Final Project Report

Incorporating Mobility on Demand into Public Transit in Suburban Areas: A Comparative Evaluation of Cost-Effectiveness

Prepared for **Teaching Old Models New Tricks (TOMNET) Transportation Center**

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16. Abstract

Traditional fixed-route transit services are inefficient in low-density areas due to limited and dispersed service demand. Many transit agencies look for effective alternatives to provide adequate transportation services in these areas, especially by leveraging mobile ICT-enabled new mobility services. This study evaluates the cost-effectiveness of transit incorporating mobility-on-demand (TIMOD) compared to fixed-route bus transit, driving alone, and commercial ride-hailing services in suburban areas. It develops a comprehensive analytical framework to evaluate the cost-effectiveness of TIMOD and other alternatives from a societal perspective, considering differences in built environments. The analysis accounts for travelers' monetary and time costs, service providers' operating costs, and environmental externalities. Using real-world data from the Metro Flex program in the Seattle region and estimates based on simulation, the study compares the economic cost of Metro Flex trips with equivalent trips made using other travel modes in two different suburban areas. The results indicate that, in our study areas, Metro Flex trips have a total generalized cost for travelers that is higher than driving alone but lower than fixed-route transit and ride-hailing trips. Adding service operation and emission abatement costs, Metro Flex becomes less cost-effective than all the alternatives due to high operating costs and a higher proportion of deadheading, however, the difference is slight in comparison to fixed-route transit. Our findings also show that areas with higher density and more transit services result in lower operation costs per rider for the transit agency. Incorporating equity into the cost-effectiveness analysis shows that Metro Flex has a more equitable distribution of travel cost than fixed-route transit, but riders with high median income will have larger reductions in their travel time cost using Metro Flex compared to fixed-route transit. The study highlights the potential benefits and tradeoffs of providing TIMOD services in suburban areas, shedding light on the conditions under which such services are economically competitive.

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EXECUTIVE SUMMARY

Problem Statement

This study is aimed at further developing a comprehensive framework to explore the cost-effectiveness of Transit Incorporating Mobility-on-Demand (TIMOD) compared to other alternatives, including fixed-route public transit services, driving alone, and using commercial ride-hailing services (i.e., TNCs). This framework is applied to two suburban areas and shed light on the potential benefits and trade-offs of providing TIMOD services in such areas. The study addresses the following questions:

- From a societal perspective, what factors contribute to the comparative cost-effectiveness of TIMOD and alternative mobility services? For each alternative, what are the essential elements of the cost?
- How can the economic costs of different mobility services be consistently measured and appropriately compared?
- How does the cost-effectiveness of TIMOD compare to other alternative modes in low-density suburban areas? Under what conditions are TIMOD services relatively cost-effective?
- In what way does income affect the cost-effectiveness of each mode? What are the equity implications of different cost and benefit distributions among different income groups?

Methods

To address the questions above, the research team collected and analyzed trip data from Metro Flex, a TIMOD service in the Seattle area, to estimate the cost of TIMOD trips compared to trips made by other travel modes. We selected two Metro Flex service areas with distinct differences in built environment and demographics.

The project team addressed the research questions with two methodological components. First, we substantiated and enriched a conceptual framework for evaluating cost-effectiveness from a societal perspective, taking into account variations in users' socioeconomic backgrounds and built environment factors. The variables in the measurement of cost-effectiveness are: 1) users' (i.e., travelers) generalized costs, which consist of monetary costs and values of travel time (waiting time, in-vehicle travel time, access time, and egress time); 2) service provider's (e.g., transit agency) costs, which include the costs of labor (i.e., drivers, service managers, and planning staff), fuel/propulsion, capital, and maintenance; 3) external costs, including costs for emissions (the primary focus of our empirical analysis), crashes, noise, and congestion. Second, we developed a traffic simulation procedure that allows transit agencies to empirically compare the costs of TIMOD with those of other alternative modes. For traveler costs, we used Metro Flex trip data and simulated travel times for the alternative modes under the counterfactual scenario where Metro Flex was unavailable. An open-source simulation software, SUMO, was used to estimate travel times for fixed-route transit and driving alone. For service provider costs, we worked with King County Metro (KCM) staff to obtain cost measures for Metro Flex and fixed-route services.

For the analysis of equity implications, we employed the distributional cost-effectiveness analysis (DCEA) framework to model and evaluate the social distributions of travel cost of each mobility alternative across different income groups.

Results and Policy Implications

By estimating and comparing the total generalized cost for TIMOD and alternative modes for a representative operation day, we found the following:

- Driving alone generates the lowest generalized travel cost considering time and monetary expenses (*assuming* all travelers have access to automobiles).
- From society's perspective, Metro Flex has a comparative cost disadvantage to other alternatives. This is mainly due to the higher service operating costs of Metro Flex.
- From a traveler's perspective, Metro Flex demonstrates a competitive advantage over fixed-route transit and TNCs. Metro Flex's on-demand nature coupled with subsidized fare make it preferable for the users. Moreover, Metro Flex results in a more equitable distribution of travel cost among different income groups and areas than both fixed-route transit or driving alone.
- For the transit agency, the operating costs associated with Metro Flex are much higher than those of traditional fixed-route transit services. TNC fare paid by riders is assumed to fully capture the service operating cost.
- The two representative suburban areas, namely Sammamish and Rainier Beach in Seattle Metropolitan area, have different built environment characteristics and household income levels, resulting in different travel times and monetarized travel costs for travelers. Riders living in higher median income areas benefit more from TIMOD services with a higher reduction in the traveler generalized cost compared to fixed-route transit.

While the results show that TIMOD services can provide a more convenient and affordable travel option for residents of suburban areas with lower population density and limited transit services, they can be more expensive to operate than fixed-route transit services, especially in lower-density areas. Hence, transit agencies need to carefully design and operate these services, considering variations in the built environment, travel demand, and residents' sociodemographic characteristics. Future research should investigate alternative scenarios of transit service frequency and coverage, as well as parking facilities and charges near major transit stations. Moreover, further studies can look into different ways to optimize the deployment of TIMOD services to make them comparatively more cost-effective.

INTRODUCTION

1.1 Project Background and Components

Public transportation in low-density suburban areas faces unique challenges due to the dispersed population distribution and low service demand [1,2]. In such areas, it is difficult for residents to reach essential destinations such as healthcare facilities, schools, and shopping centers by public transportation [3]. Traditional fixed-route transit services are often unsuitable for these areas as they are costly to operate and do not effectively meet the needs of the residents, leading to a heavy reliance on private cars for travel [1,3]. As a result, transportation planners continuously seek solutions to provide adequate mobility services in areas where fixed-route services are ineffective.

The advent of app-based mobility-on-demand (MOD) services has created many exciting opportunities for transit agencies to build partnerships with new mobility providers to supplement existing public transit services with flexible and efficient travel options [4-9]. MOD services, whether commercial ride-hailing operated by Transportation Network Companies (TNCs), or demand-responsive services offered through transit agencies, have the potential to provide first-mile/last-mile (FM/LM) solutions, guaranteed ride-home options, or even a replacement for low-efficiency transit services in low-density areas [1,9,10]. These services can be designed to optimize routing and scheduling based on socio-demographic and environmental factors to ensure that transportation is accessible and efficient [11]. In this paper, we use Transit Incorporating Mobility on Demand (TIMOD) to denote projects and partnerships in which transit agencies incorporate MOD services to supplement or replace parts of traditional transit [9].

Many transit agencies have realized the potential and begun experimenting with TIMOD programs, which have been most commonly applied to supplement FM/LM connections, tackling one of the main barriers to transit ridership [12]. Similarly, TIMOD has been widely tested and adopted in low-density areas that often suffer from poor public transport service quality, where the costs of sustaining a good service frequency and area coverage are high due to the low demand density [7,9,10]. While TIMOD is a potential mobility solution in low-density areas, its suitability depends on various sociodemographic and built-environment factors that affect its cost-effectiveness. Within this context, conducting cost-effectiveness analyses of TIMOD can provide critical insights for integrating these innovative approaches into public transit networks. Cost-effectiveness analysis is a valuable tool that aids decision-making processes by quantifying alternative interventions' relative costs and benefits.

The literature evaluating the cost-effectiveness of TIMOD is still emerging, and there are several gaps in current research. First, there is a lack of standardization in the methods used to evaluate the cost-effectiveness of TIMOD projects. It is, therefore, difficult to compare the results of different studies and develop a comprehensive understanding of the cost-effectiveness of these services. In addition, consideration of externalities such as emissions, congestion, and safety in cost-effectiveness evaluations is limited. Moreover, studies vary in focus, as some examine the integration of MOD for part of a transit trip (e.g., FM/LM), while others explore a replacement of existing transit routes (e.g., point-to-point).

The primary purpose of this study is to further develop a comprehensive framework to explore the cost-effectiveness of TIMOD compared to other alternatives, including fixed-route public transit services, driving alone, and using commercial ride-hailing services (i.e., TNCs). We explore two distinct suburban areas in the Seattle region where TIMOD service was provided. While both areas are low-density relative to dense urban environments, they vary in population density, sociodemographic characteristics, and transit supply. Using real-world TIMOD trip data from two distinct, low-density contexts, we compare the cost-effectiveness of TIMOD services to other existing alternatives, including fixed-route services, driving alone, and using TNCs. To enable a fair comparison, we assume similar demand for traditional transit to that for TIMOD service. The study aims to address the following questions:

1. From a societal perspective, what factors determine the comparative cost-effectiveness of TIMOD and alternative mobility services? For each alternative, what are the essential elements of the cost?
2. How can the economic costs of different mobility services be consistently measured and appropriately compared?

