suburbs. There are 105 transit routes, that serve 6,896 transit stops plus paratransit services. There are two reasons why the PAAC was selected as the case study. First, the PAAC has proposed direct service for underserved, lower density areas namely coverage routes (Port Authority of Allegheny County, 2019). To provide basic service to these areas with coverage routes is reported to be a better choice than to deviate an existing route. Second, all trips in our scenario begin and end within county boundaries which helps with framing and completing analysis for the study.

Before the scenario analysis, the typical transit service for a census block group in Allegheny County, there were approximately 124 transit dependent riders that has access to 24 stops that connecting to one roue with service every 12 minutes. For the 16 CBGS identified as those with the lowest transit coverage service was much lower and the transit dependent population was much higher. On average these priority CBGs had 489 transit-dependent riders and only 14 transit stops within a quarter-mile radius of the CBG boundary. These CBGs also had access to one route but service increased to every 30 minutes. The disparity in service transit dependent riders in the priority census block groups experience means that there is an opportunity to improve transit access, and thus equity where it would be most impactful and can further PAAC goals of coverage routes for the system.

2.5.2. Transit Coverage & Equity in Allegheny County

Transit coverage combines the transit-dependent population and transit supply scores to identify CBGs with unmet need and low transit supply by CBG in Figure 2.2. The importance of evaluating transit coverage scores based on the transit-dependent population is to highlight areas that might be unknown regions of missing or depleted transit access. Figure 2.2 shows that many dark brown regions, which represent low transit coverage scores, are primarily beyond the

Pittsburgh city boundaries. Notably, the dark brown areas also correspond with Pittsburgh suburbs where population density is lower and therefore rider demand is typically lower. Approximately 78% of the transit-dependent population overlaps with the priority CBGs accounting for over 120,000 transit-dependent riders who are also low-income or minority households. CBGs with low-transit coverage had higher percentages of low-income and minority populations when compared to the county average. Minority populations in low-transit coverage CBGs averaged 46% while the county average was only 23 percent. Fifty-five percent of low-transit coverage CBGs were also low-income, while the county average is 32 percent.

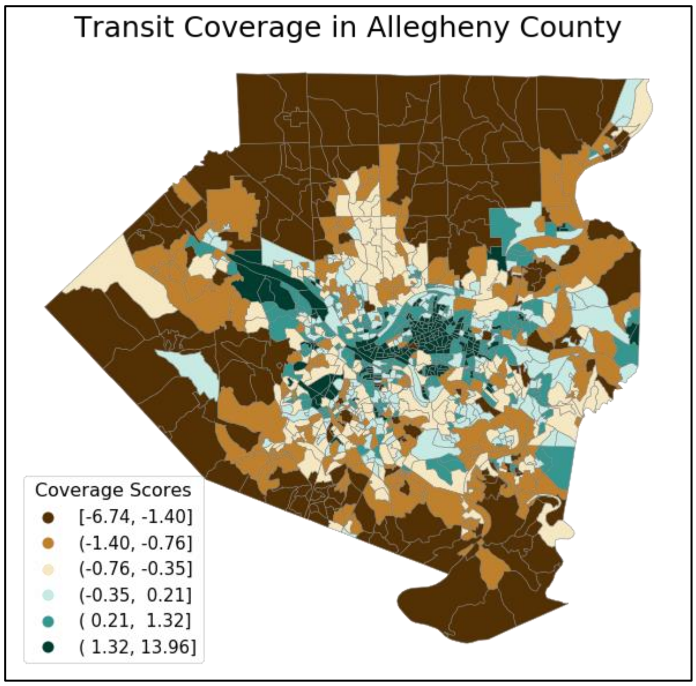

Figure 2.2: Map of transit coverage based on transit-dependent rider demand and transit supply in Allegheny County, PA. Darker colors show extremes with dark blue indicating more than sufficient coverage to match demand, and dark brown is the lowest transit coverage signifying insufficient transit access for the transit-dependent population.

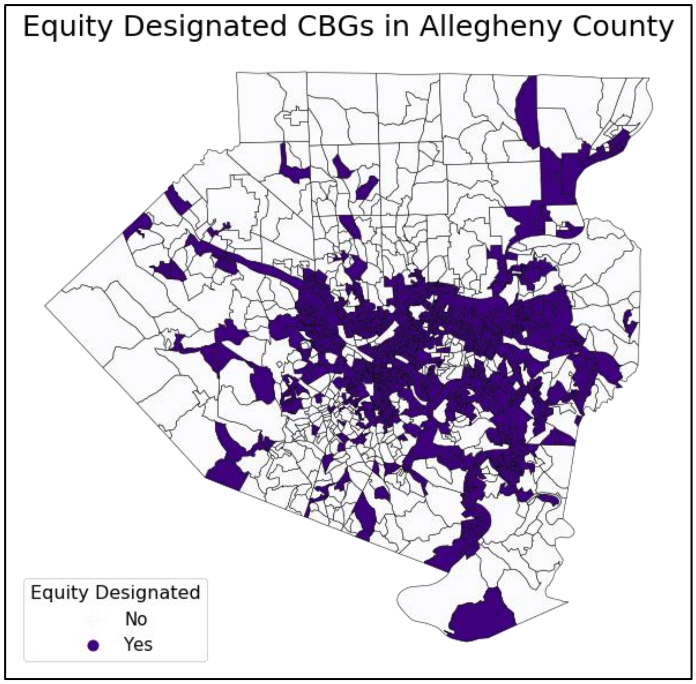

Figure 2.3: Map of low-income or minority population by census block group.

2.5.3. Cost Analysis

Table 2.4 shows the levelized cost per kilometer traveled ($/VKT), levelized cost per passenger-kilometer ($/PKT) traveled, and total costs for each analysis. Although each analysis has varying results for levelized costs due to differences in calculation, both levelized costs and total annual operating costs are within the same order of magnitude. Figure 2.4 illustrates the wider range of levelized costs from the Monte Carlo simulation. The range of cost per vehicle kilometer traveled ($/VKT) was very similar for electric autonomous shuttles and SAVs, while buses resulted in a wider range of costs per km. SAVs were lowest for cost per passenger-kilometer traveled ranging from $0.77/PKT to $0.90/PKT for each analysis. SAVs also had the lowest costs per vehicle kilometer traveled with $/VKT between $2.15 and $2.28 for each analysis. Costs per passenger-kilometer traveled were typically lower than the costs per vehicle kilometer traveled overall. Sensitivity analysis determined which parameters have the greatest influence on the levelized cost outputs.

Table 2.4: Mean levelized costs and total costs comparison for each approach.

	Levelized $/VKT			Levelized $/PKT			Total Annual Operating Costs		
	Shuttle	SAV	Bus	Shuttle	SAV	Bus	Shuttle	SAV	Bus
CBG Level Analysis	$2.79	$2.15	$4.06	$1.31	$0.90	$2.14	$158,000	$114,000	$252,000
Baseline Analysis	$2.77	$2.21	$3.85	$1.36	$1.08	$1.89	$112,000	$89,000	$155,000
Monte Carlo Simulation	$2.71	$2.28	$4.24	$0.94	$0.77	$1.49	$149,000	$122,000	$235,000

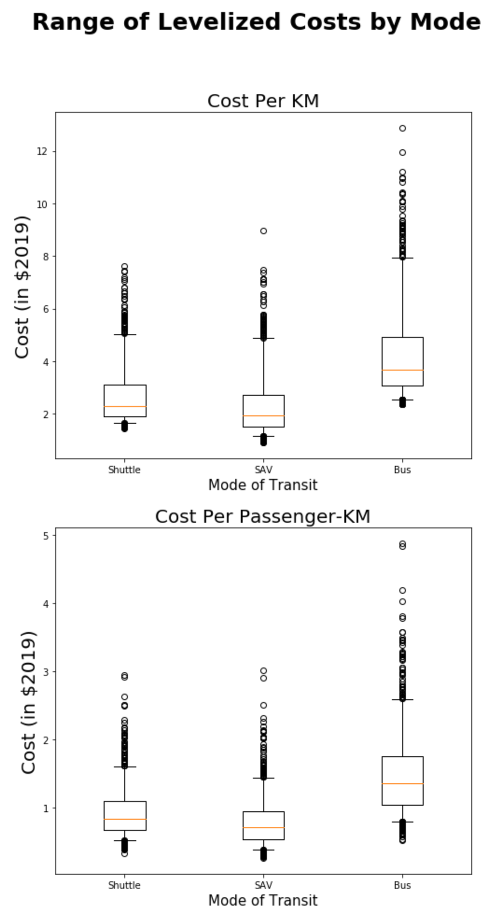

Figure 2.4: Box plot showing the full range of costs from Monte Carlo Simulation for each mode of transportation. The line inside the box plot represents the median and the whisker boundaries represent the 5th and 95th percentile.

2.5.4. Sensitivity Analysis

Table 2.5: Monte Carlo Sensitivity Analysis Ranking. Table values represent total-order sensitivity indices in descending order to show the rank order of influence for each parameter for levelized costs.

				$/VKT
Parameter	Rank	SAV	Shuttle	Bus
Vehicle KM	1	0.724	0.96	0.898
Operator Hours	2	--	0.046	0.129
Fleet Size	2	0.132	--	--
Capital Cost	3	0.001385	0.0056	0.003950
Energy Costs	4	0.000099	0.00014	0.000061
Fleet Size	5	--	0.00	0.00
				$/PKT
Parameter	Rank	SAV	Shuttle	Bus
Passenger-KM	1	0.1445	0.15167	0.1794
Vehicle KM	2	--	0.063976	0.1311
Fleet Size	2	0.049	--	--
Operator Hours	3	0.043	0.017519	0.037912
Capital Costs	4	0.00326	0.011787	0.001323
Energy Costs	5	0.0006	0.000136	0.00009
Fleet Size	6	--	0.000	0.00000

Sensitivity analysis identifies the parameter or set of parameters that have the greatest influence on the model output. It consequently provides useful insight into which model input contributes most to the variability of the model output. Sobol's approach for global sensitivity analysis revealed the parameters that most influenced levelized cost per vehicle kilometer and levelized cost per passenger-kilometer across each mode. Table 2.5 shows the rank of influence for each parameter for $/VKT and $/PKT. Across all modes, it is not surprising that levelized cost per vehicle kilometer traveled is most sensitive to the number of revenue kilometers traveled annually. The sensitivity analysis ranked the second most important parameter for SAVs and buses as operator hours. Most priority CBGs have lower ridership demand, thus one shuttle or bus provides adequate service in most cases. However, a small fleet of no more than three SAVs provides service for some of the priority CBGs. As a result, fleet size was the third most influential parameter for SAVs whereas buses and shuttles were not influenced by fleet size. Other studies have noted the importance of shared AV fleet size which is supported in these results (Golbabaei et al., 2020; Mo et al., 2021; Shen et al., 2017). Table 2.5 also shows the total effects for each parameter in the order of influence for cost per passenger-kilometer. Annual passenger-kilometer is the most influential parameter across all three modes. Similar levelized costs per km, the fleet size is the next most influential parameter for SAVs and the least influential for buses and shuttles since fleet size did not vary for these two modes. The parameters followed the same order of influence across modes from greatest to least: annual distance, operator hours, capital costs, and energy costs. These rankings provide insight into the most important factors in planning shared automated mobility services for increasing equity and transit coverage in a public transit system. When considering $/VKT, planners can focus on the annual distance, operator hours, and fleet size. If $/PKT is a metric of interest the top three factors for consideration are annual passenger-kilometers, annual distance, and fleet size.

Levelized cost analysis for each CBG offers a higher resolution exploration of parameter sensitivity along with important social indicators like the transit-dependent population served and transit coverage improvement. The five priority CBGs detailed in Table 2.6 are prioritized based on the factors identified in the sensitivity analysis as well as the equity indicators of interest. Overall, CBG #3 is the most ideal census block group for additional transit service because transit coverage improved the most. A new transit service would connect this CBG to the existing transit system, as there was only one route previously serving the area. The transit coverage score increased from -2.53 to 12.12. The positive score, 12.12, indicates that service improved for the transit-dependent population and now exceeds transit demand for this CBG. The route would operate with 79,000 km traveled annually, and 159,000 annual passenger kilometers traveled. Based on total operating costs, levelized cost per km traveled and cost per passenger kilometer traveled, one SAV is the most cost-effective service choice for the CBG.

Table 2.6: Transit coverage scores before and after analysis and lowest levelized costs for each priority CBG.

Priority CBG Analyzed	0	1	2	3	4
Census Tract ID Number	810003	900024	4511042	3001004	5623006

Transit Dependent Population	596	47	92	639	652
Minority Population (%)	0.45	0.29	0.04	0.74	0.8
Low-Income Population (%)	0.67	0.45	0.33	0.8	0.52
Stop Count (before)	36	0	0	55	36
Average Hourly Frequency (before)	4.36	0	0	5.15	5.62
Routes (before)	1	0	0	1	2
Transit Dependent Population Need Score	3.82	-0.52	-0.54	6.01	7.02
Transit Service (before)	0.95	-3.07	-3.07	3.48	4.39
Transit Coverage (before)	-2.87	-2.55	-2.53	-2.53	-2.63
Stop Count (after)	51	13	18	70	47
Average Hourly Frequency (after)	4.28	1.96	1.4	5.09	5.54
Routes (after)	16	1	2	16	16
Transit Dependent Population Need Score	3.82	-0.52	-0.54	6.01	7.02
Transit Service (after)	11.48	-2.03	-2.29	18.13	19.13
Transit Coverage (after)	7.68	-1.51	-1.75	12.12	12.11
Lowest $/VKT	$ 1.23	$ 3.02	$ 3.49	$1.23	$ 1.49
Lowest $/VKT mode	SAV	Shuttle	SAV	SAV	SAV
Lowest $/PKT	$ 0.85	$ 0.34	$ 0.47	$ 0.70	$ 2.09
Lowest $/PKT mode	SAV	Shuttle	SAV	SAV	SAV

2.6. Conclusion

This study aimed to determine the feasibility of improving equitable transit access using autonomous mobility as a part of a public transit system. The results of this study support previous work that states these new technologies can reduce transit costs. Overall, this study revealed service parameters that are important for improving transit coverage and equity with SAVs or shuttles operate at substantially lower costs than buses. Sensitivity analysis revealed the most important parameters for consideration in future transit planning and policy of shared autonomous mobility. Thus, SAVs and shuttles can be constrained to certain service metrics to improve transit coverage equity and to remain a cost-efficient complement to existing transit service.

The increase in transit coverage means that the needs of the transit-dependent, low-income, and minority populations could be better addressed in Allegheny County. Implementing SAVs or shuttle does not impact the existing transit system, so other transit rider groups are not affected. The increased access for the transit-dependent population could also result in ridership increases, as these locations are currently underserved.

By coupling transit coverage with equity analysis, the low-income and minority populations were identified in Allegheny County. The results of this study indicate while the overlap for transit-dependent, low-income, or minority populations was not significant for this transit system, there were CBGs that held both vulnerable populations. This approach could be applied to another transit system, to assess the degree of overlap in their populations. The policy implications of these findings are clear; this approach can be used to satisfy the requirements of Title VI from the FTA, where many transit agencies receive funding for most types of capital investments. Incorporating equity into transit coverage analysis will improve the transit planning process and more importantly, positively impact vulnerable populations that need transit access the most. More broadly this study supports the efforts towards low carbon mobility outlined in the 2030 Agenda for Sustainable Development and the seventeen Sustainable Development Goals (SDGs). While low carbon mobility is not explicitly articulated as a goal, increased public transit access and ridership supports many of the SDGs.

This works also strengthens the idea that SAVs and shuttles can equitably improve public transit access cost-effectively. The findings suggest public transit agencies could begin integrating shared automated mobility into their transit system. However, continued technology advancement, and an evaluation of other potential negative social and environmental impacts of these vehicles are needed before a full deployment is possible. There are opportunities for more robust transit coverage analysis tools and data that focus on the transit-dependent population.

2.7. Limitations

There were some limitations in this study. First, datasets and point estimates are from or adjusted to 2019. In some cases, the most up-to-date and comprehensive dataset available was for this time period. As more SAV and shuttle cost information becomes publicly available, future studies can update mean levelized costs and potentially realize more savings. Second, only direct costs were included in the analysis. Some additional costs such as cleaning, garaging, administrative costs, are not included. These are unlikely to affect the differences in costs across the three vehicle types we examined. Further, environmental impacts, rider comfort, safety, unbanked rider accessibility, etc., while important and socially beneficial, were not included as they do not directly contribute to operating costs. Third, analysis methods for transit coverage vary in transportation planning and research efforts. This paper did not seek to create a new approach and instead used existing tools for aggregating the transit-dependent population and transit coverage. Extracting the transit-dependent population also varies from one transit agency to another, which could be standardized for reproducibility across agencies and analysis. Lastly, further research could usefully explore the impacts autonomous mobility solutions will have as part of a public transit system. Not every public transit system is like PAAC, thus analysis that explores operational feasibility in other cities with different sized transit systems can provide more information about what is feasible with shared autonomous mobility. More research on the changes in perceived quality, willingness to pay, passenger trust in autonomous technology, transit-SAV scheduling, environmental impacts need to be developed for a more comprehensive understanding.

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3 Integrating Public Transit and Shared Autonomous Mobility for Equitable Transit Coverage in Different Sized Cities

3.1. Abstract

As automated transportation progresses, public transit agencies may address the equitable implications of integrating autonomous vehicles and shuttles into current transit systems. Capital and operating expenses for automated mobility modes handled by public transportation agencies are unknown at this point given the limited number of pilots and deployments. This study evaluated transit systems in various cities to identify opportunities for equitable improvement through shared automated mobility. We identified locations of unmet transit demand among the transit-dependent population and prioritized them for future service via shared autonomous vehicles (SAVs) or shared autonomous electric shuttles. Based on current transit and technology costs, we estimated levelized operating costs for first- and last-mile service in a transit system. The study examines transit services in four U.S. cities: New York City, New York, Chicago, Illinois, Pittsburgh, Pennsylvania, and Minneapolis-St. Paul, Minnesota. The results suggest that it is possible to operate SAVs and shuttles at a lower cost than buses as part of a public transit system under particular transit demand situations. The sensitivity study identified the critical factors to consider while developing new transportation services with shared autonomous mobility. SAVs were the most cost-effective mode of transportation for expanding transit coverage in Minneapolis-St. Paul and Pittsburgh. However, there were instances in Pittsburgh, New York City, and Chicago where shuttles outperformed SAVs, notably when ridership demand surpassed SAV capacity limits, required larger SAV fleets. This study eventually identified the characteristics of transit systems that are most conducive to the integration of SAVs and shuttles into an existing public transit system.

3.2. Motivation

Emerging mobility solutions aim to shift from a human-driven vehicle ecosystem to a computer-driven environment through the deployment of on-road autonomous technologies (Litman

2018a). Autonomous vehicles (AVs) have the potential to provide a variety of societal benefits, including fewer crashes (Anderson et al. 2014; Fagnant and Kockelman 2018; Greenblatt and Saxena 2015; Harper et al. 2016; Metz and Metz 2018), less congestion (Fagnant and Kockelman 2018; Greenblatt and Saxena 2015; Metz and Metz 2018), reduced vehicle emissions (Fagnant and Ko (Fagnant and Kockelman 2018). Automobile manufacturers are progressively equipping their vehicles with partially automated features, while policymakers are developing rules to facilitate the deployment of highly automated vehicles. However, widespread deployment of privately-owned AVs introduces new hazards, hence creating a barrier to acceptance (Bezai et al. 2020). According to one report, assessing safety through on-road testing might take hundreds of years to eliminate uncertainties (Kalra 2017). As a result, authorities are attempting to build a flexible regulatory framework that can accommodate these risks and so support the technology's successful adoption.

