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Improving Access and Equity via Shared Automated Mobility in U.S. Public Transportation Systems

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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.

1 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.

1.1 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?

2 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.

2.1 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

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

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 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.

2.2 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 2.1 and parameterize for Monte Carlo simulation in Table 2.2. 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 *2.1* and Table *2.2*. 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 *2.1* 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 Table 2.1 for both SAESs and SAVs.

Table 2.1: 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 *2.1* 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 2.1. 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 2.1 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).

2.3 Monte Carlo Simulation and Sensitivity Analysis

We address the uncertainty of costs with Monte Carlo Simulation. The simulation model parameterized the values in Table 2.1, which can be seen in Table 2.2. 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 2.2 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 2.1. Sensitivity analysis was performed using Sobol's sequence in the SALib Python package to estimate the main and total effects for each parameter.

Table 2.2: 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

2.4 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 RESULTS AND DISCUSSION

3.1 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 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

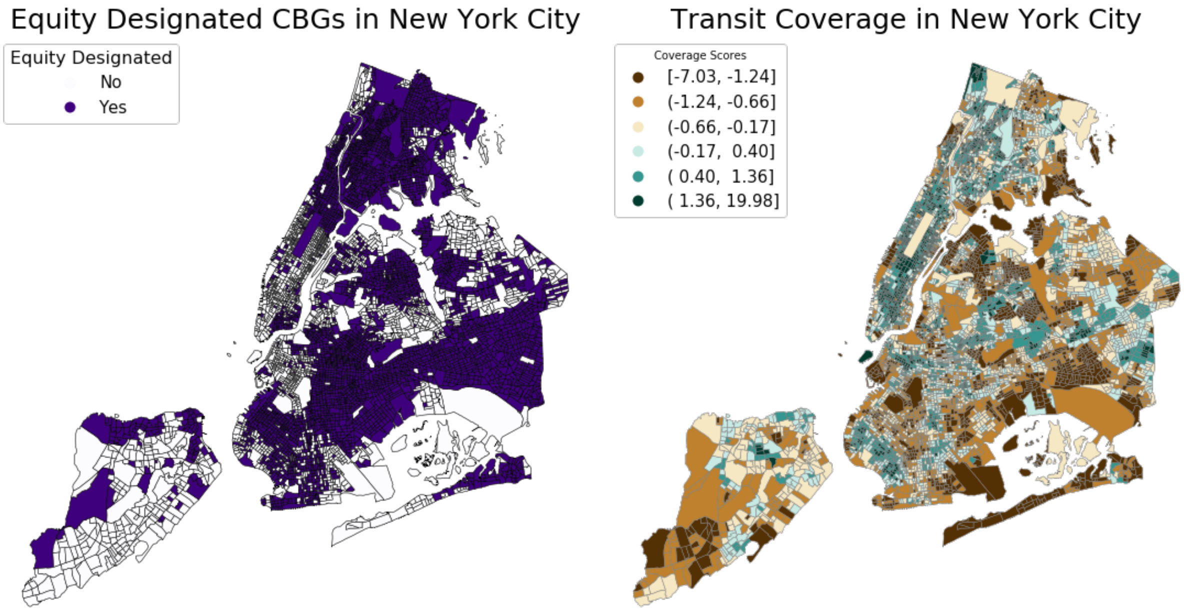


Figure 3.1: MTA New York City Transit Authority transportation system. Maps from left to right: (left) Equity designated census block groups in the city show the census block groups that have a greater than average low-income and/or minoritized population. (right) Shows the transit coverage scores in 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.

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.