3. How does the cost-effectiveness of TIMOD compare to other alternative modes in low-density suburban areas? Under what conditions are TIMOD services relatively cost-effective?
4. In what way does income affect the cost-effectiveness of each mode? What are the equity implications of different cost and benefit distributions among different income groups?

1.2 Project Report Organization

This report has five chapters. Chapter 2 provides a literature review of theoretical and empirical research on Transit Incorporating Mobility-on-Demand (TIMOD) and its comparative cost-effectiveness to other alternatives, which lays down a common foundation for the study. Chapter 3 presents the methodological part of the study, describing the conceptual framework, case background, TIMOD service data, and methods for cost-effectiveness evaluation. Chapter 4 describes the results of cost-effectiveness evaluation, including the total costs for travelers, service operation, and externalities. These costs for an average rider of the two case areas, Sammamish and Rainier Beach in King County, WA, are also compared to inform the differences between suburban areas varying with population density, household income, and transit service supplies. This is followed by Chapter 5 in which the discussions for the results are presented. The economic competitiveness of TIMOD compared to other alternatives and the sensitivity of results to assumptions are discussed. Finally, Chapter 6 reports the conclusion obtained from the study.

LITERATURE REVIEW

2.1 Transit Incorporating Mobility-on-Demand Services (TIMOD)

Information and communication technology (ICT) advancements changed mobility services, resulting in a new class of private mobility providers that leverage mobile apps and digital platforms to connect riders. These mobility-on-demand services, including ride-hailing, car-sharing, and microtransit, provide attractive features such as enhanced flexibility, comfort, and operational efficiency. By incorporating these new mobility services, transit agencies can achieve some crucial goals, such as filling service gaps, increasing on-demand options, and lowering the costs of certain services [4,6,8,9,13-15].

Many public transit agencies have realized such potential and begun testing and implementing partnerships with on-demand mobility service providers, TNCs [12]. Numerous studies have examined how, when, and where the two can work together. Scholars who have been studying MOD public-private partnerships in the United States have identified four key types of partnerships: FM/LM, low density, off peak, and paratransit [16,17]. For example, Southeastern Pennsylvania Transportation Authority (SEPTA) initiated a partnership with UberX in 2016 to enhance access to its rail stations and fill FM/LM gaps. Similarly, The Metropolitan Transit System (MTS) in San Diego offered a $5 discount on FM/LM connections to and from its transit stations during certain events [17]. Moreover, many pilot projects target low-density and rural areas. Dallas Area Rapid Transit (DART) aimed to integrate TNCs (Uber and Lyft) and other MOD providers like carpool services and bike-share programs to replace inefficient fixed-route services in low-density areas [16,19].

2.2 Evaluation of TIMOD

Several studies have evaluated different aspects of TIMOD through public-private partnerships. Patel et al. (2022) identified the most common challenges of MOD sandbox pilots as ensuring equitable access to services and estimating the cost for transit agencies [16]. While reducing costs is often not the main objective of these partnerships, providing cost-effective alternatives is essential. Zhou (2019) developed a method to identify low-demand routes in fixed-route transit using smart card data and proposed replacing them with shared mobility options if the on-demand modes had an occupancy rate greater than two [20]. Agent-based modeling studies by Shen et al. (2018) and Gurumurthy et al. (2020) investigated scenarios where MOD services can yield potential performance gains in replacing buses as FM/LM connections to urban rails [21,22].

Yan et al. (2019) examined commuters' responses to TIMOD services and predicted mode choices. They found that the proposed TIMOD service could lower costs primarily by reducing riders' waiting time. Other studies revealed that residents already using ride-hailing favored on-demand services over traditional fixed-route transit [23,24]. A lack of reliable access to necessary technological resources could be a significant barrier to adopting such services for low-income travelers [23,24].

While these studies provide initial insights into TIMOD services, they were exploratory and had limitations restricting their applicability in guiding transportation decision-making. Many studies used simulations based on hypothetical scenarios, which may only partially reflect the complexities of designing and implementing TIMOD. Other studies relied on respondents' stated preferences, which may not always align with their actual behavior for various reasons such as habit, convenience, or external factors. Future research should carefully evaluate real-world TIMOD projects to provide more transferable lessons. By analyzing real behavior and outcomes, transportation researchers can better understand the impacts of TIMOD services and better inform relevant decision-making.

2.3 Cost-Effectiveness of TIMOD Services

The comparative cost-effectiveness of providing mobility options in low-density areas has been a topic of interest in transportation research. One study highlights the cost-effectiveness challenges of fixed-route transit in low-demand and sparsely populated areas [25]. The authors argue that on-demand services can be a more cost-effective alternative in such areas. Another study argues that fixed-route services are expensive and do not provide good service at nighttime in low-density areas. In contrast, on-demand services with flexible and dynamic routing systems are more cost-effective in these areas [26].

Some studies focused on transit agency costs and aimed to solve a supply optimization problem of TIMOD services. They assumed that agencies were responsible for all service costs and made vehicle assignments in response to incoming requests. Typically, the costs considered in the optimization include the agency's operating costs (distance traveled, fleet size, labor) and the user's time cost (waiting time and in-vehicle time) [27-29]. Other studies focused on users' costs. Fixed-route transit would add to users' access and egress times because they have fixed pick-up and drop-off locations [30]. The agency's cost is often not included in these studies, for example, when assessing the incorporation of shared autonomous vehicles into public transportation systems [21,22].

The user's time costs should be transformed into dollar values to compare the alternative modes better to contribute to the rider's utility function [31]. Service performance under different levels of demand density was also discussed [20,28]. Other factors could also contribute to the rider's cost but were often not considered in the literature, such as the cost of parking if choosing to drive and the perceived discomfort in the rider's experience.

To measure the external costs, previous studies used modeling software (e.g., SUMO and EMME for microsimulation, and MatSim for large-scale simulation) to simulate externalities (e.g., emission, noise, congestion) on individual vehicles, then aggregated results for further analysis [32]. Others directly used statistical data and parameters to calculate the external costs for entire transport systems [33]. The specific methods of measuring externalities depend on the contexts and objectives. Specifically, marginal cost should be used when internalization of external costs is considered from an economic efficiency point of view.

2.4 Equity Implications of TIMOD services

New mobility services and transportation technologies such as MOD have been shown to bring substantial economic, environmental, and health benefits to society [34-36]. However, the benefits may not be distributed among population groups in an equitable manner. Although equity is conceptually well-defined, there is no standard approach for assessing the equity performance of transportation systems. Existing studies often adopt a framework that considers population measurements, cost-benefit measurement, and inequality measurements. Population measurements define the human population for which the cost/benefit measure will be determined and compared, basically answering the question "equity for whom?" [37] Outcomes can be measured for individuals and for population groups that are defined based on either spatial location, if horizontal equity is to be evaluated, or based on sociodemographic characteristics, if vertical equity is evaluated [38-39]. Cost/benefit measurement on the other hand quantifies the costs or benefits of interest (e.g., accessibility) for each population group. Inequality measurements are generally used to compare the outcomes among the spatially distributed population (horizontal equity) or among population subgroups (vertical equity) [37]. This approach is often adopted to evaluate equity separately from the cost-effectiveness analysis, which has been most commonly used to inform decisions related to TIMOD projects.

Conventional cost-effectiveness analysis focuses on evaluating the economic costs and gains of transportation services but does not address the question of who benefits and who loses from the new transportation services, which should be of important consideration for decision makers. In recent years, there has been a growing interest among government institutions in incorporating equity concerns in many fields, including transportation, which has been amplified during the COVID-19 pandemic [40]. One of the most promising methods for incorporating equity into the cost-effectiveness analysis is the distributional cost-effectiveness analysis (DCEA), which is widely used in health-related research. DCEA facilitates a quantitative assessment of how the effects and costs are distributed between groups in a population [40,41].

DATA AND METHODOLOGY

3.1 Case Background and Data

This study evaluates the comparative cost-effectiveness of Metro Flex, which is a TIMOD service in the Seattle region. Metro Flex offers convenient, fast, and affordable rides in various areas: Juanita, Kent, Othello, Rainier Beach, Renton Highlands, Sammamish, Skyway, and Tukwila. The service costs the same as a regular Metro bus ride, with fares ranging from $2.75 for adults to free rides for youth aged 6-18. The service also provides ADA-accessible vehicles for passengers with mobility devices. For this study, we selected Sammamish and Rainier Beach (Figure 3.1), two service areas with distinct differences in transit accessibility, population density, and socio-demographics. Service hours vary depending on the location, ranging from 5:00 a.m. to 1:00 a.m. in Rainier Beach and 7:00 a.m. to 6:00 p.m. in Sammamish. Metro Flex can be booked through a user-friendly app or by calling 206-258-7739, offering a convenient and efficient way to travel within the designated service areas. The service replaces two previous transit options: Community Ride, a point-to-point on-demand service in Sammamish, and Via to Transit in Rainier Beach. Metro Flex offers on-demand services within the service area limits, regardless of the trip purpose.