Until recently, research has focused on privately owned AVs; now, more studies investigating shared autonomous mobility systems with a variety of use cases are beginning to surface. SAVs are often used as an umbrella term to describe minivans, low-speed shuttles, and other light-duty vehicles equipped with automated driving systems that have different use cases. For example, some studies have assessed SAVs providing service as robotaxis: light-duty vehicles with 4-6 passenger capacity and equipped with an automated driving system. Study reports assess the impacts of robotaxis as a replacement for all privately owned vehicles in a city (Fagnant and Kockelman 2018; Spieser et al. 2014) . Case studies for this replacement scenario have looked at different cities around the world and found road and cost efficiencies. These studies help to prove that the positive benefits of AVs are especially achievable when AVs are shared, but the replacement scenario would require swift and substantial regulatory and traveler behavior changes which are not realistic. Other studies have explored the first and last mile use case where SAVs are dropping off or picking up passengers at their homes and transporting them to nearby transit or rail stations (Gurumurthy et al. 2020; Shan et al. 2021; Shen et al. 2017). Finally, studies also look at low-speed electric autonomous shuttles as a shared autonomous mobility solution (Berschet et al. 2017; Coyner et al. 2021; Smart

Columbus 2021; U.S. Department of Transportation 2017). Shuttles operate at lower speeds and their predictability reduces risks that act as a barrier for private autonomous vehicles. They also hold a greater number of people than traditional cars (National Center for Transit Research and Polzin 2016; U.S. Department of Transportation 2017). Some pilot programs for shuttles include service to the existing public transit system (Smart Columbus 2021; The Swiss Transit Lab 2018) in the form of first-mile, last-mile transit access. Overall, these studies and pilot programs further galvanize the positive benefits of shared autonomous mobility solutions over privately owned vehicles but uncertainty in costs and lack of information around equity impacts of AVs hinder progress towards a regulatory path for widespread deployment.

Costs related to operating shared autonomous vehicles are a significant factor in decision-making regardless of whether the business is managed publicly or privately. Numerous studies have been conducted too far to assess the operational expenses of automated vehicles and shuttles in a range of sharing scenarios. Automated taxis (Bauer et al. 2018; Bösch et al. 2018; Fagnant and Kockelman 2018) and autonomous vehicle ride-sharing (Fulton et al. 2020; Narayanan et al. 2020) were the more prevalent scenarios in the existing literature, with reported costs ranging from $0.11/km to $1.03/km in $2019. The variance in results could be explained by the fact that many studies exclude overhead, parking, maintenance, and cleaning from their analyses, hence exaggerating the benefits of SAVs (Narayanan et al. 2020). Additionally, these findings are constrained since automated technology is still in development, and so the associated costs vary over time and between investigations. A substantial body of literature exists on the topic of integrating shared automated mobility into public transportation. One research that examined demand-responsive transit using SAVs revealed prices ranging between $0.19 and $0.30 per kilometer (Litman 2018). Another study discovered that employing SAVs for public transit first and last-mile service costs $0.39/km (Moorthy et al. 2017). Finally, studies are constrained by their focus on single cities for case studies. By examining shared automated mobility costs in a single city at a time, there is potential to misinterpret shared automated mobility capabilities. Because transit systems in the United States and around the world are so dissimilar, one cannot assume that the same operational scenarios and operating expenses would apply to a different system. Additionally, as previously noted, because various studies assessed different components and distinct scenarios, it is hard to objectively compare one study's findings to another. While standardizing assessments may not be appropriate at this stage of shared automated mobility research, examining multiple systems using the same method can aid in understanding what is achievable with SAVs.

Shared automated mobility is still evolving to provide pragmatic data for future transportation policymaking, but is still wrestling with unknown technology prices, fleet sizing, and vehicle repositioning, among other issues. Prior research on shared autonomous shuttles has not examined transit demands within a system or the equity implications of the technology.

3.3. Research Questions

The purpose of this study is to assess the economic viability of expanding equitable transportation coverage using shared automated mobility options. We begin by identifying priority service regions in a transit system using transit gap analysis techniques that integrate transit coverage and equity analysis. According to the sociodemographic characteristics of a census block group, priority service regions have both unmet transit requirements and equity concerns. We then conduct a cost-benefit analysis of operating shared autonomous vehicles and electric autonomous shuttles as part of a public transit system using the priority service areas. We explore the following questions:

1. Can different sized cities and agencies use shared automated mobility to cost-effectively improve public transit coverage?

2. Are there any unique characteristics for cities that are best suited to improve transit access with SAVs or shared autonomous shuttles?

3.4. Data Sources & Methods

Four cities were chosen for this study to capture different size cities and public transportation systems in the various geographic regions in the United States. The American Public Transportation Association public transportation system rankings were used to select the transit systems. MTA New York City Transit and Chicago Transit Authority were selected as the two largest transit agencies in the U.S. (American Public Transit Association et al. 2017). The Port Authority of Allegheny County in Pittsburgh, PA, and MetroTransit in Minneapolis-St. Paul, MN were selected as public transit agencies that serve smaller metropolitan areas (Port Authority of Allegheny County 2016). Data from the U.S. Census Bureau and Environmental Protection Agency (EPA) provided demographic details about the transit-dependent, low-income, and minority populations in each census block group to determine transit need. The American Community Survey is a demographic survey program administered by the U.S. Census Bureau that includes population and vehicle ownership data (U.S. Census Bureau 2017). Sociodemographic data at the CBG level is available through EJSCREEN from the EPA (U.S. Environmental Protection Agency 2014). Transit stops, routes, and service frequency data from the standardized General Transit Feed Specification were used to determine the transit supply score for each census block group. The transit coverage score is determined using the transit supply score and transit need score revealing current service available to the transit-dependent population. A subset of census block groups was prioritized for service improvement based on the lowest transit coverage score and greater than average low-income or minority population. These priority CBGs are used as origin points for calculating route distances to the nearest bus stop with adequate transit service, then used as inputs for cost analysis. Finally, we estimate a range of costs in the form of levelized cost per vehicle kilometer traveled (VKT) and levelized cost per passenger-kilometer traveled (PKT) for the three modes: shuttles, SAVs, and buses. Levelized costs for operating each mode in each city are estimated across multiple scenarios to provide insight into the cost efficiency of different transit planning futures. Due to the uncertainty of shared autonomous mobility, sensitivity analysis is also performed to account for a range of AV operating costs and uncover the most important parameters influencing shared automated mobility operational feasibility.

3.4.1. Transit Coverage Analysis

Transit coverage is a measure using transit supply and transit need in a system as detailed in the Transit Capacity and Quality of Service Method (TQSM) (Kittelson & Associates, Inc. et al. 2013). Census block group (CBG) level data is used throughout the study because smaller, low-income, or minoritized communities are overlooked at more aggregate levels of geographic analysis (U.S. Environmental Protection Agency 2016). Transit need in a census block group is defined by zero-vehicle ownership data from the American Community Survey which represents the transit-dependent population in this study. Although the transit-dependent population consists of many types of riders, zero-vehicle households are a sufficient proxy to capture the population since certain demographic data is not available for a precise count of the transit-dependent population in every city. The transit-dependent population density per CBG was determined by dividing the population value by the net land area, then normalized to ensure a direct comparison between transit-dependent population and the transit supply found in the next step.

Transit supply is then determined using an approach from Jiao et al. and the TQSM observing three service measures in each CBG: the number of transit stops, transit service hourly frequency, and number of routes. Transit riders will typically walk a quarter mile to a transit stop (Federal Highway Administration 2013) thus stops within a quarter-mile or 400 km radius of a CBG were included in the count of transit stops serving the census block group. The transit stop count, service frequency, and transit route count for each CBG were normalized then aggregated into a transit supply score for each CBG. The transit supply was calculated as

$$S_i = \frac{\sum t_i}{a_i} + \frac{\sum r_i}{a_i} + f_i \qquad (1)$$

where S_i is the supply score for any CBG i, t_i is the total number of transit stops, a_i was the net acreage, r_i was the total number of routes, and f_i was the frequency of service or average bus per hour. The supply inputs were not weighted because any configuration of transit supply can satisfy the specific needs of a CBG. Finally, the transit coverage scores for each census block group *i* (C_i) based on the transit-dependent population was

$$C_i = S_i - P \qquad (2)$$

(Jiao and Dillivan 2013; Kittelson & Associates, Inc. et al. 2013). Since transit coverage is a relative measure, CBGs in the bottom 5% of transit coverage scores were considered to have low transit coverage in each city. This threshold systematically captures the most extreme cases of low transit coverage.

Sociodemographic information creates a decision-making framework to prioritize new service to CBGs where improving transit access will also improve transit equity. US EPA's EJSCREEN dataset provides low-income and minority population data at the CBG level. Minority households are defined by the EPA as the percent or number of minority individuals that are non-white, including multiracial individuals, in a census block group (U.S. Department of Transportation 1964). Households are designated as low-income when the household income is less than or equal to twice the federal poverty level (U.S. Environmental Protection Agency 2014). When a CBG had greater than average low-income population, greater than average minority population, or both, it was given an equity designation.

3.4.2. Cost Analysis of Autonomous Mobility Solutions

In order to assess the cost-efficiency of each mode we constructed three scenarios to frame the study:

1. Bus: The base-case mode adds a transit stop in a priority CBG centroid which is served by one or many conventional diesel buses connecting a priority CBG to an established transit stop with service to the central business district. The study assumes a 40-foot bus with an average bus capacity of 40 passengers.
2. Shared Autonomous Vehicles (SAVs): The first alternative mode operates as one or a fleet of autonomous vehicles traveling from the priority CBG to transit stop with service

to the central business district. Sedans and minivans are the standard vehicles used in AV testing, so this study used four-passenger gasoline SAVs to serve each priority CBG.

3. Electric Autonomous Shuttles: The second alternative mode uses electric shuttles to serve priority CBGs with service to the nearest stops with service to the central business district. Capital and operating costs were used to compute separate estimates of direct costs for the implementation of a 12-passenger electric autonomous shuttle.

For each mode, OSRM calculated the distance for service originating in the centroid of a priority CBG then traveling to the nearest transit stop. The routes represent a fixed service extension into CBG with unmet transit need. Every priority CBGs underwent cost efficiency analysis for each transit mode using levelized costs. The following equation represents the calculation of the levelized costs for each mode

$$\textit{Levelized Cost per Vehicle Kilometer Traveled} = \frac{\sum c_c + \sum c_o}{d} + c_e \qquad (4)$$

where c_c is the total annualized capital cost to acquire the shuttle, SAV, or bus. The summation for c_c accounts for the cost of the shuttle and charger for the shuttle mode scenario. Operating costs or c_o, comprises of the annual operator wages, fringe benefits, insurance, and annualized maintenance costs. The route annual revenue kilometers were captured in d, and c_e was the energy cost per kilometer for each mode of transportation. Parameter values are shown in Table 3.1 and parameterize for Monte Carlo simulation in Table 3.2. Next, the cost per passenger kilometer traveled was calculated for each mode using

$$\textit{Levelized Cost per Passenger-Kilometer Traveled} = \frac{C_0 + c_c + d(C_e)}{p} \qquad (5)$$

where p represents annual passenger-kilometers as detailed in Table 3.1 and Table 3.2. In each city, we derived the levelized operating costs for SAVs, shuttles, or bus in every priority CBG and determined the subsequent most cost-efficient mode. CBG-level analysis considers the ridership demand of an individual CBG and provides a higher resolution of levelized costs to uncover the most cost-effective routes. CBG mode analysis. Ultimately the results offer insight into operating shared autonomous mobility integrated with an existing public transit system.

Table 3.1 details point estimates for operating costs, energy costs, operator pay, and maintenance costs related to each mode. Annualized costs were calculated using a 6% discount rate from the state of Pennsylvania Department of Transportation bond rate (Port Authority of Allegheny County 2016), and an estimated ten years of use based on the average ten years of use for transit vehicles (Hughes-Cromwick et al. 2017). Capital purchase costs of electric autonomous shuttles (Local Motors 2018), gasoline SAVs (Chen et al. 2016), and conventional diesel buses (Colorado Department of Transportation 2018) were annualized. The annualized cost of wireless electric chargers for autonomous shuttle charging were also included (Nicholas 2019; Sierra Club 2016). Operator wages for bus are based on the national average city bus driver hourly wage (U.S. Bureau of Labor Statistics 2018) and fringe benefits are calculated as 31.4% of compensation according to the U.S. Bureau of Labor Statistics (U.S. Bureau of Labor Statistics 2019). While autonomous vehicles are expected to operate without a driver in the future, public or shared service may still include personnel for safety or to help differently abled riders. Alternatively, autonomous mobility operators may hire remote operators to monitor trips. Thus, operators will pay some sort of wages and fringe benefits; Wadud et al, estimated autonomous mobility will result in a 60% reduction in operator pay and wages (Wadud 2017). The estimated savings in wages and benefits are captured in Table1 for both SAESs and SAVs.

Table 3.1: Point estimate inputs for calculating $/VKT and $/PKT by transit mode. All values are $2019 and used for transit standard cost analysis and CBG-level cost analysis.

	Mode of Transit			
Parameters	Shuttle	SAV	Bus	Reference
Operator Wages ($/hour)	11.10	11.10	27.76	(Hughes-Cromwick 2019; Wadud 2017)
Fringe Benefits ($/hour)	3.36	3.36	8.41	(Hughes-Cromwick 2019; Wadud 2017)
Insurance ($/km)	0.10	0.20	0.18	(Port Authority of Allegheny County 2016;

				American Auto Association 2017; American Public Transit Association 2020)
Maintenance Cost ($/km)	0.39	0.32	0.89	(Fagnant and Kockelman 2015; Sierra Club 2016)
Acquisition (Capital) Costs ($)	238, 095	70,000	300,000	(Chen et al. 2016; Colorado Department of Transportation 2018; Local Motors 2018)
Annualized Acquisition Cost ($/year)	32,349	10,130	43,417	(Hughes-Cromwick et al. 2017; Port Authority of Allegheny County 2016)
Annualized Charger Acquisition Cost	24,796	--	--	(Nicholas 2019; Sierra Club 2016)

Energy costs for each mode found in Table 3.1 are based on 2019 data from the Energy Information Administration (EIA) (U.S. Energy Information Administration 2019). The EIA reported average diesel costs at $0.56/liter in 2019, so the median diesel price per kilometer was derived from a 1.69 km/L fuel efficiency for diesel buses (U.S. Department of Energy 2018). We used a gasoline fuel efficiency of 14.87 kilometers per liter (km/L) and a national average of $0.59 per liter for SAVs. Operator hourly pay for the conventional diesel bus was determined by the annual salary and revenue hours for operators reported by the APTA wage rate database (Hughes-Cromwick 2019) as shown in Table 3.1. Operator hourly pay is reduced by 60% for electric autonomous shuttles and SAVs to account for the potential operating cost savings (Wadud 2017). Insurance costs per mile for electric autonomous shuttles and SAVs were drawn from operation expenses outlined by the APTA (Hughes-Cromwick et al. 2017). Liability and casualty costs are 2% of operating expenses which was used to derive the insurance cost per kilometer for shuttles (similar to demand response costs) and buses (Port Authority of Allegheny County 2016). This value was used to determine the insurance cost per kilometer for electric autonomous shuttles, as they would be categorized as a form of shared-ride transit service. Insurance costs for all three modes can be found in Table 3.1 as well as maintenance costs. AAA reported insurance costs of $0.20/km for vehicles that were used for SAVs. Maintenance costs for electric autonomous shuttles came from a report by the Sierra Club (Sierra Club 2016) and the SAV maintenance cost per kilometer was estimated in a study by Fagnant and Kockelman (Chen et al. 2016).

3.4.3. Monte Carlo Simulation and Sensitivity Analysis

We address the uncertainty of costs with Monte Carlo Simulation. The simulation model parameterized the values in Table 3.1, which can be seen in Table 3.2. Triangular distributions of annual distance represent the range of annual revenue kilometers to serve one CBG in a city. Like annual distance, annual passenger-kilometers represents the range of passenger-kilometers traveled yearly to and from the CBG. Annual distance and passenger-kilometers values in Table 3.2 have best and west case scenarios for annual distances, passengers, and operating costs. When there is a greater annual distance, annual passenger-km, capital costs, and energy costs drive down costs, resulting in a best-case scenario for analysis. Conversely, lower annual passenger-km, annual distance, and operating hours are included in the pessimistic scenario because it would increase \$/VKT and \$/PKT. Base values for capital and energy costs come from the point estimates detailed in Table 3.1. Sensitivity analysis was performed using Sobol's sequence in the SALib Python package to estimate the main and total effects for each parameter.

Table 3.2: Monte Carlo Simulation Parameters Pittsburgh, PA used as an example.

Parameters	Probability Distribution	Pessimistic	Base	Optimistic
Annual Distance	Uniform	18,000	71,000	111,000
Annual Passenger-KM	Triangular	131,000	160,000	317,000
Annual operating hours	Uniform	1,700	3,000	5,000
Electric Charger ($/year)	Triangular	40,000	14,000	9,5000
Bus Fuel Costs-Diesel ($/kilometer)	Triangular	0.35	0.33	0.3
SAV Fuel Costs-Gasoline ($/kilometer)	Triangular	0.1	0.07	0.05
Shuttle Electricity costs ($/kilometer)	Triangular	0.07	0.05	0.02
Shuttle Capital Cost ($/year)	Triangular	39,000	32,000	26,000
SAV Capital Cost ($/year)	Triangular	12,000	10,000	8,000
Bus Capital Cost ($/year)	Triangular	52,000	43,000	35,000

3.4.4. Multi-City Comparison

To better understand the conditions favorable for integrating shared automated mobility with public transit, we looked at factors that lead to operability. Transit supply and sociodemographic data for each city's lowest transit coverage CBGs were compiled then compared patterns in service amongst priority CBGs that determined candidacy for new service. Transit dependent individuals who are also low income and minority provides insight into the US transit dependent population and strengthen the case for improving service by prioritizing equity. Cost-efficiency analysis in each city more accurately captures the range of operating costs for shared autonomous modes. By comparing mean levelized costs in each city we can identify a variety of scenarios where SAVs or shuttles can operate at lower costs than buses and vice versa. Sensitivity analyses tell us what parameters are most important in each city. We look at the results in each city to determine the most important parameter for all the or for certain subsets of transit systems.

3.5. Results And Discussion

3.5.1. New York City, NY

Combining transit coverage and transit equity analysis uncovers areas in a system with critical unmet transit need. Figure 3.1 highlights the low-income or minority population by CBG as defined by the EPA in purple for New York City. The minority population represents 63% of any

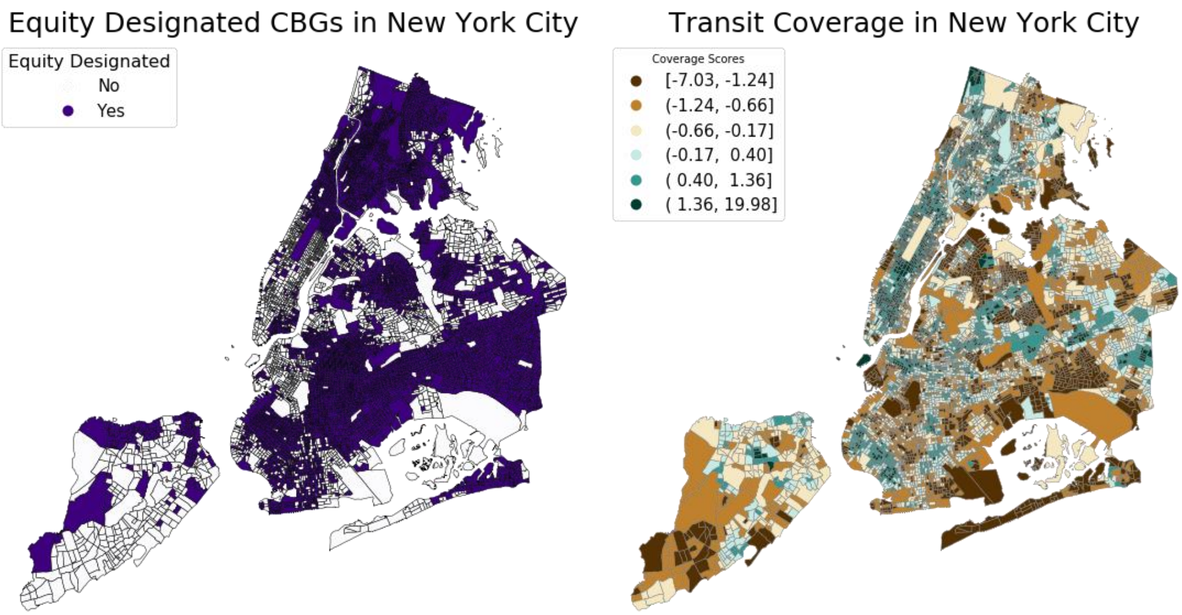

Figure 3.1: MTA New York City Transit Authority transportation system. Maps from left to right: (*left*) Equity designated census block groups in the city show the census block groups that have a greater than average low-income and/or minoritized population. (*right*) The middle figure shows the transit coverage scores in the MTA New York City system. The darker brown color represents census block groups with lower transit coverage scores with darker turquoise represents higher transit coverage scores.