3.2 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: (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.. 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 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

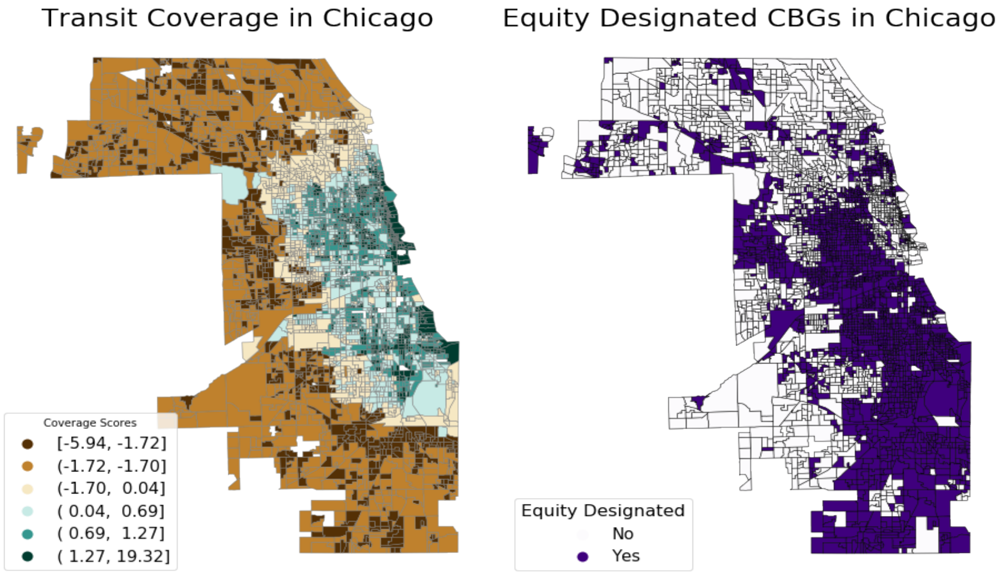


Figure 3.2: (left) Map of transit coverage by CBG in Chicago, IL. Transit coverage combines transit need and transit supply scores to identify census block groups with low transit coverage. The lower and upper values in the legend represent the range of transit coverage scores in each quantile. Darker 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.

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.

3.3 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 Figure 3.3 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 3.1 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.

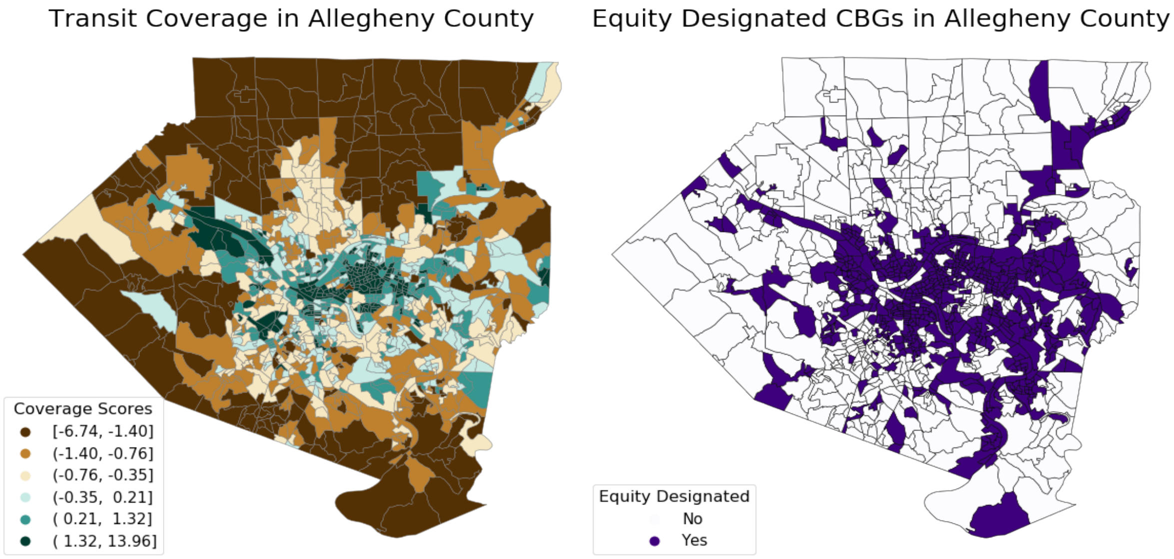


Figure 3.3: (*left*) Map of transit coverage by CBG in Pittsburgh, PA. Transit coverage combines transit need and transit supply scores to identify census block groups with low transit coverage. The lower and upper values in the legend represent the range of transit coverage scores in each quantile. 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.