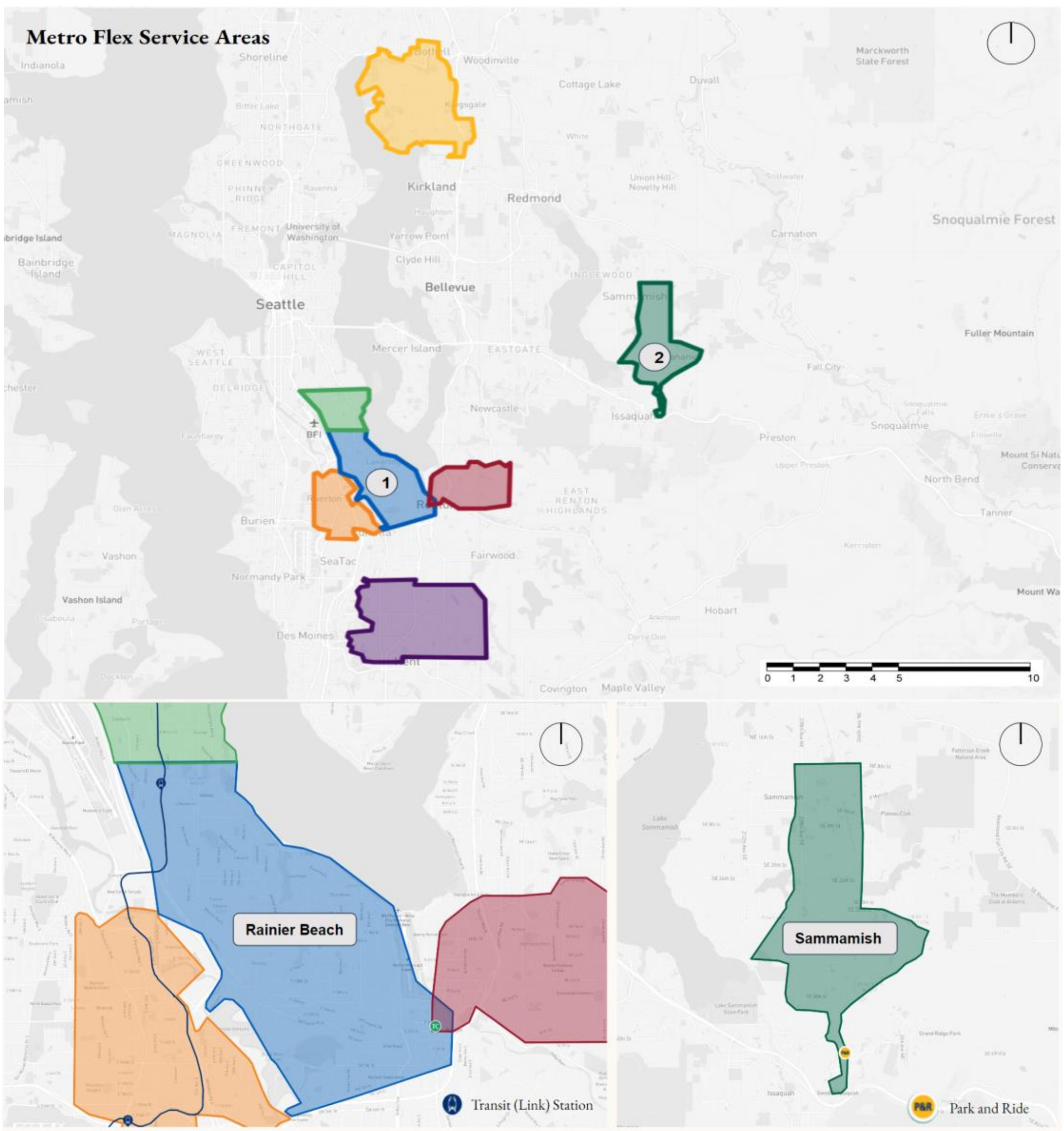

Figure 3.1 Metro Flex Service Areas and Case Studies

For Metro Flex trips, we used existing service trip data on May 4, 2023, which reflects the average ridership on a typical weekday, based on daily ridership for May 2023[1]. The data consists of the request, pick-up, and drop-off times (in minutes) for every trip, origin and destination geo-coordinates, trip distance, and the number of seats requested. For TNCs, we used publicly available service apps to estimate the service costs and trip duration for the same trips in the counterfactual scenario where Metro Flex was unavailable. For transit services, we worked with King County Metro (KCM) to obtain the costs for providing performance-equivalent fixed-route services. In the case of driving alone, we used historical traffic data from ArcGIS to estimate speed limits during different hours. We also estimated the cost of parking provided, which can be estimated using KCM data.

3.2 Methodological Framework

This study builds upon an analytical framework proposed by Wang and Shen (2023) for quantifying the economic costs of expanding mobility services in new or underserved areas [9]. The framework emphasizes using marginal cost instead of system-wide average cost when considering service expansion or new mobility options, as it provides more pertinent information for decision-making. The framework also highlights the importance of accounting for both the service provider's and the users' costs, including monetary and time costs and externalities such as environmental impacts. To accurately estimate the user's travel time, the time cost should include access, waiting, and egress times. The refined framework is shown in Figure 3.2.

The study addresses the research questions with two methodological components. First, we substantiate the conceptual framework to evaluate the cost-effectiveness from a societal perspective while considering socio-demographics and built-environment variables. Second, we build a transportation simulation procedure that allows transit agencies to empirically compare the cost of TIMOD with those of other alternative modes. Specifically, we compare the cost of Metro Flex trips versus three other mobility options: 1) fixed-route bus transit, 2) commercial ride-hailing services (i.e., TNCs), and 3) driving alone. We estimate the service provider's (e.g., transit agency's) cost and the users' (i.e., travelers') cost for each option. For the service provider's cost, we worked with KCM staff to obtain cost measures for Metro Flex and fixed-route services. For the travelers' cost, we used Metro Flex trip data and simulated travel times for the alternative modes under the counterfactual scenario where Metro Flex was unavailable and travelers needed to take the alternative modes. The travel time was then monetized using percentages of the average hourly wage rate as the travelers' values of time. For the external cost, the CO_2 emissions for each transportation mode were estimated and then monetized based on total passenger miles traveled.

3.2.1 Conceptualizing Cost-Effectiveness of Alternative Travel Modes

We substantiate and enrich economic cost variables to compare the cost-effectiveness of Metro Flex trips with other alternative modes. These variables include:

1) Cost for mobility service providers, including public transit agencies and private service providers (e.g., TNCs and Metro Flex). This typically includes the costs of labor (i.e., drivers, service managers, and planning staff), fuel/propulsion, capital, and maintenance.
2) Generalized costs for users from different socioeconomic backgrounds, including monetary and time costs of travel (waiting time, in-vehicle travel time, access time, and egress time for last-mile trips).
3) External costs, primarily environmental externalities.

[1] Metro Flex started operating in March 2023, and its ridership started to stabilize in May 2023.

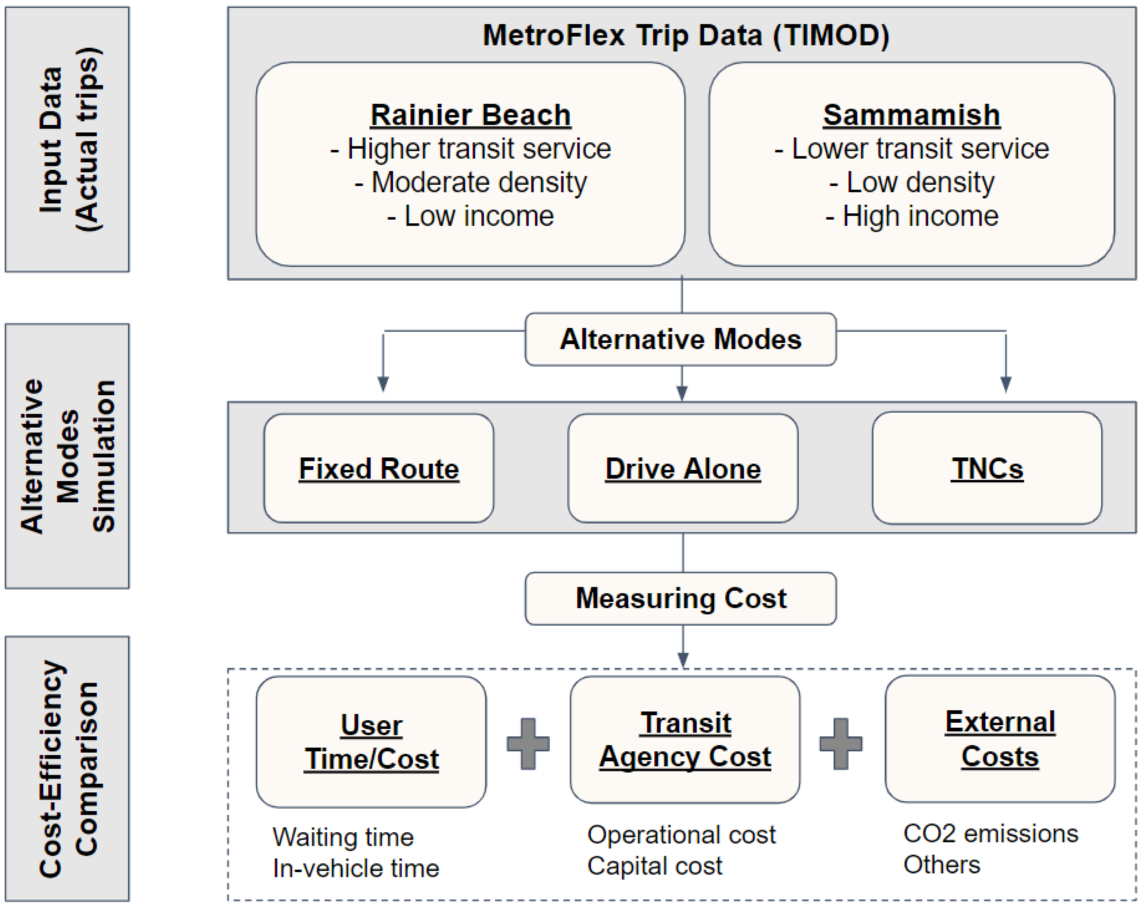

Figure 3.2 Methodological Framework

3.2.2 Simulating Travel Time and Travel Costs

Using the Metro Flex trip dataset, we applied a transportation simulation approach to model the counterfactual scenarios where Metro Flex was not an option, and all Metro Flex riders needed to choose alternative modes. We used Eclipse SUMO, a free and open-source software, for the simulation. SUMO is highly customizable and can directly model real-world road networks and individual-traveler-level traffic flows [42]. We obtained the road network map and related information on the number of lanes, speed limit, permitted vehicle types, sidewalks, pedestrian crossings, and traffic lights from OpenStreetMap (OSM) and the bus stop and route information from KCM General Transit Feed Specification General Transit Feed Specification (GTFS) data tables.