CBG on average, however, the percentage increased to 82% for CBGs with the lowest transit coverage score. The low-income population also increased in CBGs with low transit coverage. On average, the low-income population accounts for 37% of the total population in any New

York City CBG and increased to 49% for low transit coverage CBGs. In New York City, 205 census block groups were prioritized in this study for new transit service. Most priority census block groups did provide some service although inadequate when compared to the rest of the system. Priority census block groups in New York City had the most access to transit of all the cities. Riders in priority census block groups could access 4 transit stops that connected to 7 routes with service approximately every 15 minutes. In contrast, service in higher transit coverage CBGs had a markedly different experience; on average, high transit coverage CBGs have access to 30 stops with service every 8 minutes that connects riders to 11 routes. Level of service metrics in New York City, even in low transit coverage census block groups may be perceived as adequate in another system. However, 52% of the city's population live in zero car households, a larger proportion than the other cities. Thus, lack of service considerably limits individuals in low transit coverage CBGs from job, education, and social opportunities and diminishes transit equity in New York City.

Adding service in NYC exposed the higher limits of shared autonomous mobility operability. Transit dependent and choice riders in priority CBGs would experience more transit access with the addition of the transit stop to provide service to and from the priority CBG and a nearby transit stop. Updated metrics for each CBG on average showed access to 4 additional stops with service frequency approximately every 6 minutes, an access to one additional route. Transit coverage increased an average of 13% across all the priority CBGs. More specifically, thirteen of the 205 priority CBGs were identified as locations where 1, 2 or 4 shuttle fleets could provide cost-efficient service. Shuttles could travel route distances between 0.58 and 5.27 km, for a range of 35,000 to 133,000 annual revenue kilometers. Annual ridership ranged from 30,000 to 1.26 million passengers which suggests that shared, autonomous shuttles can handle high passenger densities in urban cities. Levelized costs for shuttles ranged from $1.63/VKT to $1.90/VKT, and levelized cost per passenger kilometer traveled was much lower at $0.22/PKT on average but could cost as low as $0.02/PKT and up to $0.67/PKT. Total annual operating cost for shuttle service per CBG served was $409,000 with transit coverage increasing by 24% in these CBGs, which is greater than the average transit coverage improvement seen by all the priority CBGs.

We will later compare New York City and other cities to see if the same characteristics hold when assessing operational cost efficiency in smaller transit systems.

For the New York City transit system, the bus had the lowest average VKT, and 192 of the 205 priority CBGs were found to be served by a bus in the most cost-efficient manner. Bus levelized costs were found to be $017/PKT and $3.04/VKT on average. Cost per passenger kilometer traveled resulted in a range from $0.03/PKT to $0.35/PKT while cost per vehicle kilometer traveled ranged from $2.89/VKT to $3.26/VKT. Buses can handle a wider range of annual distances as CBGs service needs as this study found bus service for annual distances between 87,000 and 134,000 km. The annual passenger demand capacity is larger than both SAVs and shuttle with the ability to serve 290,000 to 1.26 million passengers annually. Some of the CBGs may benefit from a more complete service addition because bus fleets ranged from 1 to 5 buses. CBGs with bus service reported an average of 13% improvement in transit coverage at lower costs than the other modes and $622,000 to operate annually. The buses are best for high passenger demand that would result in larger SAV and shuttle fleet sizes for the same service. Surprisingly, SAVs were not cost-efficient providing insight into condition constraints for SAV service. Levelized cost per vehicle kilometer traveled for SAVs had an average of $1.20/VKT, with a range from $1.14/VKT to $1.28/VKT. The mean levelized cost per passenger kilometer traveled was $0.07/PKT with a range from $0.01/PKT to $0.46/PKT per passenger kilometer traveled. SAV fleet size was high with 4 SAVs per CBGs on average and up to a 17-vehicle fleet to serve one CBG. With such a large fleet, the savings from lower capital costs are lost as well as the associated cost inefficiency.

3.5.2. Chicago, IL

In Chicago, 118 census block groups were the final candidates prioritized for analysis. When comparing our prioritized census block group to the average CBGs in Chicago, there are differences in sociodemographic composition as well as public transit level of service as shown in Figure 3.2. The low-income population in the average Chicago census block group was found to be 37% and the minority population was reported to be approximately 57%. However, in our

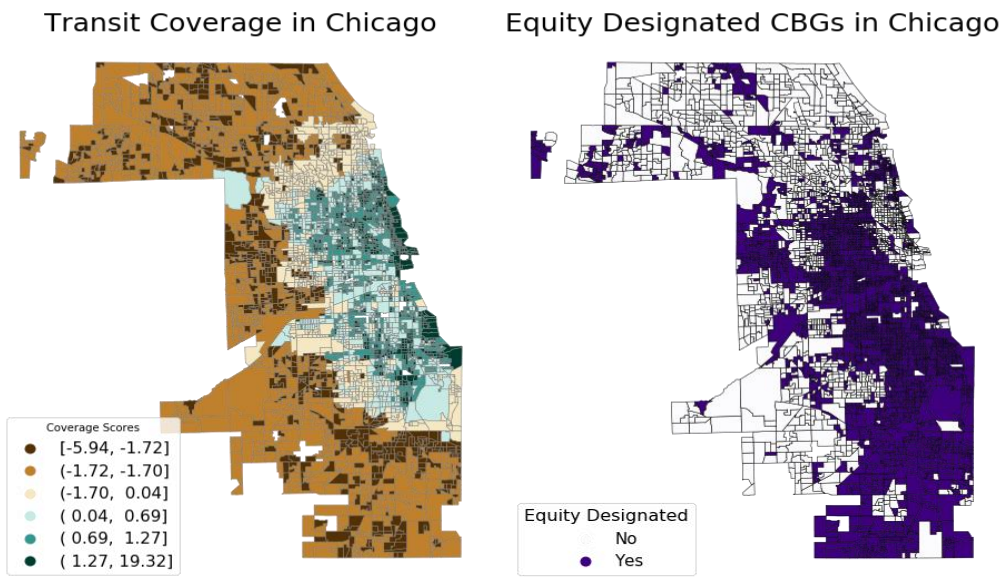

Figure 3.2: (left) Map of transit coverage by CBG in Chicago, IL. Transit coverage combines transit need and transit supply scores to identify census block groups with low transit coverage. The lower and upper values in the legend represent the range of transit coverage scores in each quantile. Darker colors show extremes with dark blue indicating more than sufficient coverage to match demand, and dark brown is the lowest transit coverage signifying insufficient transit access for the transit-dependent population. (right) Map of low income or minority population by census block in purple.

priority CBGs the low-income population and minority population increases to 51% and 79% respectively. An average census block group had service every ten minutes by 4 routes that could be accessed from one of 43 stops in or within a quarter-mile walking distance of that CBG. Public transit service in the priority CBGs was mostly non-existent; most did not have a transit stop within a quarter mile radius of the CBGs, thus no route service nor service frequency.

New transit service to the priority CBGs via shared automated mobility could address latent demand for the nearly 30,000 transit-dependent riders residing in these neighborhoods. Transit coverage was mostly non-existent in the final 118 priority CBGs; results from adding one stop showed an improvement in coverage up to 60%. Transit dependent riders in priority CBGs now have access to stops in nearby CBGs with as many as 40 stops, with pick and drop off at the priority CBG at least every 30 minutes. Route distance ranged from 1.8 km to 12.4 km one-way, for 186,000 to 238,000 passengers per year per CBG. When comparing each mode for cost-efficiency, levelized costs for SAV were surprisingly the highest on average. SAVs operating in Chicago CBGs had a mean levelized cost of $1.25/VKT and $0.07/PKT. On average, one CBG in Chicago needed 10 SAVs to provide adequate service, which contributes to the higher operating cost. Thus, SAVs are economically inefficient to improve transit coverage and equity in Chicago. However, in two of the 118 CBGs shuttles could provide service at a lower cost than buses and SAVs. The levelized operating costs for the most cost-efficient shuttle service were $1.63/VKT and $0.38/PKT on average. The route distances were on the lower end with shuttle traveling 2.6 and 6.6 km for an annual distance of 114,000 and 140,00 km. CBGs served by shuttles had a passenger demand reported as 43,000 and 149,000 riders, equivalent to 573,000 and 770,000 passenger kilometers. Transit coverage improved by 24% with the electric, autonomous shuttle fleet in each CBG for an average total operating cost around $248,000 annually. Analyses for additional service to the priority CBGs provide insight into mode cost efficiency and suitability in large, metropolitans like Chicago.

3.5.3. Pittsburgh, PA

Approximately 78% of the transit-dependent population overlaps with the priority CBGs accounting for over 120,000 transit-dependent riders who are also low-income or minority households. CBGs with low-transit coverage and shown in Figures 3a and 3b, had higher percentages of low-income and minority populations when compared to the county average. Minority populations in low-transit coverage CBGs averaged 46% while the county average was only 23 percent. Fifty-five percent of low-transit coverage CBGs were also low-income, while the county average is 32 percent.

Table 3.3 shows the levelized cost per kilometer traveled ($/VKT), levelized cost per passenger-kilometer ($/PKT) traveled, and total costs for all modes in each city. In four of the five priority CBGs analysis reported SAVs as the most cost-efficient mode to improve transit coverage in Allegheny County, PA. The model estimated 1 or 2 SAVs could provide adequate first and last mile service to each CBG. Route distances were higher than the large metropolitan cities: the SAV would travel between and 4.3 and 7 km each way. Annual passenger load ranged from 6,500 to 16,000 riders traveling up to 195,000 revenue kilometers per year. Operating an SAV under these conditions costs between from $1.12 to $1.82 per VKT and $0.30 to $2.25 per PKT. Total annual operating costs for each CBG were $125,000 on average.

One CBG was better suited for shuttle service in the Pittsburgh and surrounding region. One shuttle best served the 5.2 km route in the system equal to 36,000 km per year to and from this CBG. Approximately 30,000 passengers could be served annually from this added service. The shuttle service cost $2.63/VKT and $0.36/PKT. The transit coverage improved by 40% for total annual operating cost of $114,000.

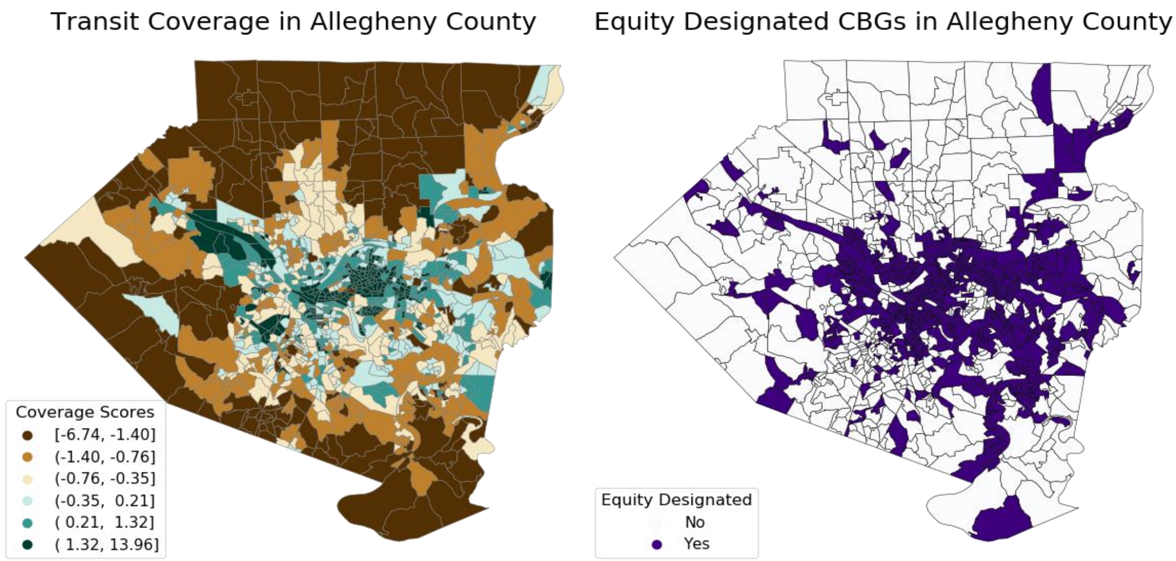

Figure 3.3: (*left*) Map of transit coverage by CBG in Pittsburgh, PA. Transit coverage combines transit need and transit supply scores to identify census block groups with low transit coverage. The lower and upper values in the legend represent the range of transit coverage scores in each quantile. Darker colors show extremes with dark blue indicating more than sufficient coverage to match demand, and dark brown is the lowest transit coverage signifying insufficient transit access for the transit-dependent population. (*right*) Map of low income or minority population by census block in purple.

3.5.4. Minneapolis And St. Paul, MN

Minneapolis-St. Paul metropolitan transit system analysis starts by examining the sociodemographic profile. MetroTransit is the public transit system that serves the Minneapolis-St. Paul with 125 routes and 12,633 transit stops for buses, light rail, and commuter trains. Figure 3.4 shows a map of transit coverage by CBG in Minneapolis-St Paul, MN. Census block groups that are shades of blue represent sufficient transit coverage to demand and dark brown represents CBGs with the lowest transit coverage. The lowest transit coverage scores ranged from signifying insufficient transit access for the transit-dependent population. Our CBG analysis found that the transit-dependent population accounts for 12% of the total population. Seventy-eight percent of the transit-dependent population were also identified as low-income or minority households. The proportion of lower-income and minority populations in equity designated CBGs was higher than the county average as shown in Figure 3.4. Minneapolis-St. Paul, like the

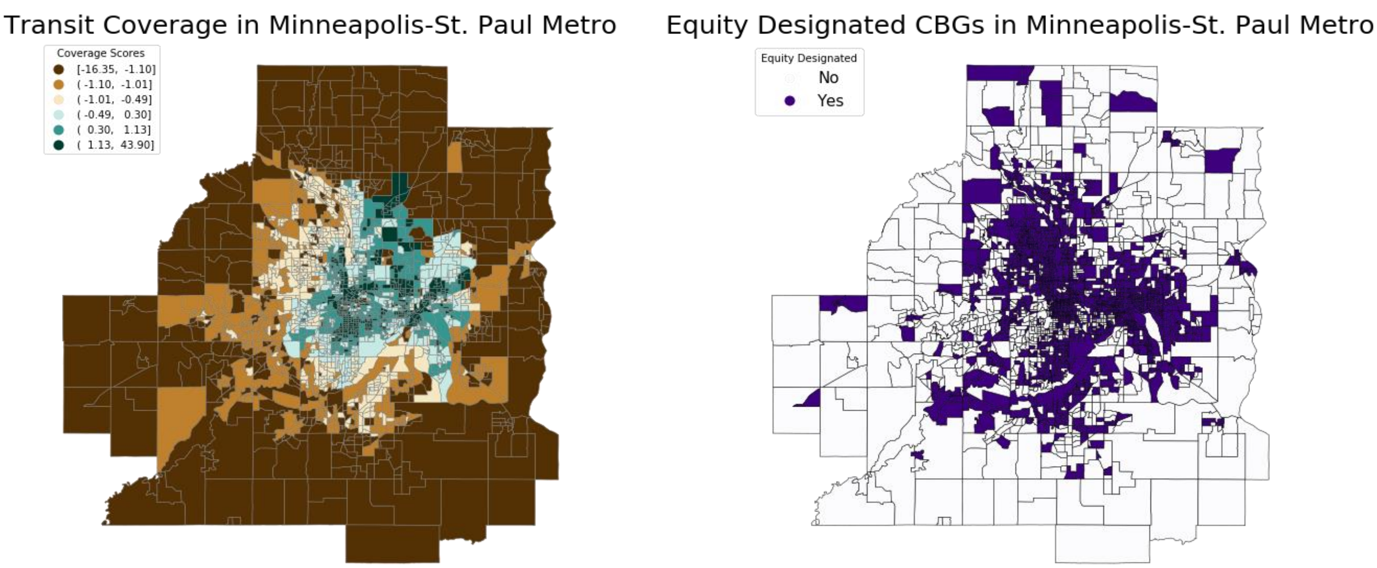

Figure 3.4: (*left*) Map of transit coverage by CBG in Minneapolis-St Paul, MN. The lower and upper values in the legend represent the range of transit coverage scores in each quantile. Darker colors show extremes with dark blue indicating more than sufficient coverage to match demand, and dark brown is the lowest transit coverage. (*right*) Map of low income or minority population by census block in purple. Low-income, minority census blocks are defined as having a larger percentage of minority residents than the city average.

other cities, also had higher than average low-income and minority populations in the census block groups with the lowest transit coverage scores.

Assessing cost-efficiency along with sensitivity analysis in Minneapolis-St. Paul provided more insight into SAVs operability when integrated with public transit. The mean levelized costs per vehicle kilometer traveled for shuttles, SAVs, and buses were $1.99/VKT, $1.26/VKT, and $3.28/VKT, respectively. Levelized cost per passenger-kilometer traveled had a mean value of $2.11/PKT, $1.35/PKT, and $3.50/PKT for shuttles, SAVs, and buses, respectively. Unlike the other cities, all eight priority CBGs in Minneapolis-St. Paul were best served by SAVs in terms of cost-efficiency. Service to the transit system did not require a fleet, one SAV was capable of traveling a route distance between 1.65 km and 7.5 km in the Minneapolis St Paul transit system, equal to 67,000-91,000 km traveled annually. The passenger capacity ranged from 8,600 to 21,000 passengers annually for up to 204,000 passenger-km traveled annually. CBGs transit coverage increased up to 43% for no more than $195,000 per census block group to operate annually.

3.5.5. Comparative Analysis

One goal of a multi-city analysis is to identify the prevalent characteristics that make autonomous vehicles and shuttles feasible in public transportation systems of varying sizes. Examining levelized operating costs and the subsequent sensitivity analysis between each city revealed transit system conditions favorable for first and last-mile service via shared automated mobility. The analysis starts with examining sociodemographic data because it offers a compelling argument regarding equity for additional service. Table 3.3 shows that over 70% of the transit-dependent population in each city lives in CBGs with high proportions of low-income, minority populations, and low transit coverage. Our findings suggest that many transit-dependent riders are also low-income, minority, or both. Regarding transit coverage, Minneapolis-St. Paul, Pittsburgh, and Chicago follow similar spatial patterns where transit coverage is highest in the center of the city and decreases once beyond city boundaries (see Figure 3.3 and Figure 3.4). New York City similarly has high transit coverage in the Manhattan borough which contains the central business district, but high transit coverage continues into most boroughs and low transit coverage was observed in small clusters and around county line boundaries. Once we identified the priority CBGs eligible for new service, census block groups in Minneapolis-St. Paul and New York City were mostly clustered in certain parts of the city whereas Pittsburgh census block groups were spread out. As discussed in the data and methods section, sociodemographic data were used to determine transit demand with an emphasis on improving equity. The differences in the spatial distribution of transit demand imply that in some systems one fleet could potentially serve the cluster instead of assigning one transit vehicle to a priority CBG as done in this study. Additionally, when transit demand is scattered and cannot be serviced with one fleet, costs are still lower than conventional transit service modes.

Table 3.3: Summary data for comparative analysis.

City	**New York City**	**Chicago**	**Minneapolis - St. Paul**	**Pittsburgh**
Transit Dependent Population	4,390,000	795,000	218,000	157,000
Percent of Total Population Transit Dependent	52%	15%	7%	12%
Average CBG Low-Income Population	37%	37%	28%	32%
Average Priority CBG Low-Income Population	49%	51%	38%	46%
Average CBG Minority Population	63%	57%	17%	23%
Average Priority CBG Minority Population	82%	79%	25%	36%
Shuttle				
Mean Levelized Cost per VKT	$1.73	$1.83	$1.99	$2.45
Mean Levelized Cost per PKT	$0.11	$0.10	$2.11	$1.39
Mean Total Cost per CBG	$1,050,000	$869,000	$179,000	$168,000
SAV				
Mean Levelized Cost per VKT	$1.20	$1.25	$1.26	$1.35
Mean Levelized Cost per PKT	$0.08	$0.07	$1.35	$0.88
Mean Total Cost per CBG	$1,934,000	$1,563,000	$125,000	$135,778
Bus				
Mean Levelized Cost per VKT	$3.04	$3.18	$3.28	$3.62

Mean Levelized Cost per PKT	$0.20	$0.18	$3.50	$2.29
Mean Total Cost per CBG	$612,000	$495,940	$295,000	$271,000
Cost-Efficient Shared Autonomous Mode	Shuttle	Shuttle	SAV	SAV
Total System Transit Coverage Improvement	13%	24%	18%	315%

Next, we compared levelized costs and used sensitivity analysis to make inferences about the factors that influence the operability SAVs and shuttles in different transit scenarios. Overall, findings from our sensitivity analysis suggest annual revenue kilometers, annual passenger-kilometers traveled, and fleet size are the most influential parameters when SAVs or shuttles are integrated into a transit system. We look at these results to explore the service conditions that are best for shuttles and SAVs. Figure 3.5 illustrates the service ranges aggregated for each mode.