3.4 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: (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. 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: (left) Map of transit

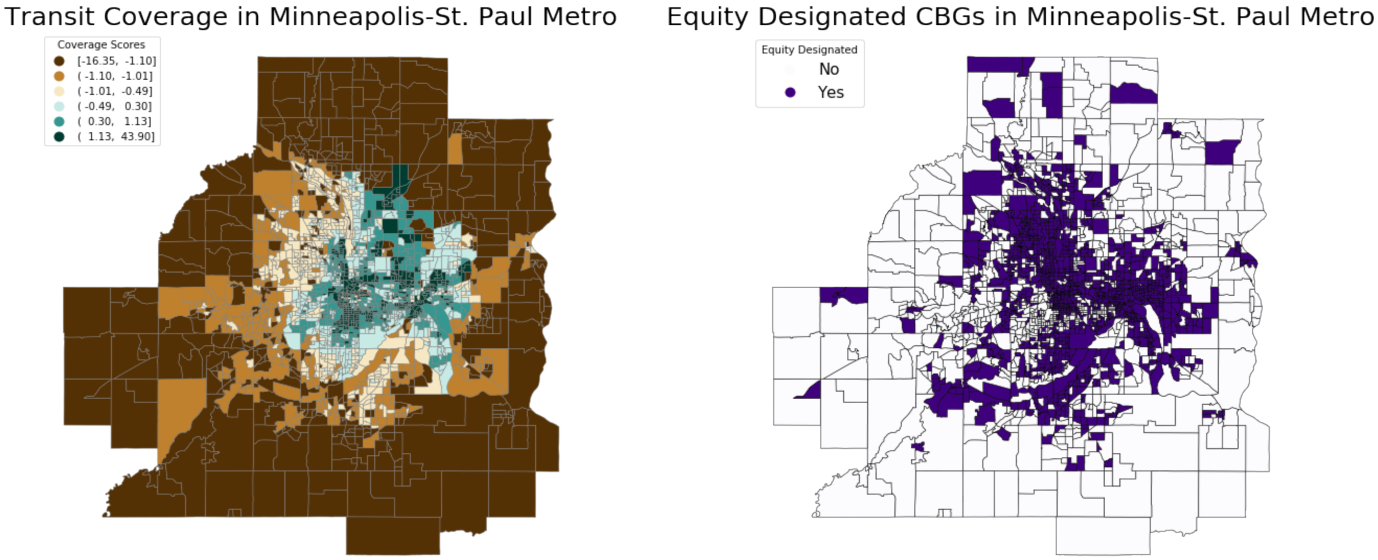


Figure 3.4: (left) Map of transit coverage by CBG in Minneapolis-St Paul, MN. The lower and upper values in the legend represent the range of transit coverage scores in each quantile. Darker colors show extremes with dark blue indicating more than sufficient coverage to match demand, and dark brown is 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.

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..

Minneapolis-St. Paul, like the 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 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 3.1 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: (*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. and 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.). 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 3.1: Summary data for comparative analysis.