In the simulation, travelers were assumed to depart at the same time as when they requested Metro Flex for the counterfactual modes. We applied speed factors to reflect traffic levels, using historical traffic data from Esri online. For TNC trips, we used Uber and Lyft apps to estimate the trip fare for every trip. Because TNCs also involve waiting times, we applied the average waiting times estimated by Hughes and Mackenzie (2016) for different areas in Seattle [43]. These values were validated through a sample of requests to the TNC apps. The outputs of the simulation are the access, waiting, in-vehicle travel, and egress times needed for travelers using either mode. Figure 3.3 presents the simulation framework.

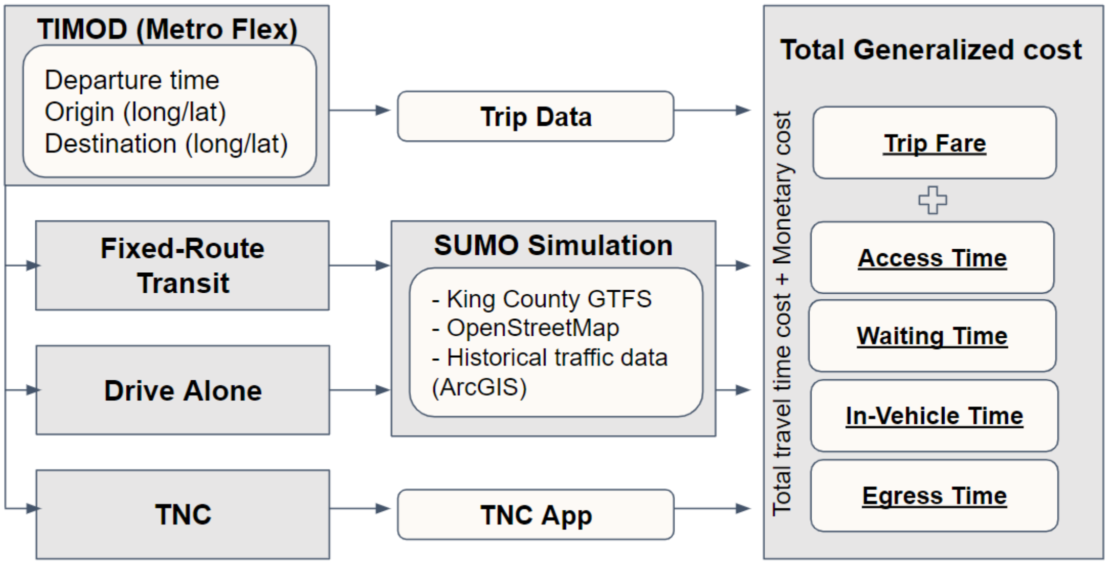

Figure 3.3 Alternative Modes Simulation Framework

3.2.3 Estimating the Generalized Costs for Travelers

Travel time for each mode was monetized using percentages of the average hourly wage rate as the values of travelers' time during trips, under the simplified assumption that the trips were either commuting trips or non-commuting trips made by average working adults during a typical weekday. The average hourly wage for the Seattle Metropolitan Statistical Area was $38.47 in 2022 [44]. Travelers' values of time for various trip components are listed in Table 3.1. These values were determined for the following reasons:

1) The U.S. Department of Transportation recommended plausible ranges for personal trip values of travel time savings for surface modes other than high-speed rail [45]. These were 35% to 60% of hourly earnings for time spent in a vehicle and 80% to 120% of hourly earnings for time spent on walking.
2) For the value of in-vehicle time as a percentage of hourly earnings, Metro Flex and TNCs were assigned the lowest value rounded to the nearest 10 (i.e., 40%), while driving alone was assigned the highest value (60%). Metro Flex and TNC vehicles were expected to have a higher level of comfort than buses given their available seats for all passengers, which contributes to their lower opportunity cost of in-vehicle time than transit. Compared to other modes, drivers of private vehicles cannot use their in-vehicle time freely, and therefore they were expected to have the highest opportunity cost of in-vehicle time.
3) Metro Flex and TNC were also set to have a lower wait time value than transit [46]. Metro Flex and TNC riders have more control over the distribution and use of their time waiting and walking to pickup locations. Even if they were a few minutes later than the estimated pickup time, drivers would stay for a short time (about 2 minutes) to allow riders to arrive at pickup locations.

Table 3.1 Travelers' Values of Time for Trip Components as Percentages of Hourly Wage

Time components	Metro Flex	Transit (bus)	TNC	Drive alone
Access time	100%	100%	100%	100%
Waiting time	50%	75%	50%	/
In-vehicle time	40%	50%	40%	60%
Egress time (parking time)	/	/	/	100%

The other monetary costs for travelers by mode are shown in Table 3.2. First, an adult using Metro Flex or transit pays only a standard fare of $2.75. The cost of a TNC trip consists of the base fare, the cost of the miles traveled, and the cost of the time traveled. If the sum of costs is less than the minimum fare, the minimum fare will be paid. The ranges of TNC fares shown in Table 3.2 was obtained for the study areas of this research [47].

Moreover, trips made by driving alone do not have to pay a ride fare. Instead, these trips pay for the cost of fuel consumption and the cost of maintaining and owning a vehicle for the miles traveled. The average price of gasoline (including all taxes) in Washington State is currently $4.821 per gallon [48]. Fuel consumption for driving alone was estimated using the SUMO simulation, which accounts for the influence of a vehicle's speed and acceleration during a trip on fuel consumption [49].

Table 3.2 Travelers' Monetary Costs by Mode

Monetary Cost	Metro Flex	Transit (bus)	TNC[2]	Drive alone
Base Fare	$2.75	$2.75	$0 - $3.53	/
Minimum Fare	/	/	$5.77 - $7.88	/
Cost Per Mile	/	/	$1.60 - $1.99	/
Cost Per Minute	/	/	$0.27 - $0.85	/
Cost of Fuel Consumption	/	/	/	$4.821 per gallon (including all taxes) [48]
Car Maintenance Cost	/	/	/	$0.0982 per mile [50]
Car Ownership Cost (including insurance, license, and depreciation	/	/	/	$0.564 per mile [50]

3.2.4 Estimating Service Provider's Operating Costs

In this research, the service provider is King County Metro (KCM), the primary transit agency in King County, WA. According to KCM, the operating cost of a Metro Flex vehicle is $55.58 per vehicle hour, and the average bus operating cost in King County is $183.9 per vehicle hour. The agency's total operating costs for Metro Flex and transit are calculated using equations (1) and (2). Metro Flex vehicle hours in the study areas were provided by KCM. Vehicle hours by bus route were calculated using GTFS schedule data. Average weekday boardings by bus route in May (or June if the data was missing for May 2023) were obtained from the KCM route dashboard [51]. In addition, KCM pays nothing to operate the TNC service. TNC operating costs are not known nor are they a direct, public financial cost; they are assumed to be fully covered by fares collected from the users.

$$C_{MF} = O_{MF} * H_{MF} \tag{1}$$

[2] TNC fare breakdown varies by time of the day and service areas. The actual TNC fares used in this study were estimated using Uber Estimate website (https://www.uber.com/global/en/price-estimate/).

$$C_{transit} = O_{transit} * H_{transit} * D/R_{transit} \quad (2)$$

Where C_{MF} is the total operating cost of Metro Flex vehicles on the selected day, O_{MF} is the Metro Flex's operating cost per vehicle per hour, H_{MF} is the total vehicle hours of Metro Flex on the selected day. $C_{transit}$ is the total operating cost of buses traveling through the study areas on the selected day, $O_{transit}$ is the operating cost per bus vehicle per hour, $H_{transit}$ is the total vehicle hours of buses traveling through the study areas on the selected day, D is the total number of persons generating the demand for the observed trips of Metro Flex on the selected day, and $R_{transit}$ is the total ridership of those buses on the selected day.