In Figure 3.5, we see that SAVs are best suited for the lower end of transit demand. When annual ridership is less below 21,000 passengers and the annual distance is less than 130,000 km SAVS remain cost efficient. This corroborates with our previous findings detailed in the Pittsburgh and Minneapolis analysis where priority census block groups were lower density in comparison to the density in Chicago and New York. Further, SAVs were only cost efficient when 1or 2 vehicle fleets could serve one CBG. Interestingly, SAVS were not suitable for lower route distances, where shuttles and buses could still provide service as shown in Figure 3.5a. The results suggest that SAVs are the most cost-efficient mode to improve transit coverage and equity for lower density areas with unmet demand. Shuttles, however, travel up to 1.26 million passenger kilometers and still outcompete buses in certain census block gups as shown in Figure 3.5d. This may be influenced by fleet size; shuttles could operate in one, two, or four shuttle fleets and remain cost-efficient thus carrying more passengers at a lower cost than one bus. Overall shuttles in our comparative analysis proved as an intermediate step, provide coverage where SAVs did not provide enough service and demand was too low for buses.

Finally, shared automated mobility was not appropriate in every situation. While SAVs and shuttles were more cost efficient than buses in Minneapolis-St. Paul and Pittsburgh, for many priority CBGS in NYC and Chicago, buses were still the most cost-efficient. Our analysis supports studies that caution against replacing all public transportation with robotaxis. There are certain conditions where it is still most cost-efficient to add transit access with more

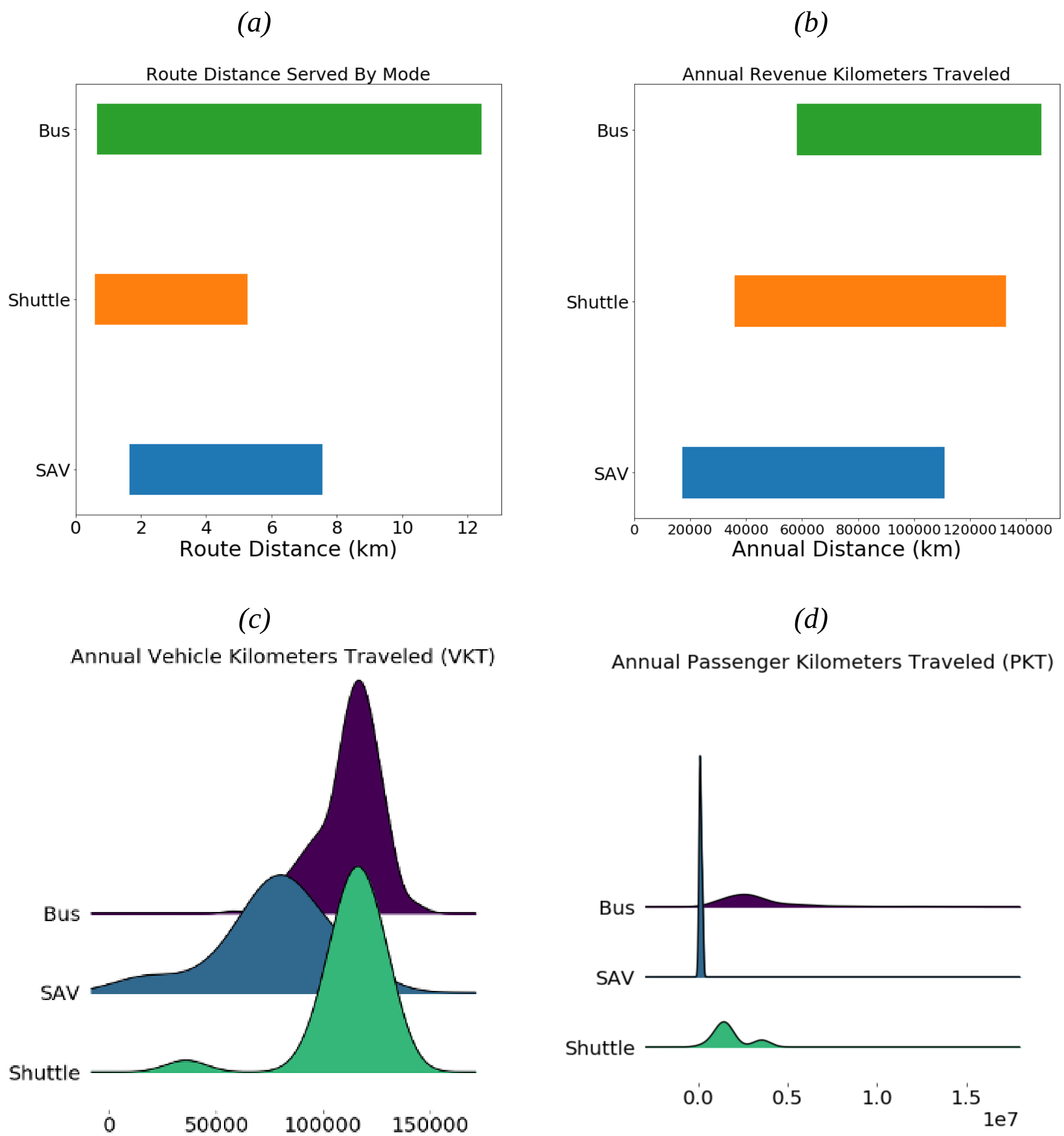

Figure 3.5: Four graphs depicting aggregate ranges for service domains of shared automated mobility. Together, the figures highlight the feasibility for shuttles and SAVs to address a transit needs where adding buses are an inefficient use of resources. (a) Graph showcasing the range of route distances served by each mode. (b) Graph showing the service range in revenue kilometers traveled (VKT in this study) for each mode. (c) Annual passengers served by each mode. (d) Service range in terms of annual passenger kilometers traveled (PKT in this study) for each mode.

conventional modes like bus. However, this study shows that shared automated mobility provides a cost-effective alternative to connect neighborhoods to existing transportation services.

3.6. Conclusions

Autonomous shuttles and SAVs offer a potential new transit mode that agencies can use to improve transit coverage equitably and cost-efficiently. This study compares transit systems in different cities to address research gaps regarding improving equity through shared automated mobility. This study also aims to reveal transit system characteristics that are best for SAVs and shuttles to operate when integrated into a public transit system. First, prioritizing low-income, minority, and transit-dependent populations is advantageous to these riders and the agencies that provide transit service to them. Riders will benefit from increased service with more options to pursue educational, vocational, and social opportunities. Transit equity is a goal that is increasingly pursued in policy and planning therefore transit agencies benefit when equity in their transit system increases. Additionally, any equity and access improvements further transit systems in federal regulation compliance.

Second, our study provided insight into service parameters that lead to the cost-efficient operation of shared automated mobility in different public transit systems. In New York City, there were ten CBGs identified as locations for shuttle service. On average these CBGs experienced a 13% improvement in transit access and costs $1.1 million per CBG on average. In the second largest system, Chicago, two census block groups were most cost-efficiently served by shuttles with a mean cost of $869,000 per CBG for service. One of the mid-sized cities in this study, Minneapolis-St. Paul saw an 18% improvement in transit access for CBGs served by a small SAV fleet. On average adding SAV service in this city cost approximately $179,000 per CBG. Finally, Pittsburgh was compared to our other cities and had the greatest increase in transit coverage at 315% for SAV service in 4 CBGs. New service for Pittsburgh cost approximately $168,000 per CBG. The findings indicate that SAVs and shuttles are not cost-efficient in certain high-density service scenarios, mostly due to increased fleet size. Another consideration worth mentioning, although not included in the study, is larger fleet sizes utilizing road resources thus contributing to congestion in areas that are already grappling with the issue. In contrast, CBGs that are suitable for SAVs or shuttles can operate at substantially lower costs than buses with smaller fleet sizes, namely less than 4 shuttles and less than 2 SAVs. Sensitivity analysis revealed the most important parameters for consideration in future transit planning and policy of shared autonomous mobility. SAVs and shuttles can be constrained to certain service metrics to improve transit coverage equity and to remain a cost-efficient complement to existing transit service.

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4 Replacing Regional Air Travel with Shared Electric Autonomous Vehicles: An Economic and Environmental Analysis

4.1. Abstract

Across aircraft classes, regional aircraft traveling on flights less than 500 km are the second largest emitter of greenhouse gases in the United States aviation sector. The aviation sector needs to minimize emissions in response to mounting environmental demands by incorporating new technology or advanced materials, but market adoption is impeded. Shared autonomous mobility in on-road electric vehicles may offer a new option for passengers who would choose flights under 400 kilometers. This study explored how modal shifts from regional flights to shared autonomous electric vehicles (SAEVs) might offer economic and environmental benefits in places with significant CO_2 emissions from regional air travel. Ninety-seven of the most popular regional flight travel routes were identified as potential SAEV intercity travel candidates. These origin-destination (O-D) pairs represent more than 1.2 million flights per year that are within the current driving range of an electric vehicle. After comparing the levelized operating costs of battery electric vehicles, internal combustion engine vehicles, shared autonomous electric vehicles, and commercial regional aircraft, SAEVs were reported as the most cost-efficient and lowest CO_2 emitter. SAEVs cost less than planes at $0.33 per revenue kilometer traveled, while planes had a levelized operating cost of $12.22 per revenue kilometer traveled. SAEVs demonstrated cost parity with privately owned vehicles while reducing emissions by 39% on average, implying the possibility of economic and environmental efficiencies can be achieved via intercity shared autonomous mobility services.

4.2. Introduction

The transportation sector is the second-largest producer of CO_2 emissions globally (Baumeister 2019). While light-duty travel and trucks make up a large share of transportation sector emissions, air travel emissions, which make up 12% of transportation sector emissions, is growing the fastest at 6% per year globally (Miller 2020). Aviation, like other forms of transport, generate externalities that have a large human and environmental impact. Air travel activity has increased in the last few years, which makes decarbonization more difficult with low-density, regional air travel being the worst emitter (Baumeister 2019). Regional airports are a critical part of transport infrastructure (Gao and Sobieralski 2021) however, a portion of these trips could be replaced by shared, automated, and electrified land-based transportation. One study speculates that driverless vehicles could disrupt airline travel (Liu et al. 2020) and another study found a willingness-to-pay for longer distance trips via shared AVs (LaMondia et al. 2016). However, the economic and environmental impacts of mode shift are still uncertain.

Automated vehicle (AV) technologies are advancing rapidly and can potentially improve travel by reducing congestion and increasing access (Acheampong et al. 2021; Anderson et al. 2014; Fagnant and Kockelman 2015; Harper 2017; Tirachini Hernández and Antoniou 2020; Wadud 2017). Once these vehicles are widely available, autonomous vehicles could provide a viable and new alternative for flights. Currently, private entities are the sole providers of autonomous mobility services (Krafcik 2018). Companies like Uber and Waymo have begun deploying fleets of automated vehicles into cities.

The purpose of this study is to assess the environmental and economic implications of replacing intercity travel trips that are currently done by airplane, with private and shared AVs. Levelized operating costs and emissions factors for aircraft, shared autonomous electric vehicles (SAEVs), privately-owned internal combustion engine vehicles (ICEVs), and privately owned battery electric vehicles (BEVs) are used to assess the environmental and economic costs and benefits, respectively.

4.3. Literature Review

4.3.1. Aircraft Emissions and Mitigation Efforts

In recent years, there has been a growing concern over the environmental impacts of air travel. Globally, 2.4% of all CO_2 emitted in 2018 came from the 39 million flights taken, totaling 918 million metric tons of CO_2 from fossil fuel use (International Council on Clean Transportation 2018). Studies show that 90% of aircraft emissions occur at higher altitudes, specifically during the cruise phase of flight (Federal Aviation Administration 2005; Grobler et al. 2019). Aircraft emissions are approximately 70 percent CO_2, 30 percent H_2O, and less than 1% each of NO_x, CO, SO_x, and other trace components during flight (Federal Aviation Administration 2005). Passenger transport accounts for 81% of total global emissions and the United States is the top emitter, contributing one-fourth of all passenger travel-related emissions come from U.S. travelers. As a result, U.S domestic air travel is responsible for approximately 13% of the world's aviation emissions. Annually, aircraft are responsible for 3% of total U.S CO_2 emissions and 9% of the U.S. transportation sector (Sobieralski 2021). If aviation activity increases as projected, emissions could triple by 2050 without any regulations or policy in place (Environmental and Energy Study Institute 2021) When comparing emissions by aircraft class, regional aircraft that carry passengers less than 500 km are the second-highest emitter. The carbon intensity and environmental impact of regional aviation continue to grow in the US.

Over time, U.S. regional aviation has continued to grow and so has its impact on the national aviation sector. Total passenger capacity from regional aircraft increased 3% from 2009 to 2018, totaling 90 million available seat miles. The result is an increase in passenger load factor from 75% to 80%, while at the same time medium- and long-haul aircraft only experienced an increase from 82% to 84% in passenger load. Increasing jet fuel consumption from regional flight is the result of the higher passenger capacity plus the increase in passenger load. Research shows that short-haul flights have the most inefficient fuel consumption per passenger (Chester and Ryerson 2013). While total emissions are lower than trips over 1000 km, the emissions per ton-km are much higher due to the energy-intense take-off phase, lower passenger capacity, and lower passenger load. Regional aviation undermines the aviation sector's fuel efficiency and CO_2 emissions reduction goals and mitigation efforts have the potential to markedly reduce aviation emissions in the U.S. and the world.

Mounting environmental pressure on the aviation industry has prompted significant efforts to reduce emissions. International and federal governing bodies have established standards and regulations that promote new technologies, materials, and travel behavior as mitigation practices (Federal Aviation Administration 2005; Graham et al. 2014; Singh et al. 2018). At the international level, the International Civil Aviation Organization (ICAO) acts as a global aviation coordinator and set CO_2 standards for industrialized countries under the Paris Agreement. In 2010 the ICAO aimed to achieve carbon-neutral growth by (1) developing and deploying fuel-efficient technologies, (2) introducing state of the art engines technologies, (3) using lightweight materials in aircraft design, (4) more efficient airport operations, (5) incorporating of less carbon-intensive fuels and (6) global carbon-offsetting scheme for international travel. The International Air Transport Association (IATA) outlined a low carbon aviation growth starting in 2020 with 50% reduction in CO_2 emissions relative to 2005 levels. In the U.S., the EPA and FAA work within the IATA and ICAO standards to initiate federal rulemaking under the Clean Air Act 231. In 2020 the EPA finalized rulemaking that set emission standards for domestic aircraft. Unfortunately, emissions have increased 10% between 2012 and 2019 despite the emissions reduction goals set by the IATA, NASA, and ICAO in the early 2000s (Graham et al. 2014; Sobieralski 2021). Goals for reducing greenhouse emissions are difficult to achieve without addressing holistic mitigation strategies, from technology advancements to passenger behavior changes.

Fuel burn during flights primarily emits CO_2, so considerable research has investigated and identified a viable replacement to conventional jet fuel. Studies have identified more alternative jet fuels such as biojet fuels, hydrogen made with zero carbon electricity, and electrofuels and determined that they can reduce CO_2 emissions up to 50% (Dahal et al. 2021; RAND Corporation 2009; Sherwin 2021). Alternative jet fuels were approved for use in commercial flights in 2009 and now over 300,000 flights have used an alternative jet fuel Life cycle sustainability and fuel production costs constrain alternative jet fuel adoption (Babikian et al. 2002; Dahal et al. 2021; RAND Corporation 2009; Turgut et al. 2019). Currently, alternative jet fuel can cost anywhere from twice to ten times as much as conventional fuel. Even at the lowest costs achievable, direct operating costs will increase by 15% when compared to direct operating costs from conventional jet fuel due to higher fuel costs (Dahal et al. 2021; Sobieralski 2021). Biojet fuel, for example, is the most viable alternative fuel because it is compatible with existing aircraft engines and production technology is readily available (Turgut et al. 2019). Viable feedstock for biojet fuel like wheat straw, forestry residues, lignocellulosic biomass are expensive to convert with high capital investments which contribute to higher biojet fuel production costs (Wang 2016). Zero-carbon hydrogen and electrofuels could also become feasible alternatives bearing modifications to the aircraft engine (Dahal et al. 2021; Singh et al. 2018). Therefore, shifting passengers to a more sustainable mode is a mitigation strategy may slow demand and contribute to reducing emissions.

Broadly, environmental mitigation efforts in aviation that involve new technology or advanced materials are available but some challenges delay market adoption. First, many of the technologies being presented are a long way from being readily available for adoption. Growing demand for air travel may outpace technology advances leaving emissions reductions goals unrealized. Secondly, the increase in operating costs for these technologies may disincentivize aircraft carriers to adopt them without regulatory guidance. Finally, independently improving aircraft for efficiency or adopting an alternative fuel is not enough for substantial emissions reduction. Both mitigation strategies must be achieved in tandem with additional efforts including changing passenger behavior.

Regional flight is already competing with other modes but mounting pressure to decarbonize aviation along with the pending deployment of autonomous vehicles presents new competition. Since 2000, the market share for regional flights, routes traveling an average 754 km, has declined by thirty percent (National Academies of Sciences, Engineering, and Medicine 2019). Regional airports are a critical part of the transport infrastructure as they connect regional towns and small communities to the air transportation network (Gao and Sobieralski 2021), however, a portion of these trips are potential candidates for a different mode. Various studies have explored replacing regional air travel trips with land transport (Baumeister 2019; Liu et al. 2020; Miller

2020). Rail is the most common replacement mode in the existing literature. Studies show that a reduction in CO_2 emissions is possible, especially for routes under 400 km (Baumeister 2019). Even in a country where air travel only has a 0.1% market share, rail travel can result in a 2.19% emissions reduction for the entire transportation sector and a 0.44% emissions reduction of the country's entire CO_2-equivalent emissions (Baumeister 2019). Another study analyzed the established rail system in the Northeastern U.S. and found that rail offers CO_2 emission savings (Miller 2020). The case for a transition to land-based transportation is well documented and feasible in many countries with an existing rail system (Adler et al. 2010; Baumeister 2019; Dalla Chiara et al. 2017; Miller 2020; Turgut et al. 2019). However, not every region in the U.S. has adequate rail service, and emerging technologies offer a flexible alternative to building rail lines.

4.3.2. Alternatives To Air Travel

Electric vehicles (EVs) are a promising technology as they may reduce local pollution and greenhouse gas emissions by running on electricity stored in their batteries instead of an internal combustion engine (Borlaug et al. 2020; Chen et al. 2016; Government of Canada 2021). Improvement in alleviating past challenges regarding battery costs, charging stations, and charging time have contributed to the worldwide growth in EV sales (Sheppard et al. 2021). EVs can ultimately reach net-zero emissions if the electricity generation is carbon neutral (Logan et al. 2021, 2022). However, the current electric grid in the U.S. relies on a mix of power generation sources that have been getting cleaner over time, but still relies heavily on natural gas and to a lesser extent coal. Studies purport that privately owned EVs could reduce GHG emissions by 46-53% of ICEVs (Sheppard et al. 2021). Unfortunately, even if the entire U.S. vehicle fleet switched to EVs the emissions reduction would not be sufficient for current emission reduction targets set by the U.S., without a concurrent continued decarbonization of the electricity grid. Interestingly, a SAEV fleet replacing today's vehicle fleet would only require 9% of the vehicles on the road today while reducing emission by 70% and 41% of the lifecycle cost of private EVs (Sheppard et al. 2021).

Shared autonomous mobility can provide a new alternative for short haul flights, specifically those under 400 km (LaMondia et al. 2016; Liu et al. 2020). Currently, private entities are the sole providers of autonomous mobility services (Krafcik 2018). Studies are exploring the financial implication of shared autonomous electric vehicle fleets. Researchers predict an 80% reduction in mobility costs (Boesch et al. 2017), reporting ranging from \$0.61-\$0.72/km for service in a city (Richter et al. 2021). The same study found that larger fleets (2,000 vehicles) allowed for lower prices and increased profit more immediately. However, over the long term smaller SAEV fleets (500) were more efficient and lead to few zero passenger miles. Further, positive environmental benefits can potentially be realized; Mackenzie et al. found a 20% reduction in emissions with a transition to SAEVs (Wadud et al. 2016). Intercity travel with shared autonomous electrified vehicles (SAEVs) is not undergoing testing, but some studies suggest passengers are willing to pay for such a service (Gurumurthy and Kockelman 2020).