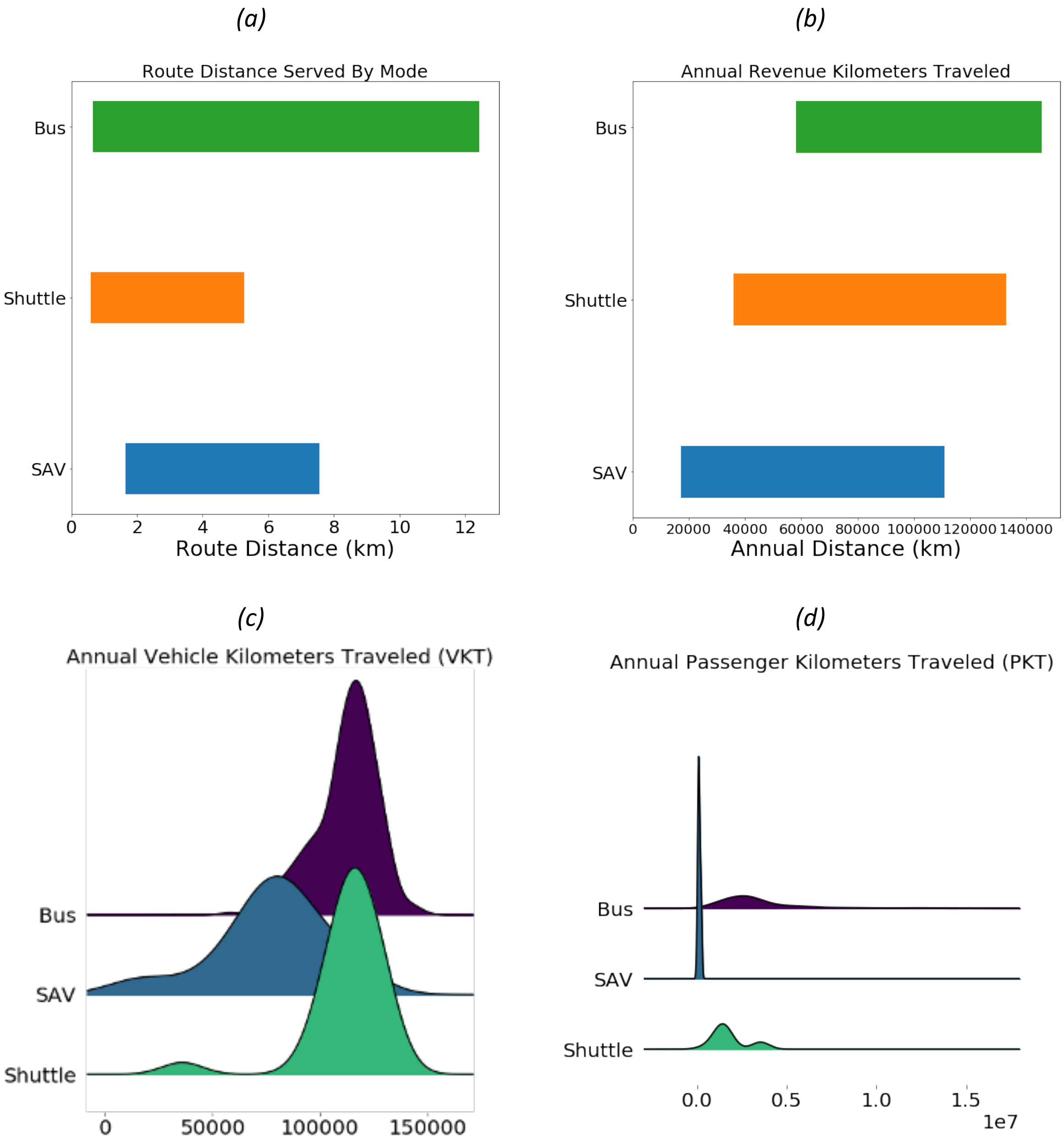
City	**New York City**	**Chicago**	**Minneapolis - St. Paul**	**Pittsburgh**

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: 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. illustrates the service ranges aggregated for each mode.

In 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., 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 3.5: 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.a. 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 3.5: 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.d. 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 conventional modes like bus. However, this study shows that shared automated mobility provides a cost-effective alternative to connect neighborhoods to existing transportation services.



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4 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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