3.2.5 Estimating External Cost of Greenhouse Gas Emissions

The CO_2 emissions for each mode of transportation were estimated based on vehicle miles traveled. A typical passenger vehicle used by Metro Flex and TNC would generate 410 grams of CO_2 emissions per vehicle mile traveled [52]. The deadheading of both the Metro Flex services and TNC have also been taken into account in the emission costs as an additional proportion of the travel distance of the trips. The average percentage of deadheading for a Metro Flex trip was provided by King County Metro's statistics, and for a TNC trip was provided by Uber Estimate. A typical bus generates 291 grams of CO_2 emissions per passenger mile traveled [53]. We used equation (3) to estimate the emission cost of each mode. CO_2 emissions were then monetized using the global average marginal abatement cost of \$0.68 per kilogram of CO_2 emissions or CO_2 emissions equivalents (CO_2E) [54].

$$C_E = M * E_{mode} * L_{mode} \quad (3)$$

Where C_E is the CO_2 emission abatement cost of a mode, M is the abatement cost per gram of CO_2 emissions, E_{mode} is the CO_2 emission equivalents per passenger mile traveled, L_{mode} is the total miles traveled by passengers on the selected day.

3.2.6 Incorporating Equity into Cost-Effectiveness Analysis

Transit agencies often have concerns about both improving overall mobility services and reducing inequality in mobility, which has important equity implications. Traditional cost-effectiveness analysis does not provide information about inequality impacts or tradeoffs between improving mobility services and reducing inequality. Distributional cost-effectiveness analysis (DCEA) is a framework that is widely utilized in health-related studies but can also be used to incorporate inequality impacts into transportation services evaluation. In this study, we employ DCEA to 1) model social distributions of travel cost of each mobility alternative across different income groups, and 2) evaluating social distributions of the travel costs.

The modeling stage involves estimating the baseline travel cost, which is represented by the generalized cost associated with existing fixed-route services, modeling changes to this distribution due to the introduction of a new MOD service (Metro Flex) and adjusting the resulting generalized travel cost for alternative social value judgments [40,41]. In this study, we have followed the Love-Koh et al. (2019) approach, conducting the following analysis steps [40,41]:

1) Define the relevant groups of interest: The first step includes defining the groups, which could be by geography, age, socioeconomic status, etc. Defining the group is analytically simple but can be a challenge as there is no "right" group subdivision. Due to the lack of available data, we have used the American Community Survey (ACS) median household income data by census block group, and spatially joined the median income with the trips data in ArcGIS, assuming that trip origins represent users home location. We used the median income to estimate the hourly rate for each rider based on the origin point of their trips. Finally, we grouped the sample into six equal interval income groups (\$30k - \$60k), (\$60k - \$90k), (\$90k - \$120k), (\$120k - \$150k), (\$150k - \$180k), and (\$180 and above). Figure 3.4 illustrates the distributions of trip origins and census block group median household incomes.

2) Measure the baseline situation: While recognizing that there are more alternative modes and various inter-modal scenarios of using existing fixed routes, we simplify the comparison by considering three mutually exclusive options in our analysis:
   - Baseline (bus): existing fixed-route service, which consists of buses in both service areas.
   - Metro Flex: using the TIMOD service as an alternative to fixed-route transit.
   - Drive alone: driving alone as another alternative to fixed-route services.

   We measured the generalized cost for each trip by multiplying the different components of travel time (in-vehicle time, wait time, access, and egress times) and their estimated coefficients with the hourly income rate for every user. The resulting cost is presented as the average cost for every income group by mode. Different income groups have different numbers of trips that also vary by service area, which affects the total generalized cost in each.
3) Measuring inequality in the resulting cost distribution: The impact of the technology here is seen as the difference in the cost of travel between fixed-route bus and Metro Flex. We have also looked at the impact of using drive alone, as it resulted in the minimum generalized cost in the cost-effectiveness analysis. Inequality in cost distributions can be quantified in multiple ways, but we use two main indices to inform different inequality concerns from transit agencies. The first index is Atkinson, which is a relative inequality index that measures the proportional change in cost across the distribution. The Atkinson index considers the number of population groups and inequality aversion, to quantify how social welfare is reduced by relative inequality, as shown in equation (4):

$$A\varepsilon = 1 - \left[\frac{1}{N}\sum_{i=1}^{N}\left(\frac{Qi}{Q}\right)^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}} \tag{4}$$

   Where $A\varepsilon$ is the Atkinson index, Q_i is the quality gained for income group i by introducing a new service (Metro Flex), measured by the generalized cost reduction for group i, Q is the baseline cost for using existing fixed-route services, N is the number of individuals or subpopulation groups , and ε the inequality aversion parameter that quantifies the concern for relative inequality (ratios), which ranges from 0 to positive infinity, where 0 implying no aversion to income inequality, and a value of 1 or less represents moderate aversion to income inequality, and values greater than 1 indicate strong aversion to income inequality. The specific value of ε is often arbitrary and determined based on the context and the objectives and preferences of the researcher or decision-maker. It can also be chosen based on the desired level of sensitivity to income inequality in a particular economic or social study. The Atkinson index formula typically includes the aversion coefficient ε in its calculation, allowing for flexibility in measuring income inequality based on the degree of aversion chosen. We also looked at Kolm index, which measures the absolute change in cost across the distribution, as shown in equation (5):

$$K\alpha = \left(\frac{1}{\alpha}\right) log\, log\, \left(\frac{1}{N}\sum_{i=1}^{N} e^{\alpha[Q-Qi]}\right) \tag{5}$$

   Where Kα is the Kolm index, Qi is the quality gained for income group i by introducing a new service (Metro Flex), measured by using generalized cost for group i, Q is the baseline cost for using existing fixed-route services, N is the number of individuals or subpopulation groups, and α representing the level of constant absolute inequality aversion. Comparing both Atkinson and Kolm indices before and after the introduction of a TIMOD service (e.g., Metro Flex) provides insights into the inequality of the generalized cost distribution between different income groups. If the Atkinson index decreases with TIMOD service, it indicates a decrease in the cost distribution inequality, especially if it decreases for higher ε values, which suggests a focus on reducing inequality. Similarly, a decrease in the Kolm index signifies a reduction in cost distribution inequality to achieve equity. Hence, a lower Atkinson index values (with the same ε) indicate reduced inequality, and a lower Kolm index value means less cost needs to be distributed among different income groups for perfect equality.

4) Social welfare analysis: Having separately quantified average cost for every income group and inequality resulting from each alternative mode (Metro Flex and drive alone), we combined concerns for maximizing quality gained through cost reductions, and concerns for minimizing inequality across different income groups using social welfare analysis. We compared the different modes using social welfare indices that explicitly trade off increases in the mean cost against greater equality in the distribution of cost, by calculating an "equally distributed equivalent" (EDE) level of cost each income group would receive in a hypothetically perfectly equal distribution. We focus on two social welfare indices constructed by combining the mean cost with the Atkinson and Kolm indices respectively.

$$EDEx_{A\varepsilon} = (1 - A\varepsilon)Q \tag{6}$$

$$EDEx_{K\alpha} = (Q - K\alpha) \tag{7}$$

In the case of no concern for inequality (α = ε = 0) the social welfare indices just collapse to the average cost. The difference between the average cost by mode and EDE for different inequality aversion values indicates the average increase in cost for travelers to achieve a perfectly equal distribution of cost, which allows for ranking alternative travel modes over a range of possible inequality aversion levels.