Most experts are focused on how autonomous vehicles affect intra-city transport leaving inter-city travel impacts relatively understudied. First, longer distance trips via AVs have been presented as an easier service to deploy as the highway environment is easier to navigate than city streets (LaMondia et al. 2016; Perrine et al. 2020). Other studies have tried to estimate the medium and long-distance travel behavior if AVs are available. Specifically regional mode shifts estimates have ranged from 16% to 25% of trips shifting from air to an AV (Babikian et al. 2002; Liu et al. 2020). Another study assessing the introduction of AVs into the intercity travel market included estimating emissions from ICE AVs. The existing literature establishes the potential competitive advantage for AV in short and medium-distance intercity travel (National Academies of Sciences, Engineering, and Medicine 2019; Perrine et al. 2020; “Transportation Modes, Modal Competition and Modal Shift” 2017). But the current research is limited as operating costs and environmental impacts from different uses cases. Operating costs for SAVs in intercity travel studies are based on other previous works that use intracity city travel scenarios for analysis (Perrine et al. 2020). As such, no study directly calculates the operating costs for a medium to long-distance shared autonomous mobility service. Additionally, the environmental benefits of SAEVs in medium to long-distance travel have not been studied to date. Thus, this study makes a contribution to the literature by estimating the costs and environmental benefits of displacing regional flights in the U.S. with SAEVs.

4.3.3. Research Questions

This chapter investigates the impact of autonomous vehicles on intercity regional air travel. It aims to answer the following questions:

1. Which origin-destination pairs in the United States are candidates for long-distance SAEV service?
2. What are the total emissions savings from replacing the subset of regional flights with a fleet of SAEVs?
3. Could SAEVs provide long-distance service equivalent to regional air services at lower environmental and economic costs than travel by air or a privately owned vehicle?

4.4. Methods

4.4.1. Data And Measures

We use data from the Airline Origin and Destination (O-D) Survey collected by the Office of Airline Information of the Bureau of Transportation Statistics, the statistical authority of the U.S. Department of Transportation ("Origin and Destination Survey Data | Bureau of Transportation Statistics" n.d.). The survey is a 10% sample of airline tickets from reporting carriers and includes a variety of itinerary details for domestic trips. The O-D Survey database has been collected quarterly since 1993 and provides information about air traffic patterns, air carrier markets, and passenger flows. The information we use here comes from freight and passenger aircraft carriers and is highly reliable. The database contains 9,846,816 unique observations for the first quarter of 2019 and determined the 1000 most popular trips by air. Passenger itineraries were aggregated by O-D pair to determine the quarterly passenger demand and later used for estimating fleet demand in each mode scenario. The average range for EVs is 315 km ("EV Database" n.d.), which we used to find the final 195 O-D pairs within driving distance of each other.

This study evaluates the economic viability and environmental impact of shifting regional air travel to road passenger travel via shared autonomous and electric vehicles. Economic feasibility is measured by comparing levelized operating costs for aircraft operators, SAEV operators, privately owned internal combustion engine vehicles (ICEVs), and privately owned electric vehicles (BEVs). According to a study from the National Academies of Sciences, Engineering, and Medicine, 16% of aircraft passengers will shift away from air travel if autonomous vehicles are made available (National Academies of Sciences, Engineering, and Medicine 2019). Further, the same study estimates that regional travel will be most impacted by the mode shift which substantiates the trips and passengers shifting modes as detailed in Table 4.1. For each mode, levelized operating costs represents the cost per revenue kilometer traveled ($/RKT) one way from the origin to destination of a city pair. CO2 emissions are SAEVs are the alternative mode of interest and compared to privately owned vehicles. ICEVs and BEVs are included in the study because an individual shifting from air travel may decide to use their personal vehicle to complete the trip using either vehicle type. This study also includes planes as the business-as-usual case to compare to the alternate modes. Levelized cost calculation varies by the information available for each mode and is explained in further detail in Sections 4.2. Environmental impact is assessed in two ways: (1) calculating air emissions avoided from flying or driving an ICEV for the trip, and (2) comparing the fleet size and vehicle kilometers traveled from SAEVS, ICEVs, and EVs. The assessments are described in Section 4.3

Table 4.1: Annual mode shift scenario values.

Annual Trips by Aircraft	1,200,488
Annual Aircraft Passengers	1,328,000
Annual Trips after Mode Shift	192,310
Annual Passengers after Mode Shift	212,682

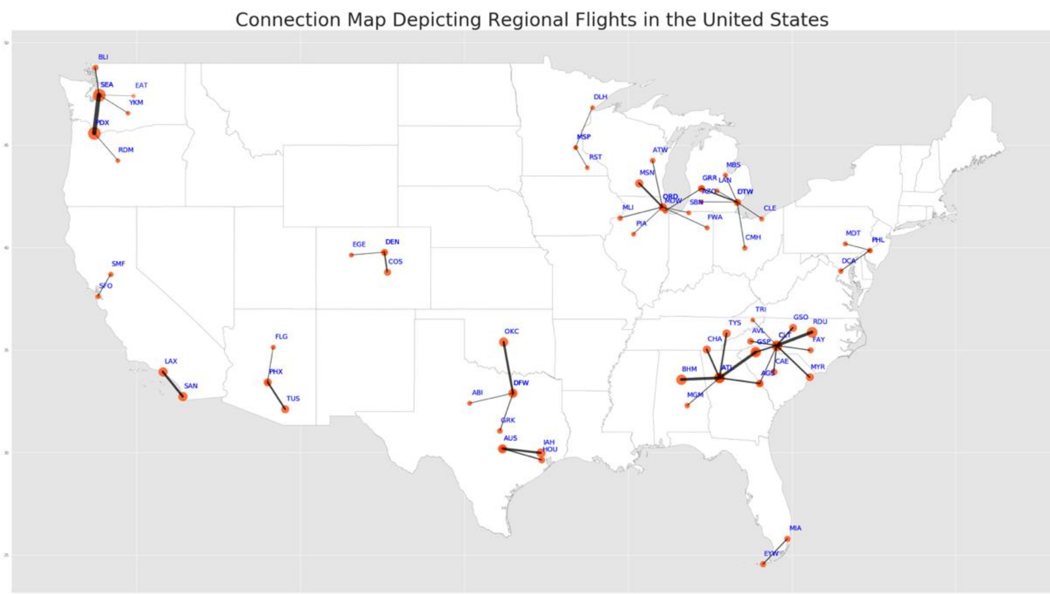


Figure 4.1: Map of the contiguous United States and the most popular city pairs for air travel within EV driving distance without recharging.

4.5. Levelized Cost Calculations

4.5.1. SAEVs

Annualized costs for SAEV fleets were calculated using a 6% discount rate from the state of Pennsylvania Department of Transportation bond rate (Port Authority of Allegheny County 2016), and an estimated ten years of use based on the average ten years of use for transit vehicles (Hughes-Cromwick et al. 2017). Operator wages and fringe benefits or *W* for SAEVs were developed under the assumption no driver or safety personnel were inside the vehicle. Operators' pay was determined by the intercity and charter bus drivers as reported by the U.S. Bureau of Labor Statistics (U.S. Bureau of Labor Statistics 2018) and shown in Table 4.2. Previous studies have estimated a 60% reduction in operator pay (Wadud 2017). We propose an additional 10% in savings, for a total of 70% savings in wages and fringe benefits if the vehicles have no driver but instead are monitored by individuals in a remote site. Since the driving environment is less complex than point-to-point travel in a city, individuals can oversee multiple trips at a time, thus the additional savings beyond estimated savings for intracity travel by shared AVs. Insurance costs per mile for SAEVs were drawn from AAA's cost of driving report (American Auto Association 2019). SAEV maintenance cost per kilometer was estimated in a study by Fagnant and Kockelman (Fagnant and Kockelman 2015). Annual revenue kilometers were represented in *d*, and c_e represents energy costs per revenue kilometer traveled. Energy costs for SAEVs, c_e in equation 1 are based on AAA's report fuel costs for EVs (American Auto Association 2019). Point estimates are detailed in Table 4.2 for operator wages and fringe benefits, maintenance, insurance, and energy costs. All costs are adjusted to 2020 dollars.

Finally, fleet size, *f*, was based on air travel statistics provided in the O-D survey. The trips that shifted from air travel to SAEVs. Given the FAA reporting that 12% of all daily travel takes place during peak times, we assumed a corresponding 12% of annual air travel occurred during peak times (Federal Aviation Administration 2022). For this study, we assumed the peak demand is distributed evenly across 365 operating days which we use to determine the peak trip demand per day and multiplied it by the aircraft passenger capacity to determine peak passenger capacity. Since a SAEV fleet would need to provide the same passenger capacity as an aircraft, the fleet size was determined by dividing peak air passenger demand by SAEV 4-passenger capacity. For example, if an O-D pair had 100 passengers on a plane at peak demand then 25 vehicle fleet of SAEVs would provide equivalent level of service via ground travel.

The following equation represents the calculation of the levelized costs per revenue kilometer traveled ($/RKT) for SAEVs:

$$\$/RKT_{SAEV} = \frac{f(C_{SAEV} + W + M + I) + 2C_{CHARGER}}{d} + c_e \quad \text{(Eq. 1)}$$

where c_{SAEV} represents the annualized capital cost to acquire the SAEV and $c_{CHARGER}$ represents the annualized capital cost for a charger at each airport location. Maintenance (*M*), Insurance (*I*), and wages (*W*) are also given for SAEVs and can be found in Table 4.2.

Table 4.2: Levelized Cost Parameters for analysis. These values were used to determine the operating costs for intercity travel via SAEV, ICEV, BEV, and plane. The units differ by mode due to data availability. Values are adjusted for 2020 dollars.

	Mode of Transit				
Parameters	SAEV	ICEV ($/km)	BEV ($/km)	Plane ($/block hour)	Reference
Operator Wages	$17,250	--	--	$444	(U.S. Bureau of Labor Statistics 2018)
Fringe Benefits	$5,692	--	--	--	(Hughes-Cromwick 2019; Wadud 2017)
Insurance ($/km)	$0.10	$0.08	$0.08	--	(American Auto Association 2019; Richter et al. 2021)
Maintenance Cost	$328	$0.06	$0.04	$431	(American Auto Association 2019; Federal Aviation Administration n.d.; Richter et al. 2021)
Fixed Costs	--	--	--	$397	(Federal Aviation Administration 2022)
Acquisition (Capital) Cost	$37,950	$23,995	$30,660	--	(American Auto Association 2019; Richter et al. 2021)
Charger Acquisition Cost	$24,796	--	--	--	(Nicholas 2019; Sierra Club 2016)
Fuel Cost ($/km)	$0.093	$0.057	$0.093	$115	(American Auto Association 2019; Federal Aviation Administration n.d.)

4.5.2. Plane

The FAA provides values for economic analysis regarding investments and regulatory decision-making (Federal Aviation Administration n.d.). The values in the guide include aircraft that are determined by the Office of Aviation Policy and Plans. Operating costs for passenger aircraft are organized in fixed and variable costs by block hours. The O-D survey included flight distance between the origin-destination pairs which was converted into block hours. Aircraft levelized costs are defined as follows:

$$\$/RKT_{flight} = \frac{C_{FIXED} + (M + I + W)T}{d} \qquad \text{(Eq. 2)}$$

In equation 2, T is the annual block hours, d is the annual revenue kilometers traveled C_{FIXED} is the fixed cost for regional jets. Maintenance (M), Insurance (I), and crew (W) are also given variable costs based on block hours. Lastly, the total annual operating costs are divided by the annual revenue kilometers traveled in flight.

4.5.3. ICEV/BEV

Levelized operating costs for privately owned ICEVs and BEVs are found in AAA's driving costs report and used in Equation 3 to calculate levelized cost(American Auto Association 2019).

$$\$/RKT_{POV} = \frac{C_{VEH} + I}{d} + (M + c_e) \text{ (Eq. 3)}$$

The average purchase cost *(c_{VEH})*, insurance *(I)*, maintenance *(M)*, and energy cost *(c_e)* for mid-sized sedans were available in the report. Purchase costs for ICEVs and BEVs were annualized based on the costs reported in AAA's Driving Costs. Annual RKT, d, is assumed as 15,000 to represent the average distance traveled per year by a privately owned vehicle in the US. Since ICEVs and BEVs are privately owned ,the fleet size is determined by the U.S. average of 1.6 passengers that occupy private vehicles ("2021 Urban Mobility Report – Appendix B: Change in Vehicle Occupancy Used in Mobility Monitoring Efforts" 2021).

4.5.4. Environmental Impact

Aircraft are the fast-growing greenhouse gas emitter in the U.S., thus reducing emissions from a mode shift to SAEVs has the potential to slow the growth of aircraft emissions. Estimating emissions from the flights replaced with SAEV service provide the emissions reduction measure of interest. To assess the impact of the mode shift, we used the global aviation authority, the International Civil Aviation Organization's (ICAO) distance-based approach to calculating carbon emissions (International Civil Aviation Organization 2017). Simply put, CO_2 emissions are calculated from the fuel burned by the aircraft serving the O-D pair. The flight distance between city pairs is given the O-D survey data. Fuel burn data comes from the ICAO Fuel consumption table. The ICAO Fuel Consumption Table presents average fuel consumption by aircraft type and stage length. The averages are based on airline fuel consumption as reported in the U.S. DOT Form 41 each year.

ICEVs also emit greenhouse gases -- approximately 251 grams per km (U.S. EPA 2016). Multiplying the annual distance by the ICEV emissions factor provides the annual CO_2 emissions for comparison to flight, SAEVs, and EVs. Finally, an increase in vehicle kilometers traveled may also result in other negative social outcomes. As such we compare SAEVs, ICEVs, and EVs fleet size and annual kilometers are driven to better understand the potential congestion impacts as a result of the proposed mode shift.

SAEV and BEV emissions come from the Emissions and Generation Resource Integrated Database (eGRID), which is the leading source of data on the environmental characteristics for electricity generated in the United States. The eGRID data set comprises emissions from power plants broken down by 26 United States regions, linking air emissions to electricity generated. Since fully electric cars, like the SAEVs and BEVs used in this study, do not emit tailpipe emissions, emissions associated with power generation are accounted for using eGRID. To begin, the OD pairs are assigned to the regions for which CO_2 emission rates are available via eGRID data. We can estimate CO_2 emissions from the complete SAEV and BEV fleet traveling to and from the OD pairings by utilizing the average EV fuel efficiency for a car.

4.6. Results And Discussion

The first objective of analysis determined and compared levelized operating costs for shared autonomous, electrics vehicles, ICEVs, BEVs, and aircraft that serve regional city pairs. The second objective of the analysis was to assess the environmental impact from shifting transportation modes by estimating CO_2 emissions and thus reductions from said mode shift. Figure 4.1 depicts 97 city pairs that are most popular for regional flight and are also within the EV driving range. The final city pairs are potential service routes for regional SAEV service because one vehicle could travel one way without recharging assuming the SAEVs have an average EV mileage range. Our scenario also assumes that 16% of regional flight activity for each city pair shifts to ground travel via SAEV, privately owned ICEV, or privately owned BEV. In this section, we explore both levelized operating cost and environmental impact at the national, regional, and city pair levels to explore economic and environmental suitability for regional SAEV service in comparison to existing conventional travel modes. The economic and environmental policy implications will also be discussed followed by limitations that affected the research.

4.6.1. Levelized Costs

Table 4.3 shows the summary statistics for all modes. The average levelized cost for SAEVs was \$0.33/RKT, which is markedly lower than the \$12.22/RKT determined for planes. Since ICEVs and BEVs were determined under the assumption that the city pair trip is one of many trips taken in a privately owned vehicle in a year, the cost to operate the vehicle was constant at \$0.34/RKT and \$0.39/RKT for ICEVs and BEVs respectively. Studies exploring SAV costs have estimated costs to range from \$0.19 to \$1.03/VKT. SAEV levelized costs are slightly lower than previous studies but within the same order of magnitude, some of these studies assess AVs for shorter distance trips which may equal fewer miles traveled annually compared to a long-distance trip. The discrepancy in operating cost for SAEVs may be due to the longer distance being traveled for regional service, additionally, the higher capital cost to electrify the SAV fleets contributes to the higher cost as well. Both shared modes, plane, and SAEV, have higher \$/RKT than traveling to the city pairs via personally owned vehicles. In the cases where passengers are still looking to travel via shared mode, SAEVs provide a cost-competitive alternative to driving one's own car. However, the economic impact is rarely the sole decision-making factor; environmental impact is also important. Single occupancy travel is an ongoing issue in the U.S. and will be discussed later in the document to establish reasoning to continue exploring shared autonomous electric vehicles as an alternative.

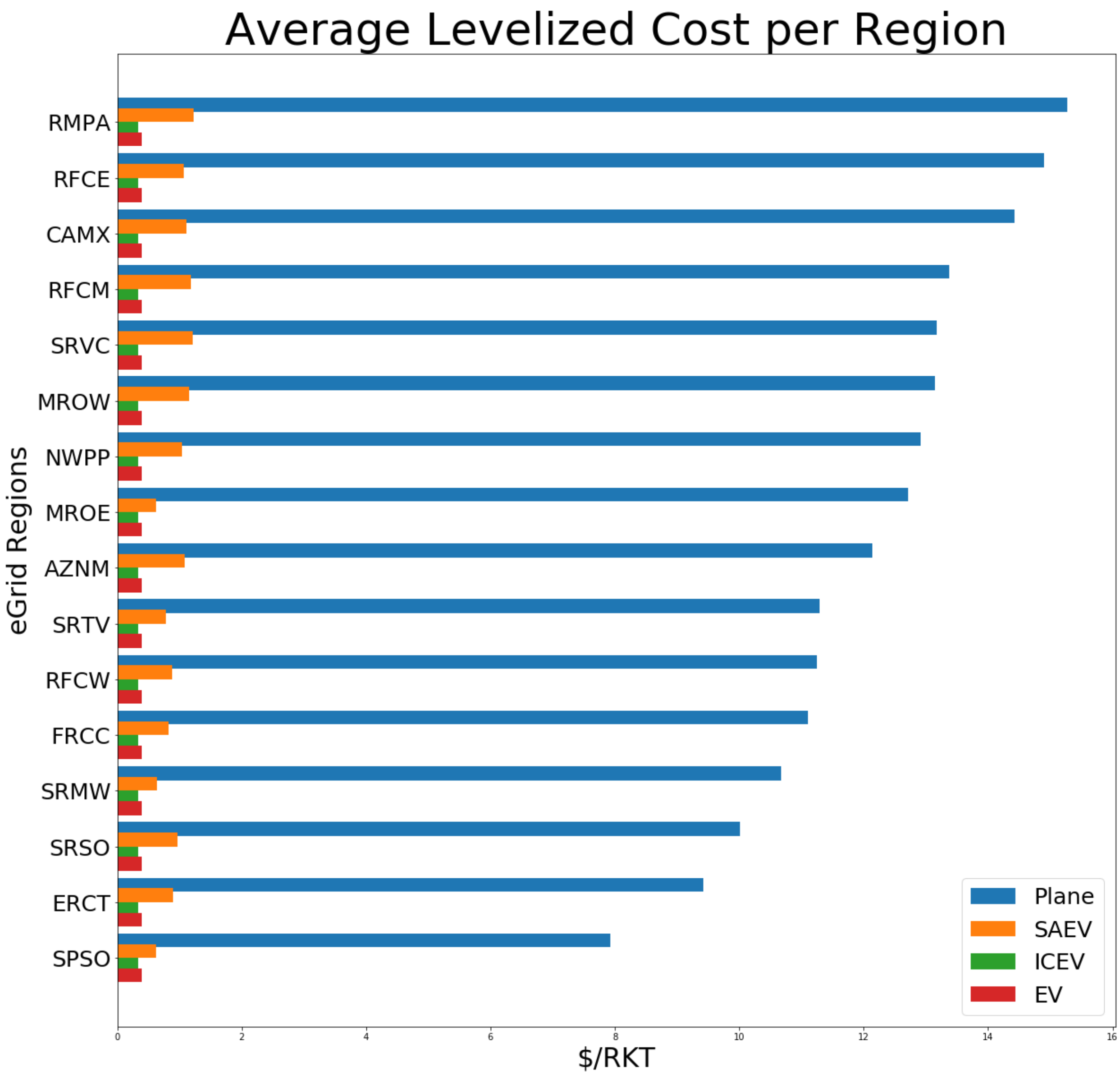
Table 4.3: Average Levelized Operating Costs for each mode across all city pairs.