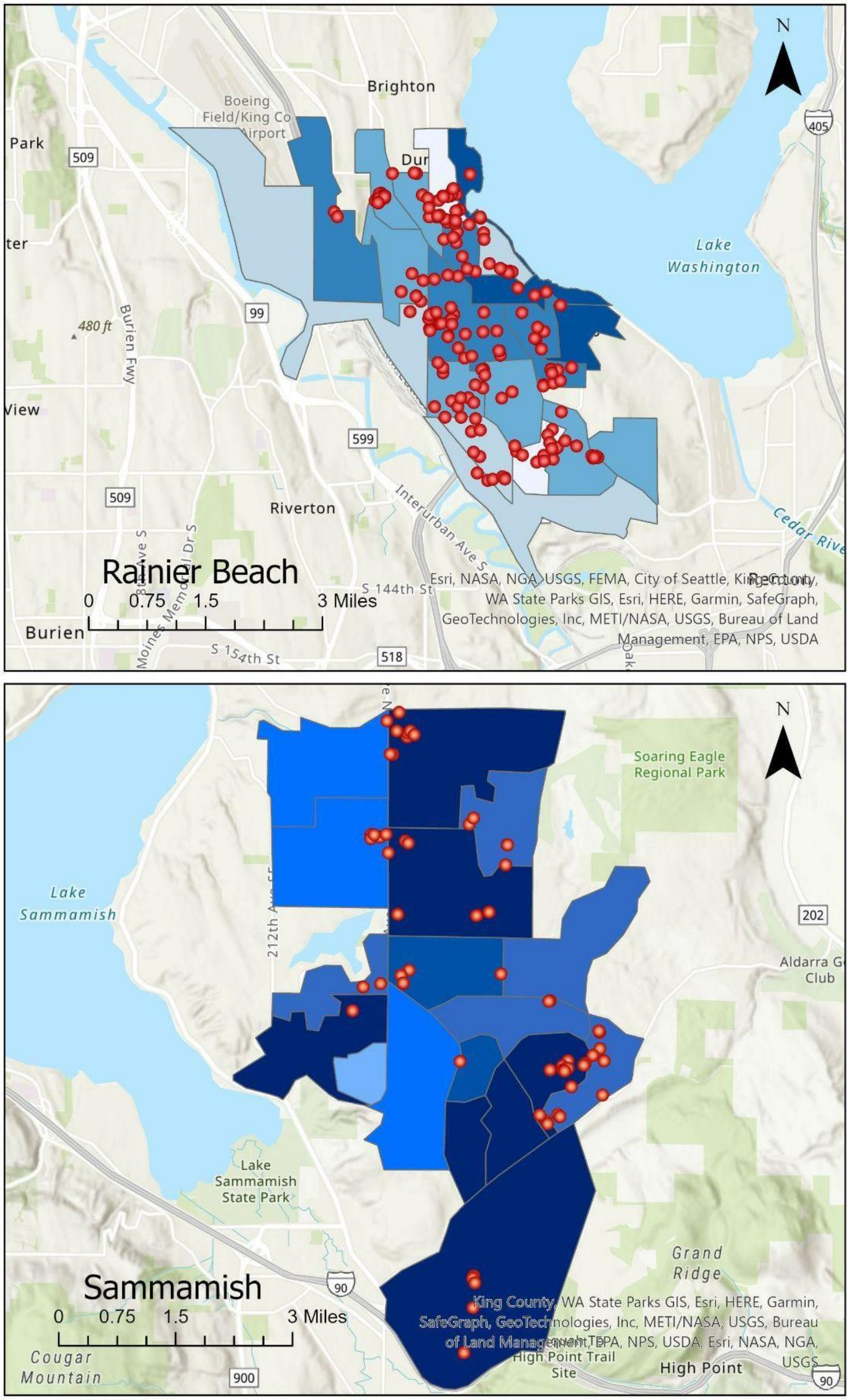

Figure 3.4 Median Income and Metro Flex Trips

RESULTS

4.1 Comparing Travel Time by Mode of Transportation

Figure 4.1 and Table 4.1 show the distributions of travelers' total travel time by each transportation mode. Table 4.1 provides a detailed breakdown of the time components for each mode. The travel time by Metro Flex was obtained from observed trip data. The time interval between request creation time and pickup time equals the sum of walk access time and waiting time. We assumed that the maximum walk access time was 5 minutes. If the time interval between request creation time and pickup time was less than 5 minutes, the passengers were assumed to spend all the time walking. The travel times by driving alone, TNC, and transit were estimated by SUMO simulation.

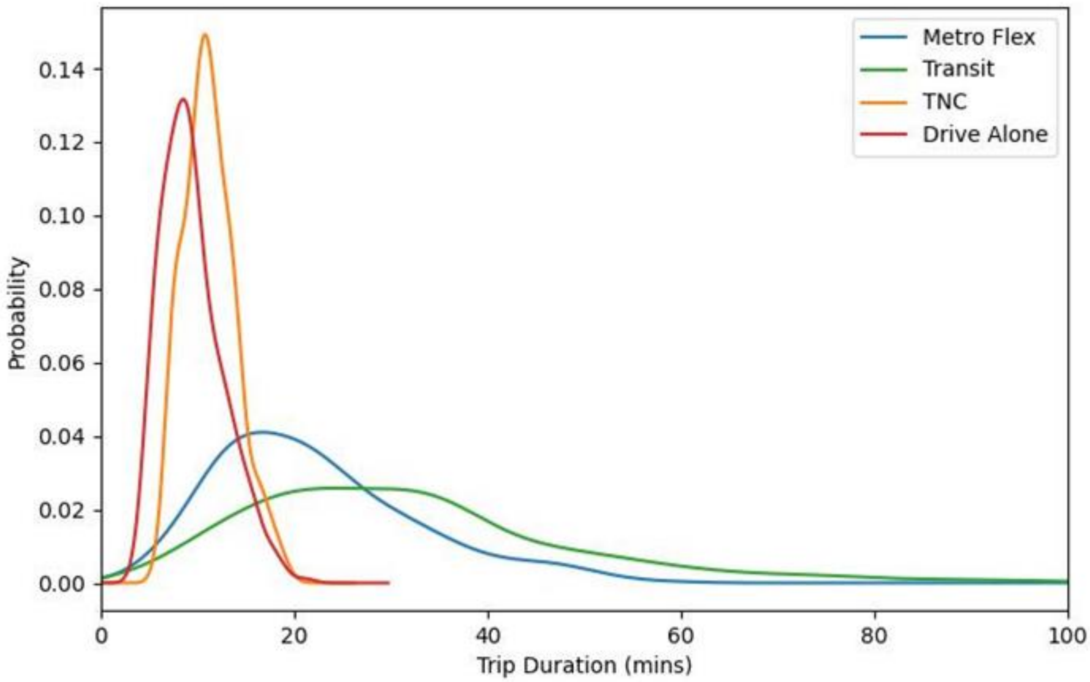

Figure 4.1 Distribution of Total Travel Time by Mode (N of Trips = 369)

Table 4.1 Descriptive Statistics of Travel Time by Mode

Mode	Mean	Std.	Min.	Max.
Metro Flex	22.16	10.35	3.09	58.72
Access Time	4.85	0.53	1.05	5.00
Waiting Time	7.49	7.36	0.00	38.46
Shared Trips	8.03	7.37	0.00	38.46
Non-shared Trips	6.42	7.23	0.00	36.99
In-vehicle Time	9.82	5.99	1.32	34.50
Shared Trips	11.30	6.32	1.80	34.50
Non-shared Trips	6.88	3.85	1.32	27.63
Transit (bus)	31.72	16.67	4.78	96.95
Access Time	15.73	11.45	0.28	56.62
Waiting Time	8.12	10.72	0.00	68.58
In-vehicle Time	7.72[3]	6.97	0.00[4]	38.27
TNC (e.g., Uber, Lyft)	12.13	3.24	6.00	25.13
Waiting Time	4.70	0.95	4.00	6.00
In-vehicle Time	7.44	3.17	2.00	19.13
Drive Alone	9.44	3.17	4.00	21.13
In-vehicle Time	7.44	3.17	2.00	19.13
Parking Time	2	0	2	2

From the overall distribution of trip durations, Metro Flex takes more time than driving alone and TNC, but less time than transit. Compared to driving alone and TNC trips, Metro Flex trips have a somewhat longer average in-vehicle time, and a much longer average waiting time which is similar to transit. Although non-shared Metro Flex trips have a shorter average waiting time than shared trips, it is still over 6 minutes. In addition, the long transit trips with long access and waiting times are a result of the low coverage of transit service in the study areas. The average in-vehicle time for transit excludes trips that could not be made through transit.

4.2 Total Costs for Travelers, Service Operation, and Externalities

The total generalized cost for travelers by mode is shown in Table 4.2, which presents the sum of monetized travel time and monetary costs paid by travelers. Not surprisingly, driving alone has the lowest total generalized cost on the traveler side because it takes travelers much less time. Metro Flex also has a relatively lower total generalized cost for travelers than transit and TNCs because of its on-demand feature and low ride fare. However, Metro Flex generates much higher operating costs for the transit agency compared to fixed-route transit service. It also has the highest total emissions abatement costs among all the modes because of a higher proportion of deadheading. In contrast, fixed-route transit service generates the lowest emission abatement costs.

[3] The average in-vehicle time for fixed-route transit is shorter than that of Metro Flex because the low density of transit service in the study areas results in many transit riders only taking bus for a small segment of their trip.
[4] The minimum in-vehicle time by fixed-route transit is zero because for some of the trips, transit is not even an option due to the limited service coverage. In these cases, people are assumed to walk to their destinations, resulting in a long access time.

Table 4.2 Travelers' Generalized Cost, Service Provider's Operating Cost, and Emission Abatement Cost by Mode

Mode	Cost for the selected day (N of trips=368, N of persons=425)					Cost for one month
	Travelers' total generalized cost	Service provider's operating cost	Emission abatement cost	Emission abatement cost per person	Total cost[5]	Total cost
Metro Flex	$4,603.46	$6,391.70	$468.28	$1.10	$ 10,294.70	$ 308,840.91
Transit (bus)	$7,847.27	$2,431.29	$127.47	$0.30	$9,534.28	$286,028.52
TNC	$8,004.67	NA[6]	$408.58[7]	$0.96	$8,413.25	$252,397.51
Drive alone						
No parking space provided	$2,775.88	NA[8]	$323.90	$0.76	$3,099.78	$92,993.51
Park-and-Ride site with 250 parking spaces: Lifespan of 50 years	$2,775.88	$2,941.66	$323.90	$0.76	$6,041.44	$181,243.34
Park-and-Ride site with 250 parking spaces: Lifespan of 30 years	$2,775.88	$4,466.78	$323.90	$0.76	$7,566.56	$226,996.77

[5] For Metro Flex and transit, the ride fares paid by passengers but collected by transit agencies were excluded from the total cost.
[6] We recognize that TNCs have not been generating enough revenues to cover their operating cost, though we do not have the data needed to estimate the operating costs not covered by fares paid by passengers.
[7] TNC has lower emission costs than Metro Flex because TNC has a lower proportion of deadheading.
[8] We acknowledge that even if no additional parking is provided by King County Metro, it does not mean that shifting all Metro Flex trips to driving would not create other costs. For example, shopping centers may need to expand their parking infrastructure to accommodate associated parking demand.

For driving alone, we assumed that KCM might need to build park-and-ride spaces for parking and transferring to nearby transit lines. These park-and-ride spaces would be free to drivers. If a park-and-ride space serves two trips per day, a minimum of 213 park-and-ride spaces would be needed to serve a total of 425 trips. We therefore assume that KCM would build 250 parking spaces to accommodate the increased parking demand from the shift of these Metro Flex trips to driving. According to KCM, the price per parking space at a park-and-ride facility is $167,000 for permanent, dedicated, structured parking. The total construction cost for 250 spaces with a 50-year life would then be $167,000*250/50/365 = $2,287.67. In addition to the construction costs for the parking spaces, we assume an on-site maintenance employee would be hired during the hours of operation and paid an average wage (i.e., $38.47) for the hours worked (assumed to be 17 hours per day). As a result, the total agency cost would be the sum of the parking space construction cost and the employee's salary: $2,287.67+$38.47*17=$2,941.66. Considering the two scenarios in terms of the life span of 30 and 50 years, the agency costs for the construction of the parking lots are shown in Table 4.2.

Table 4.2 shows that driving alone has the lowest generalized cost to travelers among the modes. From the traveler's perspective, Metro Flex has a competitive advantage over fixed-route transit and TNCs due to its on-demand nature and subsidized fare. From the transit agency's perspective, the operating costs associated with Metro Flex are much higher than those of traditional fixed-route transit services. From a societal perspective, Metro Flex has a cost disadvantage compared to the other alternatives due to much higher operating costs . It should be noted, however, that the total social cost of Metro Flex is only modestly higher than that of fixed-route transit.

Table 4.3 shows the traveler's total generalized cost, service provider's operating cost, and emission abatement cost per rider for each of the two case areas, Sammamish and Rainier Beach. Except for the TNC alternative, the traveler's total generalized cost and service provider's operating cost per rider are lower in Rainier Beach. Additionally, for both Sammamish and Rainier Beach, driving alone has the lowest social cost among the alternative modes, primarily because drivers do not experience waiting time nor must deadhead miles. In comparison, Metro Flex has the highest social cost for both suburban areas. This is due to the high operating costs of running long vehicle hours for a smaller group of riders, as well as a high proportion of deadheading that contributes to higher emissions costs. Again, the social cost of Metro Flex is only modestly higher than that of fixed-route transit in both study areas.

Table 4.3 Traveler's Generalized Cost, Service Provider's Operating Cost, and Emission Abatement Cost per User for the Two Service Areas

Area	Mode	Cost per rider for the selected day				Cost/rider for 1 month
		Travelers' total generalized cost per rider	Service provider's operating cost per rider	Emission abatement cost per rider	Total cost per rider	Total cost per rider
Sammamish (N of trips = 67, N of persons = 89)	Metro Flex	$11.57	$22.48	$1.11	$32.41	$972.18
	Transit (bus)	$22.57	$7.94	$0.17	$29.16	$874.83
	TNC	$14.75	NA	$0.86	$15.61	$468.34
	Drive alone					
	No parking space provided	$6.59	NA	$0.77	$7.36	$220.93
	Park-and-Ride site with 50 parking spaces: Lifespan of 50 years	$6.59	$12.49	$0.77	$19.85	$595.60
	Park-and-Ride site for 50 parking spaces: Lifespan of 30 years	$6.59	$15.92	$0.77	$23.28	$698.42
Rainier Beach (N of trips = 301, N of persons = 336)	Metro Flex	$10.64	$13.07	$1.10	$22.06	$661.66
	Transit (bus)	$17.38	$5.13	$0.33	$20.65	$619.55
	TNC	$19.92	NA	$0.99	$20.90	$627.13
	Drive alone					
	No parking space provided	$6.52	NA	$0.76	$7.27	$218.25
	Park-and-Ride site with 200 parking spaces: Lifespan of 50 years	$6.52	$7.39	$0.76	$14.67	$440.04
	Park-and-Ride site with 200 parking spaces: Lifespan of 30 years	$6.52	$11.02	$0.76	$18.30	$548.98

4.3 Equity Implications and Tradeoffs of Alternative Services

The baseline distribution of generalized travel cost for fixed-route bus is shown in Figure 4.2. We can see from the distribution that generalized cost using existing fixed-route bus is disproportionately higher for high income groups.

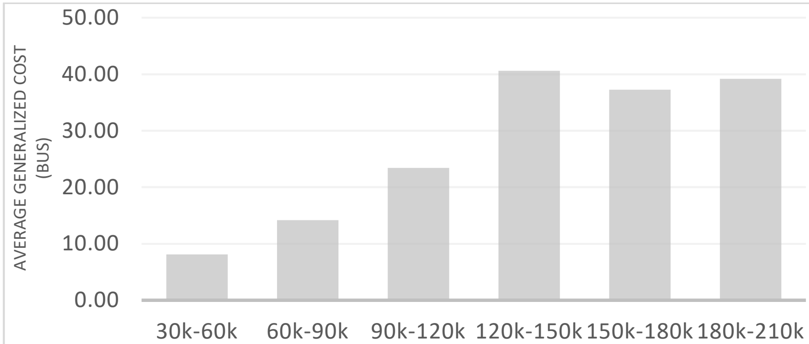

Figure 4.2 Bus (baseline) Generalized Cost by Income Group

However, it is worth noting that the two service areas have distinctively different income compositions, with Sammamish having predominantly higher-income groups compared to Rainier Beach (shown in Figure 4.3). Yet, Rainier Beach has a much higher trip volume than Sammamish.

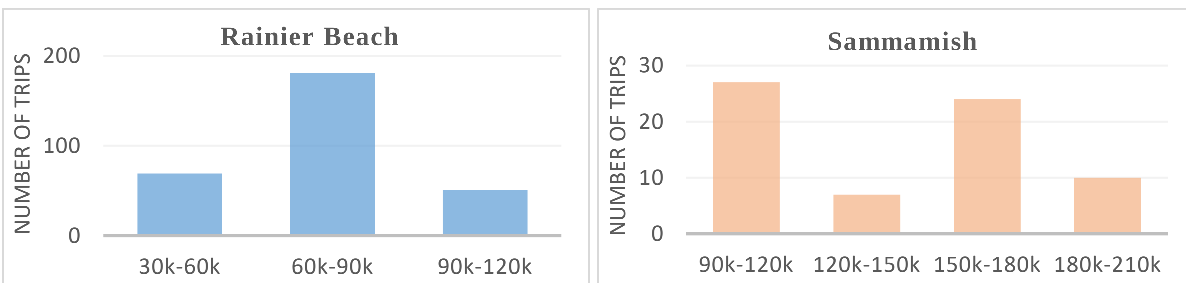

Figure 4.3 Number of Trips per Income Group

We next look at the impact of the new TIMOD intervention (Metro Flex) on the baseline cost distribution and compare it to drive alone. Figure 4.4 shows the average generalized cost for every income group by mode. Figure 4.5 shows the total generalized travel cost for every income group by mode, which reflects the difference in demand levels and volume of trips. The latter shows that lower income groups have higher demand for TIMOD services, indicating a higher need to prioritize equity among the poorest.

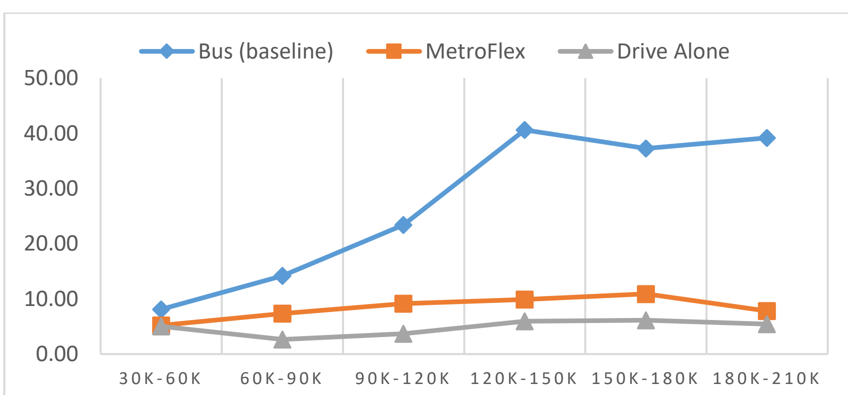

Figure 4.4 Average Generalized Travel Cost by Income Group

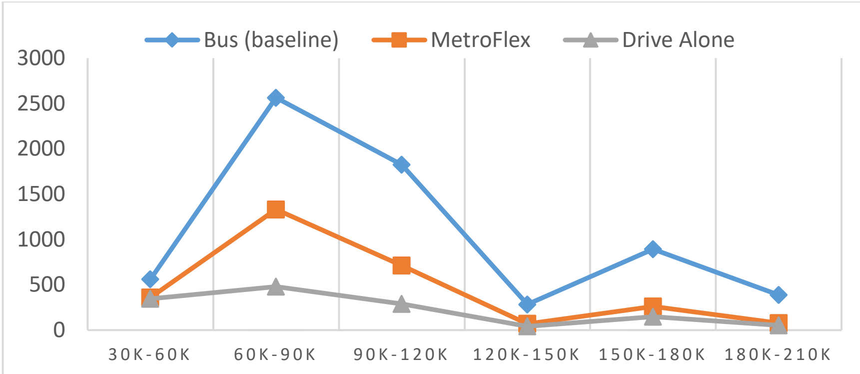

Figure 4.5 Total Generalized Travel Cost by Income Group

Compared with fixed route (bus), the average generalized travel cost and total generalized travel cost drop for all six income groups using Metro Flex or drive alone. Table 4.4 shows the average generalized cost for different income groups by mode per service area, reflecting different hourly wage rates for each group.