	MEAN		ST. DEV		MIN		MAX	
SAEV $/RKT	$	0.34	$	0.13	$	0.13	$	0.72
PLANE $/RKT	$	12.22	$	3.03	$	7.93	$	19.00
ICEV $/RKT	$	0.34	$	0.00	$	0.34	$	0.34
EV $/RKT	$	0.39	$	0.00	$	0.39	$	0.39

At the regional level, it becomes easier to determine where operating costs for regional flights are highest and thus the greatest savings can be realized. What stands out in the figure is the markedly lower operating cost for SAEVs compared to travel by plane. The operating cost for SAEVs is closer to the cost of a privately owned vehicle. The most expensive region for air travel, RMPA, mostly serves Colorado with two city pairs being serviced: Denver, CO to Colorado Springs, CO, and Denver, CO to Vail, CO. The second most expensive regional city pairs are between Washington, DC to Philadelphia, PA, and Philadelphia, PA to Harrisburg, PA. The third most expensive levelized operating costs for planes are located in the CAMX region which serves California, specifically San Francisco to Sacramento and Los Angeles to San Diego.

When we compare the levelized cost at the city pair level as shown in Figure 4.2, we can confirm that all city pairs operate at lower costs than planes. Here we examine the city pairs from most to least expensive operating cost. We see there is no concise trend or pattern between SAEV and plane costs, an increase or decrease in SAEV costs is not proportional to plane operating costs. This may suggest that high-resolution analysis, such as evaluation at the city level is key for identifying economically viable opportunities within a region.

Overall, when comparing levelized costs the analysis found that the operating costs are lower for SAEVs than regional air travel. When compared to previous levelized cost of driving studies on autonomous mobility we find that our values are within the same order of magnitude although on the higher end of the range of costs. The more expensive levelized cost of driving might be due to the longer distance as well as the additional cost for electrifying an autonomous vehicle in comparison to an ICEV AV. Further, it is possible to find different economic opportunities by looking at the output at different levels of granularity which can better inform policymaking based on the priorities of a state region or national rulemaking body. Economic viability is only a portion of the bigger picture, and we transition to the environmental analysis and impact to determine to further determine SAEV intercity travel feasibility.



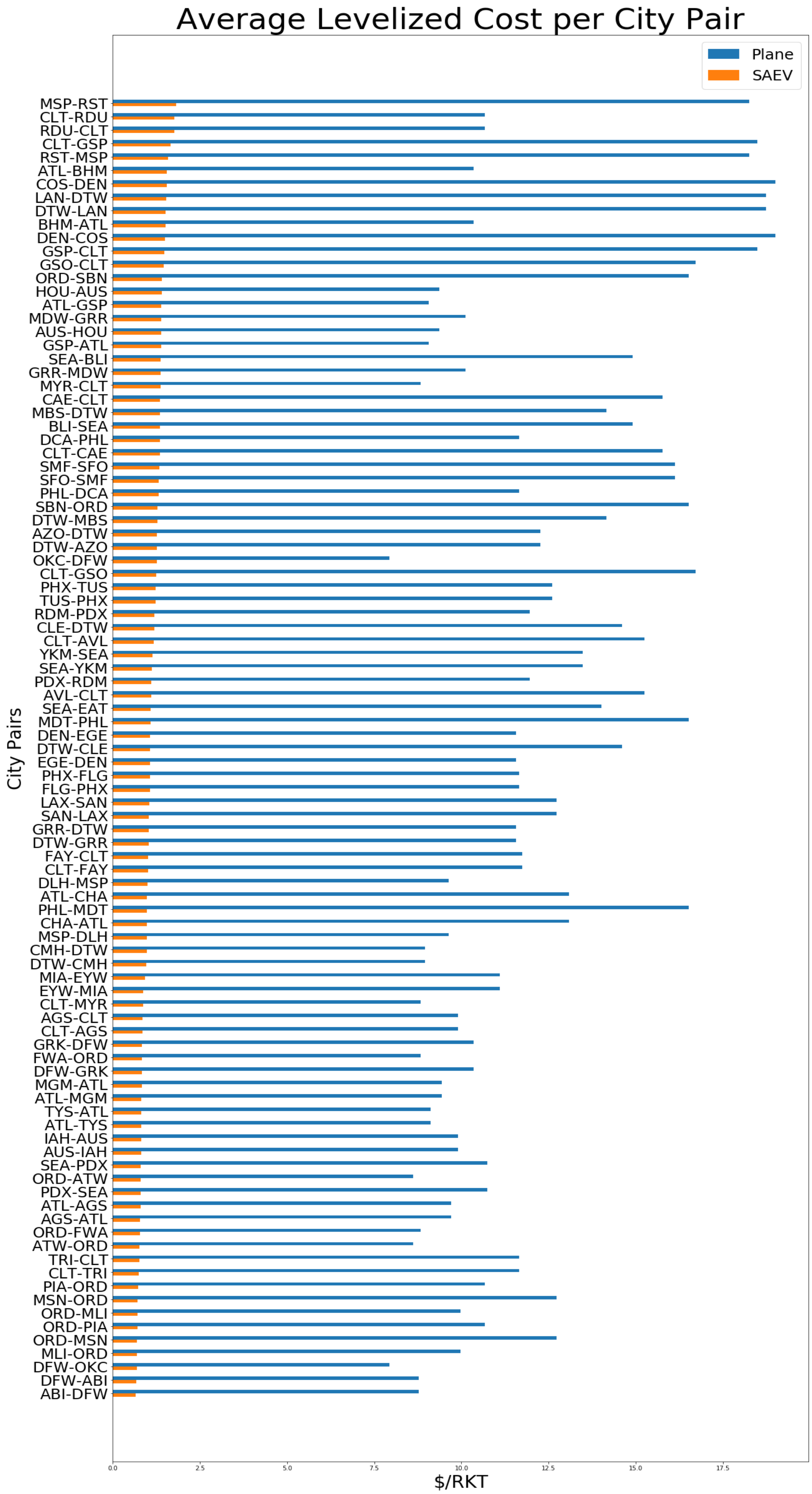


Figure 4.2: SAEV and Plane Levelized Costs for all city pairs.

4.6.2. Emissions

As stated, the model identified 97 city pairs with the most regional flight activity and within EV driving range. In addition to comparing levelized cost, CO_2 emissions from regional aircraft, SAEVs, ICEVs, and BEVs for all city pairs were evaluated. As expected, regional aircraft were the largest CO_2 emitters on average in this study. Table 4.4 shows annual regional aircraft emissions were orders of magnitude larger than SAEVs, ICEVs, and BEVs. The total emissions for 16% of regional travel for the city pairs are 2.26 million tons of CO_2 in 2019. At the national level, the carbon emissions related to these city pairs account for only 0.5% of all CO_2 emissions in the U.S. and a little over 1% of all passenger air travel in the U.S. As shown in Table 4.4, CO_2 emissions are considerably lower when SAEVs or privately owned ICEVs or BEVs replace regional aircraft. SAEVs, ICEVs, and BEVs save 99.1%, 98.7%, and 99.2% of the 2.26 million tons of CO_2 from being emitted. However, CO_2 emissions per passenger provide further insight into the environmental impact of privately owned BEVs and ICEVs. The CO_2 emission per passenger for ICEVs, BEVs, and planes is higher than the emissions found for SAEVs. By examining a different output variable, we begin to see the environmental impact of single-occupancy travel and its overall contributions to CO_2 emissions. A deeper investigation into regional and city pair impacts will further elucidate the benefits from SAEVs in this use case.

Table 4.4: Mean Emissions from each mode in analysis.

	MEAN	ST. DEV	MIN	MAX
SAEV CO_2 EMISSIONS (ANNUAL)	55,351	42,488	15,029	241,960
SAEV CO_2 EMISSIONS/PASSENGER	7.09	1.99	3.23	11.04
PLANE CO_2 EMISSIONS (ANNUAL)	6,539,199	6,010,851	1,484,313	27,424,393
PLANE CO_2 EMISSIONS/PASSENGER	44.59	7.40	29.56	57.59
ICEV CO_2 EMISSIONS (ANNUAL)	82,709	68,698	20,285	367,584
ICEV CO_2 EMISSIONS/PASSENGER	36.85	7.86	20.31	49.72
EV CO_2 EMISSIONS (ANNUAL)	51,212	42,658	13,616	252,106

EV CO_2 EMISSIONS/PASSENGER	23.62	6.63	10.77	36.80

At the regional level, it is clearer that certain parts of the country are more positively impacted by the reduction in emissions from mode shift. Figure 4.3 shows the emissions by the passenger by flight on the top and the bottom shows the emissions per passenger by SAEV. Most interestingly, certain regions move from the largest emitter to the lowest emission range. The bar graph in Figure 4.3 further elucidates the difference in emissions per passenger from all four modes in each region, where on average SAEVs are the lowest emitter. MROE, SRNW, RFCE, FRCC, and SPSD are the top-emitting in this study. When shifting modes these regions see some of the greatest reduction in emissions. The CO_2 per passenger findings is valuable as they point to the impact of single-occupancy travel. CO_2 emissions per passenger are higher for single-occupancy trips, nearly comparable to traveling by plane, even for BEVs. Further, if 16% of passengers traveling via regional aircraft were to switch and travel via their privately owned vehicles to make the same trip there would be an additional 7,500 vehicles on the roads. The influx in vehicles may contribute or add to existing congestion, especially during peak travel times. Conversely, a smaller SAEV fleet can provide an equivalent service thus more efficiently using existing road infrastructure as well as maintaining lower CO_2 emissions per passenger.

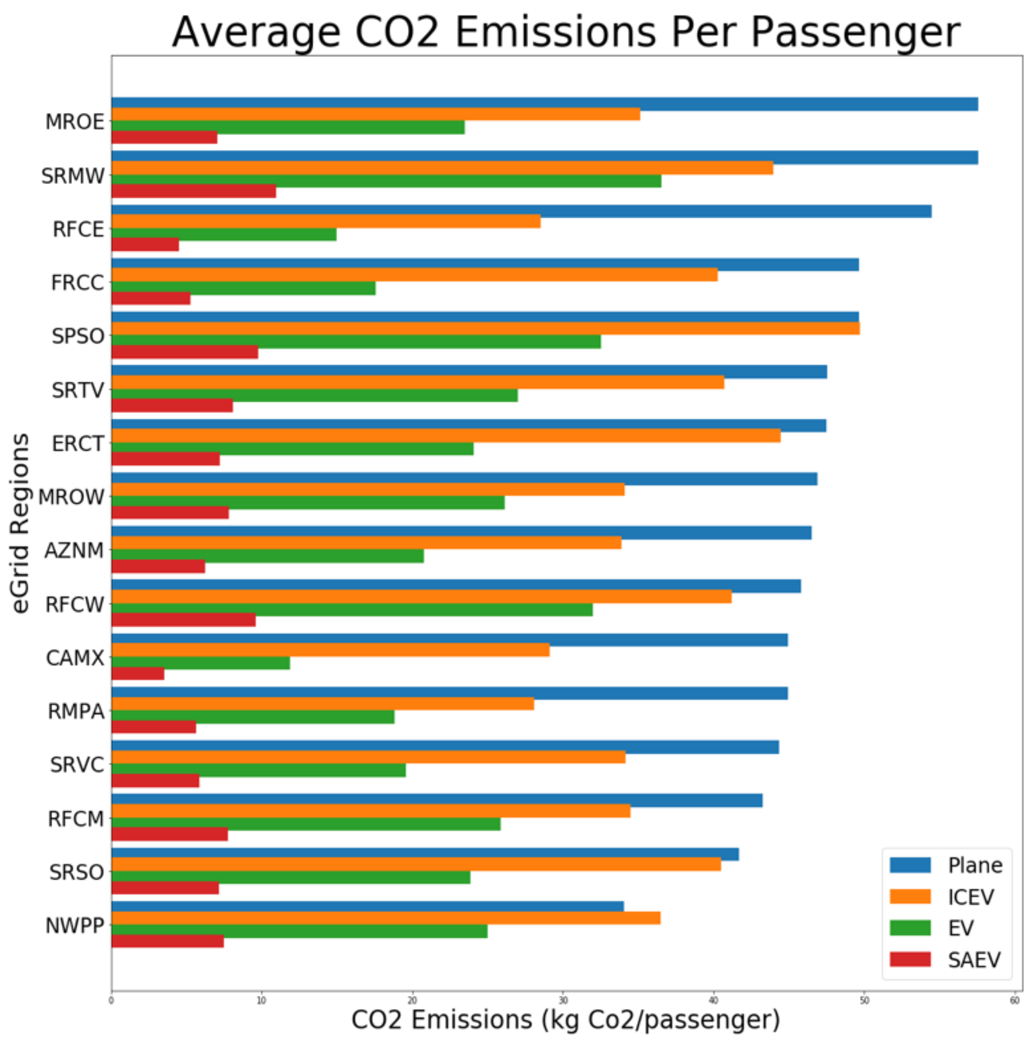


Figure 4.3: CO_2 emissions per passenger by eGRID region.

4.7. Conclusions

This study presents a case where modal shift can lead to lower economic cost to the operator and offers environmental benefits to regions with high CO_2 emissions from regional air travel. The study also presents a new use case for shared autonomous mobility that has not yet undergone deliberate study. As such our first-order analysis estimates economic viability and environmental impact from such a service. First, 97 O-D pairs were identified as candidates for SAEV intercity travel. These pairs represent over 1.2 million flights annually that are within the current EV driving range. Then we compared the levelized operating costs of BEVs, ICEVs, SAEVs, and planes. Indeed, SAEVs did have a lower cost per RKT than planes, with a reported cost of $0.33/RKT and $12.22/RKT respectively. SAEVs had the lowest operating cost for shared modes. Privately owned ICEVs and BEVs also reported lower levelized operating costs overall at $0.33 /RKT and $0.39/RKT respectively. SAEVs proved to be cost-competitive with privately owned vehicles suggesting that they could provide an economically viable shared autonomous mobility service.

The environmental impact of SAEVs further demonstrates the suitability for intercity travel. The environmental analysis evaluated each mode as total emissions and emissions per passenger to reveal said environmental impacts. While SAEVs had the lowest overall total emissions, the more interesting outcome was shown in emissions per passenger. Here, the impact of single-occupancy travel was made clear as privately owned ICEVs and even BEVs were CO_2 intensive. These findings point to the SAEV being a viable alternative in terms of cost but also in emissions reduction Although a mode shift would result in reduced aviation activity and subsequent economic activity, the aviation industry is also under the direction to reduce the emissions contribution. Regional aircraft emissions continue to grow as passenger demand climbs; there is a limit to the number of passengers a plane can hold, and even then, there may come a point when efficiencies gained through aviation technology advancement erode due to demand. As such, the aviation sector may reach a level where alternative modes will be necessary to address demand and maintain efficiency constraints imposed by FAA regulations. So, the shift ultimately supports that effort by reducing the passenger load for air carrier companies. Aircraft carriers can shift focus to long-distance travel and realize efficiencies from fuel and engine technology. It is important, however, that rebound effects from an uptick in long distance flights are constrained. The cascading impact is a more efficient use of aircraft operations like airport resources and flight crew. Additionally, a new intercity travel service provides passengers more options for travel and doing so affordably and conveniently. There is even potential for access for those who are unable to afford and physically able to travel by plane. Policymakers can use this information to devise a mitigation solution that addresses regional aircraft emissions.

The potential new use case for an autonomous vehicle may prove attractive to AV manufacturers or aircraft carriers. AV companies are exploring a variety of business models using shared AVs and this study identified candidate city pairs as well as estimating operator costs for such a service. Alternatively, aircraft carriers looking to reach emissions reduction targets while still providing service may find this option attractive for connecting service. Similar to Amtrak's bus service between rails, aircraft carriers can offer SAEVs as the connector to longer haul flights.

4.8. Limitations

As a first-order level analysis, there are limitations to this study. First, there remains uncertainty around the costs associated with autonomous vehicle technology. Many studies expected cost to continue to decrease as the technology matures. As such it can be expected that levelized costs for SAEVs will decrease over time. . Notably, cleaning and overhead administrative costs are not included in the levelized operating cost calculation which can also contribute to the SAEV operating cost. Also, the study's scope is intentionally limited to one scenario where a 16% mode share for regional air travel is replaced with alternative transportation modes. It is also assumed that flights shifted to the new mode are not replaced with other flights of any distance. If deployment is successful mode share could increase and therefore greater CO_2 emissions reductions for the aviation sector could be realized. In terms of CO_2 emissions, we used the ICAO table which was an update as of 2019. There may have been advances in aviation technology that have resulted in fuel burn efficiency improvements that are not accounted for in the aircraft emissions calculations.

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5 Engineers' Roles and Responsibilities in Automated Vehicle Ethics: Exploring Engineering Codes of Ethics as a Guide to Addressing Issues in Socio-technical Systems[2]

5.1. Abstract

The ethical implications for the engineering profession of the development and deployment of automated vehicles (AVs) can be explored by analyzing the implications of AVs across three major socio-technical systems—technology, transportation systems, and policy. Mapping the ethical canons of professional engineering societies to these domains provides a lens to investigate existing ethical issues and uncover issues that still need attention. The codes of ethics for five engineering societies direct engineers to consider, identify, mitigate, and manage how their work affects the public. AV ethics literature in the technology domain has focused mainly on crashes, AV software capabilities, and hardware. This narrow focus signifies that engineers in the technology domain can do more to understand potential impacts beyond AV crash behavior. In the transportation systems domain, among the many ethical issues affected by AVs, how engineers design and deploy surface transportation infrastructure is an example of an ethical system-level problem yet to be addressed. Lastly, the policy domain has begun addressing primary effects like protecting the public from physical harm, but other ethical aspects remained unaddressed. All three domains could benefit from more holistic system-level assessments of the ethical implications of AVs. Engineers can use their professional engineering organization ethical canons to evaluate their contribution to managing ethical issues in these AV domains and improve how automated vehicles serve and safeguard the public.

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5.2. Introduction

Automated vehicles (AVs) shift the tasks from human drivers to machines. When introduced to the passenger transportation sector, AVs could potentially result in many societal benefits–fewer crashes, less congestion, reduced vehicle emissions, increased mobility, increased access, and increased productivity (Anderson et al. 2016; Harper et al. 2016b, 2018; Levin and Boyles 2015; Mersky and Samaras 2016; Wadud et al. 2016). Yet they may also amplify negative externalities and inequities of transportation. There are increasing concerns about adverse impacts on land use and sprawl (Duarte and Ratti 2018; Freemark et al. 2019), mobility (Bagloee et al. 2016; Feigon et al. 2016; Zmud and Sener 2017), vehicle registration and licensing (Fagnant and Kockelman 2015), transportation infrastructure (Csiszár and Zarkeshev 2017; Litman 2018; Martinson 2017), wireless connectivity (Anderson et al. 2016; Hanna and Kimmel 2017), insurance and liability (Winkelman et al. 2019; Fagnant and Kockelman 2015; Hevelke and Nida-Rumelin 2015), and environmental impacts (Alarfaj et al. 2020; Chase et al. 2018; Greenblatt and Saxena 2015; Vasebi et al. 2018; Wadud et al. 2016).

The transition to automated vehicles on the road poses a challenge for those involved in developing, deploying, regulating, and using the technology. There are ethical issues that require input from policymakers, economists, automakers, the public, and many other stakeholders. Engineers from many disciplines contribute to or interact with AV technology, which offers a unique opportunity to contribute to the AV ethics conversation in a meaningful way.

A prominent AV-related ethical dilemma that was widely discussed revisited a thought experiment called the "trolley problem," which focused on the ethical choices between minimizing harm to drivers or bystanders when a crash is unavoidable (Thomson 1984). Ethical concerns about an AV’s decision-making algorithm in the event of a crash have captured public and academic attention. The trolley problem is hypothetical, simplistic, and overused; however, the activity around this thought exercise has at least provided a benefit. AV ethical issues are now at the forefront, creating an opportunity to expand the discussion to more critical ethical issues that surround AV technology (Goodall 2016, 2017).

Here we focus on the responsibilities of one group of AV stakeholders: the engineers involved in the AV domains of technology, transportation systems, and policy. To elucidate the ethical responsibilities of engineers, we explore the codes of ethics established by the following engineering societies: American Society of Civil Engineers (ASCE), Association for Computing Machinery (ACM), Institute of Electrical and Electronic Engineers (IEEE), Institute of Transportation Engineers (ITE), and Engineering Council in the United Kingdom (EC). The ethical canons from these codes are then superimposed onto AV issues in the three AV domains. Each engineering organization was selected because AV development and deployment rely on the expertise of members found in these organizations.