Table 4.4 Traveler's Generalized Cost for Different Income Groups by Mode[9]

Sammamish			
Group	Bus (baseline)	Metro Flex	Drive Alone
90k-120k	34.00	10.20	6.34
120k-150k	40.61	9.89	5.98
150k-180k	37.26	10.91	6.14
180k-210k	39.16	7.79	5.41
Average QALE	36.61	9.27	5.95
Difference vs. Baseline	-	27.34	30.66
Rainier Beach			
Group	Bus (baseline)	Metro Flex	Drive Alone
30k-60k	8.11	5.20	5.01
60k-90k	14.17	7.36	2.65
90k-120k	17.81	8.59	2.33
Average Q	13.36	6.90	4.67
Difference vs. Baseline	-	6.46	8.69
Rainier Beach + Sammamish (combined)			
Group	Bus (baseline)	Metro Flex	Drive Alone
30k-60k	8.11	5.20	5.01
60k-90k	14.17	7.36	2.65
90k-120k	23.41	9.15	3.72
120k-150k	40.61	9.89	5.98
150k-180k	37.26	10.91	6.14
180k-210k	39.16	7.79	5.41
Average Q	28.86	9.32	4.62
Difference vs. Baseline	-	19.54	24.24

[9] The generalized costs in this table are adjusted based on the hourly income rate of individuals.

Combining the baseline cost distribution and the estimated distribution of cost changes associated with each alternative mode provides the overall cost distribution associated with each mode. Table 4.5 reports a range of absolute and relative inequality measures calculated for each strategy.

Table 4.5 Relative and Absolute Inequality Indices by Mode

Mode	**Bus (baseline)**	**Metro Flex**	**Drive Alone**
Relative Inequality Indices			
Atkinson Index (ε=2)	0.29	**0.06**	0.09
Atkinson Index (ε=5)	0.55	**0.15**	0.22
Atkinson Index (ε=10)	0.64	**0.26**	0.34
Absolute Inequality Indices			
Kolm Index (α=0.1)	12.87	1.60	**1.10**
Kolm Index (α=0.15)	14.14	1.70	**1.10**
Kolm Index (α=0.5)	15.71	1.80	**1.20**

Bold font indicates the most equal mode.
ε=2 represents low relative inequality aversion while ε=10 represents high relative inequality aversion
α=0.01 represents low absolute inequality aversion while α=0.5 represents high absolute inequality aversion

Relative inequality measures (Atkinson) calculated across a range of inequality aversion is lower for Metro Flex while absolute inequality measures are lowest for drive alone, which means that the two modes have different distributional effects. The results show that Metro flex is more effective at reducing inequality at the lower end of the distribution, which represents lower income groups, while drive alone is more effective at reducing inequality at the upper end of the distribution. Table 4.4 shows that the cost reduction compared to fixed route (bus) is disproportionately higher for high income groups ($120k and above) for both driving alone and Metro Flex.

To maximize quality gained through cost reduction and minimize inequality using social welfare analysis, we estimated cost distributions associated with every mode using our social welfare indices evaluated across a range of inequality aversion levels. The values of these indices are shown in Table 4.6.

Table 4.6 Relative and Absolute Social Welfare Indices by Mode

Mode	**Bus (baseline)**	**Metro Flex**	**Drive Alone**
Mean Cost (ε=α=0)	27.12	8.38	4.82
Relative Inequality Indices			
Atkinson EDE (ε=2)	19.13	7.91	**4.40**
Atkinson EDE (ε=5)	12.32	7.15	**3.77**
Atkinson EDE (ε=10)	9.70	6.20	**3.17**
Absolute Inequality Indices			
Kolm EDE (α=0.1)	14.25	6.74	**3.70**
Kolm EDE (α=0.15)	12.98	6.67	**3.67**
Kolm EDE (α=0.5)	11.41	6.50	**3.60**

The social welfare indices show that driving alone maximizes the social welfare even as inequality aversion increases, followed by Metro Flex then fixed route. The results show that Metro Flex is worthwhile in terms of improving equality of generalized cost distribution for travelers, and increasing social welfare compared to fixed-route transit (bus).

DISCUSSIONS

Compared to fixed-route transit, Metro Flex has the advantage of saving travelers' time. As a tradeoff, the operating cost and the generated emissions per rider are both higher for Metro Flex than for fixed-route transit. Although TNC operating cost is assumed to be covered through trip fares, we know that TNCs likely incur high operating costs not fully covered by fares. Driving alone appears to be the most cost-effective mode in the study areas. The situation may differ in densely populated areas, where heavy traffic and induced congestion can significantly and negatively affect driving speed. In Sammamish, where the density of transit service is relatively low, the total generalized cost per transit rider is relatively high. In the Rainier Beach area, Metro Flex operates in a slightly denser area compared to Sammamish, and the operating costs are nearly half the costs for Sammamish. This suggests that whether TIMOD can be cost effective as an alternative option to fixed-route transit is context dependent.

The cost-effectiveness of a transportation mode is sensitive to the assumptions we made in this research. First, for most of the analyses performed in this study, we assumed that all Metro Flex riders earned the average wage per hour of work. As a result, these riders would have the same values of time for traveling. Second, the value of waiting time for on-demand mobility services is sensitive to the origins of trips. For home-based trips, riders may be able to make better use of their waiting time at home to do other things. In comparison, for non-home-based trips, riders must stay at the locations where they create requests with less flexibility to do other things. Third, estimated egress time is sensitive to the purposes of trips. For example, if the trips serve as FM/LM mobility to transfer to other modes, it could take riders several minutes to get to the transfer location. If the trips are for commuting or shopping, the egress time of these trips could be close to zero.

The costs of other externalities should also be considered in measuring the cost-effectiveness of transportation modes. These other external costs include noise, congestion, and accidents caused by increased travel demand. To estimate these external costs, it is necessary to know the traffic flow before travel demand is shifted in order to measure the marginal cost of shifting travel demand. Due to the unavailability of traffic data, this study could not measure externalities other than emissions. While our framework serves as a basis for comparison of cost-effectiveness across travel modes, future studies will ideally incorporate roadway segment-based externalities.

The distributional cost-effectiveness analysis shows that for all three levels of relative inequality aversion (ε=2, ε=5, and ε=10), the Atkinson index is lowest for Metro Flex, followed by drive alone, and then fixed-route transit (bus). This suggests that Metro Flex is the most equitable mode of transportation in terms of relative inequality. Driving alone on the other hand appears more attractive in terms of its absolute inequality and maximizing social welfare, mainly due to its lower travel costs. While both alternative modes improve social welfare compared to fixed-route bus, providing TIMOD services such as Metro Flex reduces relative inequality of travel cost especially among lower income groups, which provides affordable options of travel in suburban areas, especially for those who don`t have access to cars.

This research has several other limitations. First, the average waiting time of transit may have been overestimated because, since departure times were based on Metro Flex's on-demand service, these times do not relate to transit time schedules. Presumably, a traveler departing with a transit trip in mind would make some effort to reduce their waiting time by aligning their departure with expected bus schedules. Second, scenarios for increased transit frequency could be tested for a more robust analysis of the cost-effectiveness comparison. Increased transit frequency may reduce waiting times for transit riders, but it would also result in higher operating costs for transit agencies. Further research is needed to provide a more comprehensive discussion for comparing the cost-effectiveness of different modes. Lastly, due to the lack of available data, we utilized median household income instead of individual income to estimate different value of travel time in the distributional cost-effectiveness analysis.

CONCLUSIONS AND POLICY IMPLICATIONS

This study further developed a framework to compare the cost-effectiveness of TIMOD to three alternative modes -- fixed-route public transit services, driving alone, and TNCs -- using real-world MOD trip data. The study addressed questions related to the factors determining the comparative cost-effectiveness of TIMOD and alternative mobility services, the measurement and comparison of societal costs across different mobility services, and the conditions and arrangements under which TIMOD services are more cost-effective in low-density areas. While both areas considered are low-density suburban areas, they have distinct transit service provisions, built environments, and socio-demographic characteristics.

The study employed a conceptual framework focusing on marginal cost of expanding mobility service and accounting for service provider and user costs, including monetary and time costs and externalities. The results revealed various insights into the cost-effectiveness of different modes of transportation. Driving alone emerged as the least costly option for travelers considering time and monetary expenses, while Metro Flex, as a TIMOD service, demonstrated a competitive advantage over transit and TNCs from the traveler's perspective.

Compared to fixed-route transit and TNCs, TIMOD's on-demand nature and subsidized fare make it preferable for users. However, the study also highlighted that the operating costs for the transit agency associated with Metro Flex were much higher than traditional fixed-route transit services, indicating that implementing TIMOD may require careful consideration of service delivery optimization and financial resource allocation. Additionally, the study shed light on the importance of accounting for externalities, particularly greenhouse gas emissions. TIMOD services like Metro Flex generated higher emission abatement costs than fixed-route transit due to a high proportion of deadheading, which should be factored into the overall cost-effectiveness analysis.

As discussed earlier, Sammamish and Rainier Beach have different built environments and sociodemographic characteristics, resulting in different values of time for users of fix-route transit and microtransit in the two areas. The areas with lower density and transit accessibility have an overall higher total generalized travel cost. Such differences should be informative for transit agencies seeking to improve their TIMOD programs. TIMOD services, though facing cost-effectiveness challenges, reflect a more equitable distribution of travel costs especially among lower income groups. Although driving alone minimizes the generalized travel cost as well as total social cost, it favors higher income groups, and might not be equally accessible to individuals in low-income suburban areas. Transit agencies can benefit from analyzing equity and efficiency tradeoffs when introducing new services such as TIMOD, as it informs their decision-making process and the selection of service areas or targeted population. Further research and policy considerations are needed to address the challenges and potential benefits of implementing TIMOD services for different contexts and urban environments.

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