The domains of technology, transportation, and policy, represent the ethical elements of key socio-technical systems and their interaction with AV technology (Borenstein et al. 2017b). Each domain was selected because they were reoccurring domains in existing engineering ethics literature on AVs, which most prominently explore the issues of this novel technology. In addition, technology, transportation systems, and policy systems are three encompassing domains that members of the professional societies we analyzed interact with. Technology is an important domain because it pertains to the development and application of software and hardware that enables the capabilities of AVs. The second domain, transportation systems, is comprised of the physical infrastructure, travel modes, and the resulting impacts from deployment. The transportation systems domain contains decisive ethical concerns because autonomous vehicles will be deployed onto existing transportation infrastructure and will influence future infrastructure decisions as AV technology diffuses through the automotive sector. Lastly, the policy domain is a critical component representing the regulatory actions at the state and federal levels as well as the bidirectional influence of AV technology and policy. Policy issues and decisions shape the transportation and technology domains and will therefore impact AV ethical issues that engineers may address. Examining ethical issues in each domain reveals focus areas for risk mitigation efforts. More specifically, issues in each domain offer an opportunity to better understand engineers' contribution to AV ethics in accordance with the canons from their given professional organizations.

In this paper, we aim to (1) analyze engineers' role and responsibilities in AV ethics (2) examine and map engineering codes of ethics in relation to the AV domains, and the explicit and implicit ethical duties and, as a result, (3) identify active topics in AV ethics literature in these three domains.

While engineers can contribute to the discovery and exploration of ethical issues in their work, they are not responsible for determining the legitimacy of topics presented as ethical issues. Borrowing a framework explored at the emergence of nanotechnology, any problem that lies at the intersection of fairness, equity, justice, or power can be considered a social and ethical issue for emerging technology (Lewenstein 2006). Here, the legitimacy of ethical issues is not argued; instead, we aim to assess engineers' responsibility using the codes of ethics established by these professional organizations.

5.3. Professional Engineering Society Codes Of Ethics

A first step in understanding the value judgments embedded in the AV landscape is to examine the ethical canons of the professional organizations that engineers follow. The codes of ethics for the ASCE, ACM, IEEE, ITE, and EC are examined to discern the ethical responsibilities engineers have in the domains that represent critical socio-technical systems.

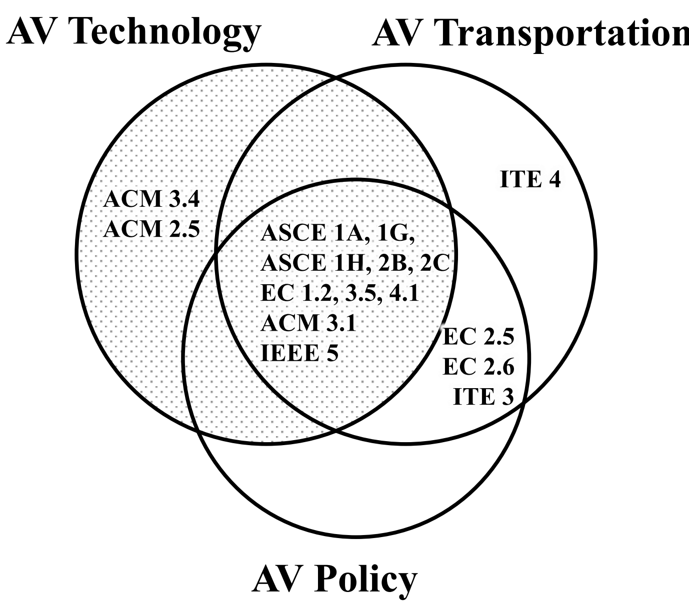
We start by classifying the ethical canons for each professional organization in Table 5.1 according to their relevance to the transportation systems, technology, and policy domains. Some canons were not included in the classification because they are not directly relevant to AV ethics. Some ethics canons provide directives about conduct in the profession such as not accepting gifts or money from clients. The remaining canons are placed in domains where they are most relevant. As shown in Figure 5.1, twelve ethical canons overlap all three AV domains, which can be summarized into five core actions that define engineers' role in AV ethics discourse. The core activities for engineers are considering, identifying, quantifying, mitigating, and communicating the risks to public welfare (American Society of Civil Engineers 2020; American Society of Mechanical Engineers 2012; Association for Computing Machinery 2018; Engineering Council 2017; Institute of Electrical and Electronic Engineers 2018; Institute of Transportation Engineers 2017).

Although five core activities apply to each domain, some canons provide more specific insight as they only apply to their respective domains. Considering the social implications of the system is the first canon that is solely relevant to the AV technology domain (Association for Computing Machinery 2018). The second canon from ACM calls its members to "understand the needs of users and to develop a system that adheres to those needs" (Association for Computing Machinery 2018). The majority of ethical issues related to transportation systems overlap with policy and technology except for ITE's fourth canon, which promotes a commitment to transportation system resiliency (Institute of Transportation Engineers 2017). Lastly, issues in the AV policy domain are also relevant in the technology and transportation domains, and consequently, the canons relevant to policy overlap both domains in Figure 5.1.

Table 5.1: Ethical codes from professional engineering organizations relevant to automated vehicle technology.

Organization Canon Number	**Ethical Responsibility**
ASCE 1A	protect the health, safety, and welfare of the public
ASCE 1G	recognize the diverse historical, social, and cultural needs of the community, and incorporate these considerations in their work
ASCE 1H	consider the capabilities, limitations, and implications of current and emerging technologies when part of their work
ASCE 2B	consider and balance societal, environmental, and economic impacts, along with opportunities for improvement, in their work
ASCE 2C	mitigate adverse societal, environmental, and economic effects

ACM 2.5	Thoroughly evaluate computer systems and their impacts
ACM 3.1	Articulate and accept social responsibilities of one’s work
ACM 3.4	Include the needs of affected users in a system and validate to ensure the system meets the requirements articulated
IEEE 5	Educate public on capabilities and social implications of emerging and conventional technologies
ITE Section 3	Improve the public’s quality of life through a sound transportation system.
ITE Section 4	Enhance society’s ability to respond to and recover from economic, technological, or physical interruption through transportation system resiliency
EC 1.2	Respect the privacy, rights, and reputations of others
EC 2.5	Protect and improve the quality of built and natural environments
EC 2.6	Maximize the public good and minimize both actual and potential adverse effects
EC 3.5	Identify, evaluate, quantify, mitigate, and manage risks
EC 4.1	Discern issues engineering and technology raise for society



Organization	Acronym
American Society of Civil Engineers	ASCE
Association for Computing Machinery	ACM
Institute of Transportation Engineers	ITE
Institute of Electrical and Electronic Engineers	IEEE
Engineering Council (United Kingdom)	EC

Figure 5.1: The ethical codes of five selected major professional engineering organizations are classified by the relevance to three socio-technical AV domains.

5.4. Ethical Issues In AV Technology

Some ethical issues in the AV technology domain are very active topics in the ethics literature, while other issues are emerging as the technology continues to develop. To date, general safety, crash avoidance, and privacy are common topics found in AV ethics literature, with the most attention placed on crash avoidance. The level of research activity suggests that while engineers are exploring a range of ethical issues in the technology domain, there is an opportunity to further expand the issues being tackled. By broadening AV ethic issues beyond crash avoidance, engineers can continue to develop a more wholistic view of ethical issues in the technology domain.

The existing body of literature on AV ethics regarding crash avoidance is the most comprehensive in comparison to other topics. Technical stakeholders have considered, identified, and quantified many impacts of crashes and safety, with a consensus that AVs will reduce crashes overall (Bagloee et al. 2016; Goodall 2016; Harper et al. 2016b; Khan et al. 2019). Although crash probability is lower, the AV ethics literature includes different crash mitigation strategies through value-laden decisions about AV software and hardware (Applin 2017; Holstein et al. 2018; Leben 2017). Finally, the communication of these concerns is significant as the potential positive and negative implications of the technology can be found in academic literature and well as mainstream media publications (Fagnant and Kockelman 2015; Hevelke and Nida-Rumelin 2015; Khan et al. 2019). The responsibility for AV safety is codified in codes of ethics canons ASCE 1A, 1H, 2B, and 2C; and ACM 2.5, 3.1, and 3.4.

Data privacy is another ethical issue that engineers are addressing as technology develops. While big data issues are not unique to AVs, the intersection with the policy domain regarding liability as well as personal and national security add new layers of complexity. The advent of automated vehicles will also bring about complementary technologies, such as vehicle connectivity. “V2X” is a broad category of vehicle connectivity technology that allows cars to be connected to other cars, traffic or road infrastructure (e.g., traffic signs and signals), pedestrians' and bicyclists' mobile phones, public transit fleets, etc. (Gerla et al. 2014).

Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) are two heavily researched subsets of V2X technologies with a focus on data transmission between vehicles and road infrastructure. Protecting all forms of data from AVs and complementary technologies is a high research priority and undergoing evaluation in terms of the magnitude of threat and mitigation options (Stark and Hoffmann 2019; Tse et al. 2015). Potential social and economic implications are already readily available to the public (Data Center Frontier 2019; Hoffmann 2018). Data privacy could also be viewed as a more indirect ethical issue that engineers will operationalize within the technology domain once policy decisions are made. The responsibility for data privacy and security in AV systems is codified in ethical canons ASCE 1A, 1G, 1H, 2B and 2C; and ACM 2.5, 3.1, and 3.4; IEEE 5; and EC 1.2.

Ethical issues in vehicle design are still emerging because AV technology may result in substantial changes to vehicle design. Recent literature has identified potential changes to future vehicle design, driver-vehicle interface (Cellario 2001), lighting (Stone et al. 2019), and more. Implications of a new human-machine interface in AV and chassis designs have been identified as an ethical issue as well (Duarte and Ratti 2018; Fink et al. 2021; Flipse and Puylaert 2018). Inclusive decisions for vehicle design and human-computer interface are priority research agendas that are underway and important to ensuring everyone has access to the technology. Stakeholders that represent certain populations (e.g., elderly, differently-abled communities) have brought attention to the potential ethical dilemmas around AV design (Borenstein et al. 2017a; Hayeri et al. 2015). The ethical considerations of AV design fall under ASCE 1G and ACM 3.4; engineers are accounting for AV users of different abilities as vehicle design changes with automated technology.

Collectively, the evidence presented in this section suggests that engineers and programmers are discussing multiple ethical issues in the technology domain. Crash avoidance and data security are highly active topics as information can be found in ethics research literature and news media. Apart from crash avoidance and chassis weight, there was not a lot of information found where impacts were quantified. This may be because AV technology is still developing, and therefore, quantifiable information may not be available until deployment. Each issue in the technology domain had a solution for managing the potential risks; but given the iterative nature of development, it would make sense that solutions are updated as more information is made available. Given the novelty of the technology, each issue has circulated to the public at varying levels and will likely iterate with more information in the future (Applin 2017; Birnbacher and Birnbacher 2017; Borenstein et al. 2017a; Gogoll and Müller 2017; Hayeri et al. 2015; Howard and Borenstein 2018; Stark and Hoffmann 2019; Tse et al. 2015). Two additional ethical canons were specific to the technology domain. ACM canon 3.5 directs members to account for all users in a system and the autonomous vehicle design issue is a fitting example of addressing this directive. Lastly, ACM canon 2.5 guides engineers to consider the social implications of a technology. The social implications of crash avoidance technology for AVs have undergone extensive study (Awad et al. 2018; Davnall 2019; Harper et al. 2016b; Hevelke and Nida-Rumelin 2015; Keeling 2019; Khan et al. 2019; Liu 2016; Marchant and Lindor 2012). AV crash avoidance research is so pervasive that other studies call for the expansion of AV ethical issues (Borenstein et al. 2017b; Goodall 2016). Studies considering the ethical issues germane to AV designs also address social impacts on certain communities, as mentioned. Studies that consider and quantify the risk to AV data privacy also address ACM canon 2.5 by explicating the potential types of threats that can come from an AV data breach. As the technology matures, engineers can use the canons related to the technology domain to further crystallize the ethical dimensions of these issues while discovering and addressing others in this domain.

5.5. Ethical Challenges For Integrating AVs Into Transportation Systems

Like engineers in the technology domain, professional engineering ethical canons direct transportation engineers and planners to consider, identify, quantify, mitigate, and manage potential threats to the public. These directives are applicable in the transportation systems domain regarding land use, environmental impacts, mobility and access, and resilience.

Land redevelopment and transportation equity are commonly found in AV literature related to the transportation domain. Land redevelopment caused by changes in parking demand has been identified as a potential effect of AV deployment. Several papers forecast a drastic decline in parking as more AVs enter the vehicle fleet (Barron 2018; Fagnant and Kockelman 2015; Harper et al. 2018; Kockelman et al. 2016) due to an AV's ability to drop off and pick up passengers as needed and decouple parking locations from passenger destinations. This could create congestion in some areas from an increase in passenger-loading demand which may hinder productive use of street space (Roe and Toocheck 2017). Many authors mentioned land redevelopment for commercial, recreation, and residential space (Bezai et al. 2020; González-González et al. 2019; Wang and Kockelman 2018), as well as impacts on parking revenue (Harper et al. 2018). Shifts in parking demand open new possibilities for street design and land development; engineers may directly or indirectly influence urban and transportation planning decisions to optimize these new opportunities. Studies by researchers and reports from a variety of stakeholder organizations elucidate the impacts of AVs on land use (Milakis et al. 2017; Organisation for Economic Co-operation and Development 2015; Rouse et al. 2018). AVs will add to the changing landscape of infrastructure, mobility, energy use, and sustainability, but the implications are uncertain. Overall, these studies demonstrate that engineers have begun identifying and quantifying the potential impacts of AV deployment on transportation infrastructure. These responsibilities are codified in ethical canons ASCE 1A, 1B, 1G, 2A, 2B, and 2C; ACM 3.1; IEEE 5; ITE Section 3; and EC 2.5 and 2.6.

AVs will also impact equitable mobility access, but the timing, magnitude, and often the direction of the implications are uncertain and largely depend on policy choices. There is a possibility that AV mobility will compete with public transport by commandeering passengers from public transit systems, causing an increase in vehicle miles traveled (VMT) and congestion (Borenstein et al. 2017b; Zmud and Sener 2017). However, AVs could improve mobility and access for individuals unable to drive because of medical conditions, lack of a driver’s license, or lack of a vehicle (Harper et al. 2016a). Shared automated mobility is another feasible deployment scenario that also provides a strategy for improving equitable access to AVs. Studies have quantified the impacts of shared autonomous mobility, reporting that shared AVs may lead to more efficient use of public transportation and equitable access (Csiszár and Zarkeshev 2017; Murray et al. 2012). Mixed fleet scenarios where AVs will share roads with public transit, pedestrians, bicyclists, and non-AVs (Nyholm and Smids 2018) allow transportation decision-makers to develop solutions to safely integrate the technology into the system. Equity concerns as they relate to autonomous vehicles have surfaced in mainstream media and research articles for public consumption (Epting 2016; Howard and Borenstein 2018). Together, these studies reveal how engineers are identifying equity and access issues, have quantified the impacts under various future scenarios, and are working towards mitigating negative impacts. These responsibilities are codified in ethical canons ASCE 1B, 1G 2B, and 2C; ACM 2.5; IEEE 5; ITE Section 3; and EC 2.6 and 4.1.

Additionally, engineers are responsible for ensuring transportation system resilience (Institute of Transportation Engineers 2017). Transportation system resilience can be enhanced by increasing or expanding access to the system as well as using information to reroute and manage traffic during emergencies. A system must be robust in operational and physical design to maintain services under stress like natural disasters and human-made events (Heaslip et al. 2009). Ethical considerations as they pertain to the system resiliency are understudied when compared to the other issues in the transportation system domain. Vehicle connectivity does pose some potential threat in terms of a data breach as described in the technology domain section. The risks of vehicle connectivity are important but cannot fully inform the threats to physical system resiliency. Therefore, engineers have an opportunity to further their contribution to AV ethics literature by developing more information on system resiliency.

5.6. Ethical Concerns About AVs In Policy

While engineering codes of ethics may not explicitly include a directive that applies to the policy domain, the bidirectional relationship between AVs and policy necessitates the investigation into AVs and potential ethical issues that are of concern within the domain. Engineers' work in the technology and transportation domains is influenced by policies set in place at the local, state, and federal levels. Concurrently, policies are developed based on the technology that engineers and others develop and deploy. Policy is also influenced by engineers conducting technical policy assessments and providing expert testimony. Engineers can contribute their expertise in the AV policy domain along with ethicists, public policy professionals, political theorists, philosophers, legal and governance experts, transportation planners, and other stakeholders.

In 2013, states began developing regulations outlining the requirements for AV testing. These regulations focused heavily on mitigating risks of physical harm from the presence of AVs on streets with conventional vehicles. The first AV-specific policies were established when California and Nevada released licensing and safety provisions for testing AVs (Lyons 2015). In California, this list of requirements for driving included: insurance bonding, ability to quickly engage in manual drive (Level 3 automation), fail-safe systems in the case of technology failure, and sensor data storage to capture information before a collision. Special AV regulations in Nevada focused on proving the ability of automated driving through complex situations such as various traffic control devices or in the presence of dynamic objects, like pedestrians and bicyclists.

Since then, AV policy continues to progress; federal entities are delineating the roles of federal, state, and local government and taking steps to identify and mitigate the potential threats. Physical safety is at the root of the discussions as stakeholders try to determine how much testing must occur to prove that AVs are as safe or safer than human drivers. The National Highway Traffic Safety Administration (NHTSA) warned against releasing a vehicle technology to the public without making sure it is safe as manufacturers claims (U.S. Department of Transportation 2017). Engineers have quantified testing time according to different safety thresholds. If regulations establish a very high testing threshold for pre-market on-road testing such as requiring hundreds of millions of miles to be driven, it could take tens to hundreds of years to complete the task with the existing autonomous fleet, resulting in more human-driver induced fatalities in the meantime (Kalra 2017).

NHTSA has released a series of reports that outline AV safety concerns. The 2018 report *Vision for Safety 2.0* outlined 12 areas of safety that could be generally grouped into the following: establishing well-defined limitations of the technology, crash avoidance protocols, data retrieval, cybersecurity, and finally, and training and education of the technology to the public (U.S. Department of Transportation 2018). The question of how an AV should act in the event of a crash is of importance in the policy domain and heavily researched in the technology domain. The U.S. Department of Transportation (USDOT) suggests that information is shared among manufacturers in addition to sharing the sensor data from a crash with NHTSA for evaluation (U.S. Department of Transportation 2017). The processes for AV data collection and retrieval are unique to the policy domain because it shifts focus from what to do in a crash to information about the crash. As stated before, engineers can operationalize policies that are set. Engineers' role, according to their engineering canons, is to offer insight into the potential benefits and risks of policies that interact with the technology and transportation domains.

Another report, *Preparing for the Future of Transportation: Automated Vehicles 3.0* builds on earlier USDOT guidance. The report considers safety concerns as they relate to all modes of transit and further expounds on the safety and cybersecurity concerns of 5G wireless technology (U.S. Department of Transportation 2018). The focus on safety and proposed policies will impact the technology and transportation domains. The dimensions of safety being considered and identified will inform the mitigation measures that come in the form of regulatory decisions.

Secondary and tertiary impacts, such as the impact on equity and other modes of transit have also been raised (Milakis et al. 2017; Mladenovic and McPherson 2016; Ryan 2020) but policy actions are not yet in place. Many policy issues still possess a great deal of uncertainty like AVs mixed with non-AVs on the road (Chase et al. 2018; Nyholm and Smids 2018), wireless connectivity standards, licensing, insurance, and previously discussed land use impacts (Anderson et al. 2016; Rouse et al. 2018; Wang and Kockelman 2018). The transition to AVs may also bring about change to the transportation labor market. Studies have shown that AVs could result in U.S. unemployment rates raising 0.06-0.13 points at the peak of AV deployment between 2040 and 2050 (Montgomery et al. 2018; W.E. Upjohn Institute and Groshen 2019). Bus, freight, delivery, and taxi driving jobs are expected to be most immediately displaced. The loss of driving occupations will disproportionately impact Black, Hispanic, and Indigenous workers whose median wages in driving occupations are greater than the median wages for non-driving jobs (Center for Global Policy Solutions 2017). Studies also highlight the opportunity to retain and retrain the workforce by training them for the new jobs that will result in AV deployment. Engineers can contribute to the conversation by articulating skills needed for the new technology. AV policy responsibilities are codified in canons ASCE 1A, 1B, 1G, 1H, 2A, 2B, and 2C; ACM 2.5; IEEE 5; ITE Section 3 and Section 4; and EC 1.2, 2.5, 2.6, 3.5, and 4.1.

5.7. Conclusion

The codes of ethics from major engineering professional societies were superimposed on three AV domains–technology, transportation, and policy, and used to identify and assess ethical issues that have garnered attention to date. The mapping of the ethical canons onto these AV domains revealed engineering responsibilities in AV ethics and the ethics literature review clarified which topics are currently being discussed. The 16 most relevant ethical canons identified five core activities that must occur in each AV domain. Engineers are responsible for considering, identifying, quantifying, mitigating, and spreading awareness of ethical issues across the AV domains. Notably, ASCE released an updated code of ethics in late 2020, explicitly guiding engineers to consider and balance the implications of current and emerging technology. This update could signal a shift in professional engineering organizations expanding their thinking about engineers' ethical responsibilities beyond the technical aspects and into the broader impacts of technology.

Our investigation into each core activity around ethical issues showed that while some ethical issues across the domains have received attention, other issues remain unresolved and are currently being explored at various stages. First, many ethical issues have already been considered and identified such as crash implications and avoidance, as evidenced by the large popular press discussion of the AV trolley problem. It is also well established that software and hardware ethics are crucial to AVs operating safely. A review of the literature with solutions to crash avoidance shows that engineers are addressing these issues in accordance with the ethical canons from their professional societies. However, issues like hardware selection, hardware validation, and safety have been considered but are still understudied in comparison. Quantification, mitigation, and education of stakeholders and the public for hardware related ethical issues are ongoing. In the transportation system domain, most studies focused on transportation infrastructure and land-use redevelopment, revealing the focus of ethical issues in this domain. The impacts for these two issues have been quantified and literature explores potential traffic management solutions. There is a gap in research that explores transportation system resiliency, which is a responsibility explicitly outlined by the ITE code of ethics. The research activity in the policy domain demonstrates that decision-makers are still focused on safety as it is a baseline structure for regulating the technology. As stated, secondary and tertiary impacts have surfaced but are not yet addressed in terms of quantitative impact or concise mitigation strategies. Issues such as data privacy, liability, transportation surface resiliency, lane allocation, and equity still need substantial quantitative research and regulatory action. Action to advance these issues proves difficult because many areas still possess a great deal of uncertainty.

While deep uncertainty pervades the AV space due to technology novelty, the ethical canons provide directives for engineers to follow but do not comprehensively address ethical issues in any domain. Engineers must work with fellow stakeholders and decision-makers with relevant expertise, which may cause some instances of responsibility gaps. Gaps can occur from a gap in ethical, technical, or other responsibilities amongst the working group (Matthias 2004). Implementing a robust multi-disciplinary process can help overcome responsibility gaps across the domains.

Engineering codes of ethics also place a responsibility on engineers to be a part of the public conversation on the benefits and negative impacts throughout the development and ultimate deployment of AVs. Public-facing conversations about AVs mainly focus on the trolley problem, VMT, and privacy. Other issues like equity and access have been considered and identified, and these issues must also be addressed in any public conversation about AVs. Engineers, again, are one of many groups in the larger AV ethics conversation, and one way they can continue to contribute is through analysis or simulation. Engineers can develop new or use established scenarios to create new information on the magnitude of impacts or issues for decision-makers and stakeholders to consider. Approaching the uncertainty in this manner is a more constructive action than the current widespread speculation. Sharing data and results publicly provides an opportunity for feedback from the public which can, in turn, be used to help prioritize issues. Low-impact or low priority issues can be kept from overpowering critical ethical issues to be addressed while including the public in the process.

The assessment approach used in this study could prove useful beyond automated vehicle technology for those that develop and use codes of ethics. By identifying the relevant domains of automated technology, the codes of ethics are evaluated through each domain. For automated vehicles, each domain highlights different concerns, which creates a more robust conversation and will improve how engineers are looking at automated vehicles to serve the needs of the public. For those that develop codes of ethics, considering the affected socio-technical systems separately can help significant value judgments emerge. In the case of engineers or other decision-makers applying codes of ethics, making sure to satisfy the directives while considering each domain will result in a more comprehensive perspective. As such, ethics can evolve with advancing technology and continue to act as a safeguard for the public.

5.8. References

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6 Conclusions, Contributions, and Future Work

This chapter begins with a brief response to the research questions detailed in the introduction. The sections that follow offer a more general conclusion, research contributions, and finally recommend possible directions for future work.

6.1. Research Questions Revisited

Chapter 2: Determine the feasibility of improving equitable transit access using autonomous technology as a part of a public transit system.

- What is the socio-demographic profile of the transit-dependent population in Allegheny County?

  Over 120,000 transit-dependent riders are also low-income or minority households which represent approximately 78% of the entire transit-dependent population in Allegheny County. Minority populations in low-transit coverage CBGs averaged 46% while the county average was only 23 percent. Fifty-five percent of low-transit coverage CBGs were also low-income, while the county average is 32 percent. CBGs with low-transit coverage had higher percentages of low-income and minority populations when compared to the county average.

- How much does it potentially cost for SAVs and autonomous shuttles to improve public transit access for transit-dependent travelers?

  Analysis in Chapter 2 revealed SAVs have the lowest cost per passenger-kilometer traveled ranging from $0.77/PKT to $0.90/PKT. SAVs also had the lowest costs per vehicle kilometer traveled with $/VKT between $2.15 and $2.28.

- Which service parameters are most important for shared automated mobility-public transportation integration to remain complementary?

Sensitivity analysis identified a set of parameters that have the greatest influence in planning shared automated mobility services for increasing equity and transit coverage in a public transit system. When considering $/VKT, planners can focus on the annual distance, operator hours, and fleet size. If $/PKT is a metric of interest the top three factors for consideration are annual passenger-kilometers, annual distance, and fleet size.

Chapter 3: Analyze four different sized public transit systems across the United States to uncover any unique characteristics of systems that have the highest improvement in coverage at the lowest operating costs.

- Can different sized cities and agencies use shared automated mobility to cost-effectively improve public transit coverage?

  Chapter 3 provided insight into service parameters that lead to the cost-efficient operation of shared automated mobility in different public transit systems. In New York City, there were ten CBGs identified as locations for shuttle service. On average these CBGs experienced a 13% improvement in transit access and costs $1.1. million per CBG on average. In the second largest system, Chicago, two census block groups were most cost-efficiently served by shuttles with a mean cost of $869,000 per CBG for service. One of the mid-sized cities in this study, Minneapolis-St. Paul saw an 18% improvement in transit access for CBGs served by a small SAV fleet. On average adding SAV service in this city cost approximately $179,000 per CBG. Finally, Pittsburgh was compared to our other cities and had the greatest increase in transit coverage at 315% for SAV service in 4 CBGs. New service for Pittsburgh cost approximately $168,000 per CBG. There are, however, certain conditions where it is still most cost-efficient to add transit access with more conventional modes like bus and rail.

- Are there any unique characteristics for cities that are best suited to improve transit access with SAVs or shared autonomous shuttles?

Overall, findings from our sensitivity analysis suggest annual revenue kilometers, passenger-kilometers traveled, and fleet size are the most influential parameters when SAVs or shuttles are integrated into a transit system.

Chapter 4: Estimate emissions savings and operating costs for a mode shift from air travel to SAEVs for regional air travel in the United States.

- Which origin-destination pairs in the United States are candidates for long-distance SAEV service?

  Ninety-seven of the most common regional aircraft routes were identified as prospective candidates for SAEV intercity travel, as shown in Figure 4.1 of Chapter 4. These O-D pairs represent approximately 1.2 million flights per year that are within an electric vehicle's current driving range. When the levelized operating costs of BEVs, ICEVs, SAEVs, and commercial airplanes were compared, SAEVs were shown to be the most cost-effective and emit the least CO_2. SAEVs were found to be less expensive than planes, costing \$0.33 versus \$12.22 per RKT. SAEVs displayed cost parity with privately owned vehicles while cutting emissions by 39% on average, signaling the prospect of achieving economic and environmental efficiency through intercity shared autonomous mobility services.

- What are the total emissions savings from replacing a subset of regional flights with a fleet of SAEVs?

  The combined emissions from 16% of regional travel for city pairs total 2.26 million tons of CO_2. At the national level, carbon emissions associated with these city pairs account for less than 0.5 percent of total US CO_2 emissions and little more than 1% of all passenger air travel in the US. When SAEVs, privately owned ICEVs, or BEVs replace regional aircraft, CO_2 emissions are significantly reduced. SAEVs, ICEVs, and BEVs cut emissions by greater than 95 percent. However, CO_2 emissions per passenger illustrate the impact of single-occupancy travel more clearly. CO_2 emissions per passenger are significantly greater for single-occupancy trips, approaching those of flying, even for BEVs. Additionally, if 16% of passengers traveling by regional aircraft switched to their privately owned autos for the same trip, an additional 7,500 vehicles would be on the road. The increase in vehicle traffic may exacerbate or contribute to existing congestion, particularly during peak travel periods. On the other hand, a smaller SAEV fleet can provide an equal service while utilizing existing road infrastructure more efficiently and emitting less CO_2 per passenger.

- Could SAEVs provide long-distance service equivalent to regional air services at lower environmental and economic costs than travel by air or a privately owned vehicle?

  Overall, when comparing levelized operating costs, SAEVs costs are lower than regional air travel. Comparing the levelized cost at the city pair level as shown in Figure 4.2, it is confirmed that all city pairs operate at lower costs than planes. Both shared modes, plane, and SAEV, have higher $/RKT than traveling to the city pairs via personally owned vehicles. In the cases where passengers are still looking to travel via shared mode, SAEVs provide operators with a less expensive service option when compared to travel via aircraft.

Chapter 5: Elucidate the ethical responsibilities of engineers that contribute to AV development and deployment within critical socio-technical domains.

- Do existing codes of ethics offer any guidance on engineers' roles and responsibilities in AV ethics within technology, transportation, and policy domains?

  The codes of ethics from major engineering professional organizations revealed engineering responsibilities in AV ethics. Engineers are responsible for five core activities that must occur in each AV domain: considering, identifying, quantifying, mitigating, and spreading awareness of ethical issues.

- Which ethical canons are being followed or addressed in existing AV literature? Which canons still need to be addressed in future research?

  While certain ethical issues have been addressed across disciplines, others remain unresolved and are actively being researched at various stages. Many ethical challenges have already been discovered in the technology domain, including crash implications and avoidance. However, issues like hardware selection, validation, and safety remain understudied. The quantification, mitigation, and public education of hardware-related ethical dilemmas are ongoing. Most studies in the transportation system domain concentrated on transportation infrastructure and land-use redevelopment. They have been quantified, and the literature analyzes possible traffic control solutions. The ITE code of ethics clearly outlines the responsibility to investigate transportation system resiliency. Research activity in the policy domain shows that decision-makers are still focused on safety as a baseline structure for regulating technology. Secondary and tertiary impacts have surfaced but have yet to be quantified or addressed with mitigation strategies. Additional quantitative research and legislation is needed on issues like data privacy and liability, as well as transportation surface resilience.

6.2. Equity

AVs present an opportunity to improve transit access for those with the greatest need and in this dissertation, I articulate the positive equity outcomes possible with shared automated mobility. Sociodemographic profiling of cities studied in Chapters 2 and 3 found that low-transit coverage CBGs had higher concentrations of transit-dependent, low-income, and minority populations. This suggests that even in the largest transit systems in the United States like New York City and Chicago – there is unmet transit need degrading equity. On average, we saw transit coverage improve by 31% by adding shuttle or SAV service to low-transit CBGs in each city. By improving transit equity and access where the need is greatest first, shared automated mobility can immediately add value to existing transit systems.

The findings in Chapters 2 and 3 broaden insights into shared automated mobility as a promising equity provider under certain conditions. Equity as a goal is becoming increasingly pursued in policy and planning and many studies have explored the AV equity impacts focusing on the elderly and individuals with medical conditions that preclude them from driving. My studies' focus on transit-dependent riders does not exclude these populations but broadens the population to include any individual who does not drive for any reason. By including all transit dependent riders as well as identifying low-income and minority populations my dissertation expands the understanding of how an AV impacts existing transit systems. In doing so, decision makers can better understand how AVs can be socially beneficial and create legislature that encourages net positive impact.

Second, comparing levelized costs for shuttles and SAVs to buses serves as a proxy for the cost to achieve equitable social benefits from shared autonomous mobility. This information serves as a major contribution as equity impacts and the associated estimated costs have not been reported. Now Chapters 2 and 3 reveal that on average transit coverage in a CBG can improve by 24% for $409,000 on average when served by shuttles and SAVs improved by 27% for $116,000 on average. It would cost $575,000 to do the same via conventional bus.

6.3. Economic

Demonstrating the cost-efficiency of shared automated mobility is paramount for considering moving forward with the technology. Overall, my findings in Chapters 2 and Chapter 3 suggest that shuttles and SAVs can be operationally cost-efficient while prioritizing equity and remaining complementary to existing transit services.

Chapter 2 confirmed that SAVs and shuttles have a lower operating cost than conventional public transit buses when adding service in low-transit coverage CBGs. These results in Chapter

2 study support previous work that states these new technologies can reduce transit costs. This study revealed service parameters that are important for improving transit coverage and equity with SAVs or shuttles operating at substantially lower costs than buses. Sensitivity analysis revealed the most important parameters for consideration in future transit planning and policy of shared autonomous mobility. Thus, SAVs and shuttles can be constrained to certain service metrics to improve transit coverage equity and to remain a cost-efficient complement to existing transit service. The findings suggest public transit agencies could begin integrating shared automated mobility into their transit system Not every public transit system is like PAAC, thus analysis that explores operational feasibility in other cities with different sized transit systems can provide more information about what is feasible with shared autonomous mobility.

Chapter 3 expanded the analysis in Chapter 2 by using the same analysis on different cities. Comparing shared autonomous mobility services in New York City, Minneapolis-St. Paul Chicago and Pittsburgh allowed for a higher resolution look at what service parameters lead to cost efficiency and transit equity. First, by defining the fleet size on unmet demand this thesis provides a baseline for shared autonomous mobility fleets. Experts have addressed uncertainty in fleet size by either replacing the entire city vehicle fleet or determining fleet size from the service parameters defined in their analysis. My findings provide an estimate for shared autonomous mobility fleet rightsizing that can inform research and policy. Further, my findings contribute to the understanding of the conditions favorable for shuttles or SAVs under different transit demand scenarios. Unlike previous work in shared automated mobility-public transit integration studies, in Chapter 3 I used the same analysis on different cities to isolate the specific service parameters for different modes. Intuitively, different shared modes have service parameters where they work best, e.g., bus and rail serve high density areas. That same intuition is limited for SAVs and shuttles as they are not yet deployed widely. Chapter 3 reveals service domains that elucidate the specific conditions where a fleet operator would choose one type of service over another. This contribution is substantial for the further articulation of AV capabilities as well as highlighting specific limitations when working with smaller size vehicles for shared mobility. By identifying these service domains, we take a step further into what shared autonomous mobility can do and serve as a counter to suggestions that AVs are always more cost-efficient than conventional public transit. Policymakers can use these service metrics and parameters to create constraints around shared autonomous mobility.

In Chapter 4, I determine and compare levelized operating costs for shared autonomous, electric vehicles, ICEVs, BEVs, and aircraft that serve regional city pairs. My finding suggests that SAEVs can operate for 91% less than planes on average. This is the first estimate of intercity travel in the US via SAEVs. Establishing a baseline to estimate the savings from a modest modal shift achieves two outcomes. First, proving the economic viability of SAEVs for intercity travel expands the suite of use cases for shared autonomous mobility. Secondly, for consumers the savings, if passed on to them, is enough incentive to shift travel modes and thus generate passenger travel behavior changes. In conclusion, establishing the economic costs of shared autonomous mobility, especially when electrified, can provide enough incentive for a potential fleet manager to pursue the deployment of intercity fleets.

Notably, in the cost-efficiency analyses in Chapters 2, 3, and 4, I consider operator supported SAVs and shuttles. While the removal of the human operators contributes largely to the savings found in other studies, it may not be immediately realistic. Whether safety or courtesy operators are inside SAV or shuttles or a remote operator monitors driving from afar, or in any other scenario, it is prudent to include operators' pay. In doing so, my findings in Chapters 2,3, and 4 show that shared automated mobility is still cost-efficient even with an operator of some form being paid. This offers an intermediate step and safety failsafe for policymakers and AV automakers as the technology continues to develop and operational design domains remain restricted at the moment. In the future, as operators are no longer required and ADS Levels 4 and Level 5 are widespread, even more cost efficiencies can be realized.

6.4. Environment

Chapter 4 illustrates how modal shift might benefit operators economically and environmentally for city pairs with significant CO_2 emissions from regional air travel. Additionally, the contributes to the shared automated mobility body of literature by introducing a novel use case that has not been fully investigated. This study analyzes the environmental impact of such a service on a first-order basis.

While a mode shift would result in decreased aviation activity and economic activity, the aviation industry is also being pushed to cut its emissions impact. Thus, the change ultimately contributes to that endeavor by lessening the passenger burden on airlines. Aircraft carriers can refocus their efforts on long-haul flights and capitalize on fuel and engine technology efficiencies. The cascading effect is a more effective use of aviation resources, such as airport infrastructure and flight crew. Policymakers can use this information to determine a regional aircraft emissions abatement strategy. Additionally, the novel use case for an autonomous car may entice AV makers to consider a new market of intercity travelers.

In Chapter 4, I demonstrate that mode shift to SAEVs can reduce emissions substantially. Proving the operational feasibility of SAEVs can incentivize EV manufacturers to increase the driving range of their vehicles to capture a larger share of regional travel, as research indicates that individuals are willing to travel up to 500 kilometers via automated vehicle rather than a regional flight. Second, we can continue to make significant gains toward meeting the US's environmental emissions reduction goals. By introducing a new application for autonomous vehicles, we broaden our understanding of their capabilities and provide policymakers with additional information and options to consider when developing a regulatory framework for widespread AV deployment.

6.5. Ethics

Finally, in Chapter 5, we discuss how AV ethics has omitted certain areas of discussion and consideration in favor of crash avoidance and propose expanding the ethical conversation. While a few studies have attempted to explain or investigate engineering ethics, I demonstrated the lopsided nature of published research through literature review. By drawing attention to the dearth of AV ethics literature, we hope to encourage other experts to broaden their perspectives on ethical issues relating to EVs. If this occurs, the range of knowledge expands rather than the current deep, narrow focus in which issues are overlooked, and could have dire consequences in the future.

Chapter 5 also defines the role of engineers within the context of AV ethics. In three AV domains–technology, transportation, and policy–the codes of major engineering professional associations were superimposed over the domains to detect and assess current ethical challenges. The 16 most relevant ethical canons identified five basic AV domain actions. Engineers must consider, identify, measure, mitigate, and raise awareness of ethical challenges in all AV disciplines. While uncertainty surrounds the AV space as a result of technological novelty, ethical canons provide guidelines for engineers to follow.

6.6. Future Work

Future work in shared automated mobility is ample as AVs approach widespread deployment. Continued technology development means that the economic, equity, environment, and ethical dimensions of AVs require continuous updating. Updating analyses ensures that positive impacts are accurately captured to demonstrate the value of developing autonomous vehicle technology. As more SAV and shuttle cost information becomes publicly available, future studies can update mean levelized costs and potentially realize more savings. Also, a consistent and continuous analysis for each dimension creates a type of historical account—a benefit within itself—and ensures that the technology is progressing in terms of economic and environmental efficiency while addressing equity goals.

There are opportunities for more robust transit coverage analysis tools and data that focus on the transit-dependent population. In this dissertation, only direct costs were included in the analyses. Analyses in Chapters 2 and 3 would benefit from further exploration into the environmental impacts of shared autonomous mobility when integrated with public transit. By updating the analysis to include electrified vehicles in the corresponding costs we can further articulate the benefits of shared autonomous mobility, especially in the presence of electrification. Adding a shared autonomous mobility service should not only be cost-efficient but environmentally sustainable and aligned with existing goals to cut emissions, thus an environmental analysis is essential. Some additional costs such as cleaning, garaging, and administrative costs, were also not included in my Chapter 2, 3, or 4 cost-efficiency analyses as these are direct operating expenses. It may be worthwhile to include these costs in a different economic analysis where profitability may be the goal. Further, rider comfort, safety, unbanked rider accessibility, perceived quality, willingness to pay, passenger trust in autonomous technology, and transit-SAV scheduling are important factors that will contribute to the deployment and adoption of shared autonomous mobility. Although these factors were not included in my analyses as they do not directly contribute to operating costs, future studies that include these factors need to be developed for a more comprehensive understanding of AV technology and its implications. Finally, the nature of this dissertation analyzes the interdependencies between current and emerging modes of transportation. AV deployment, even in its most rapid state, would be added to existing transportation infrastructure and current modes of travel. Future research that continues to explore the shared automated mobility with bus, rail, air, active transport, and freight will prove beneficial in policymaking at the city, state, and federal level.