RESEARCH REPORT

Institute of Transportation Studies | UNIVERSITY OF CALIFORNIA

Job Access, Agency Cost, and VMT Impacts of Offering Microtransit Alongside Fixed-route Transit

Michael F. Hyland, Ph.D., Assistant Professor[1]
Susan Pike, Ph.D., Professional Researcher[2]
Siwei Hu, Ph.D. Candidate[1]
Jacob Julius Berkel, Undergraduate Student[1]
Yan Xing, Ph.D., Postdoctoral Researcher[2]
Ritun Saha, Ph.D. Student[1]
Geoffrey Hans Vander Veen, Undergraduate Student[1]
Dingtong Yang, Ph.D., Postdoctoral Researcher[1]

[1]Department of Civil and Environmental Engineering, University of California, Irvine
[2]Institute for Transportation Studies, University of California, Davis

April 2025

California Resilient and Innovative Mobility Initiative

Report No.: RIMI-4I | DOI: 10.7922/G2DN43DQ

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UC-ITS-RIMI-4I	N/A	N/A

4. Title and Subtitle Job Access, Agency Cost, and VMT Impacts of Offering Microtransit alongside Fixed-route Transit	**5. Report Date** April 2025 **6. Performing Organization Code** ITS-Davis, ITS-Irvine
7. Author(s) Michael F. Hyland, Ph.D., https://orcid.org/0000-0001-8394-8064; Susan Pike, Ph.D., https://orcid.org/0000-0001-6558-3479; Siwei Hu, https://orcid.org/0000-0002-3092-279X; Jacob Julius Berkel; Yan Xing, Ph.D., https://orcid.org/0000-0003-1173-1872; Ritun Saha; Geoffrey Hans Vander Veen; Dingtong Yang, Ph.D.;	**8. Performing Organization Report No.** N/A
9. Performing Organization Name and Address Institute of Transportation Studies, Irvine 4000 Anteater Instruction and Research Building, Irvine, CA 92697 Institute of Transportation Studies, Davis 1605 Tilia Street, Davis, CA 95616	**10. Work Unit No.** N/A **11. Contract or Grant No.** UC-ITS-RIMI-4I
12. Sponsoring Agency Name and Address The University of California Institute of Transportation Studies	**13. Type of Report and Period Covered** Final Report (May 2022 – February 2024) **14. Sponsoring Agency Code** UC ITS

15. Supplementary Notes
DOI: 10.7922/G2DN43DQ

16. Abstract
Public transit ridership has declined in major US cities over the past decade. Integrating traditional fixed-route transit with flexible microtransit has been proposed to enhance ridership, mobility, accessibility, and sustainability. This project surveyed California transit agencies on their microtransit services to identify challenges to integrating them with fixed-route services. An agent-based model combining the two modes of transit was developed to evaluate different operational designs. FleetPy, an open-source simulation tool, modeled microtransit dynamics. The study examined design impacts, such as fixed route headways and microtransit fleet size, in downtown San Diego and Lemon Grove, California. Results showed that while microtransit reduces fixed-route ridership and requires higher subsidies, it significantly boosts job accessibility.

17. Key Words	18. Distribution Statement
Public transit, Microtransit, Demand responsive transportation, Transit operating agencies, Travel demand, Ridership, Operating subsidies, Accessibility	No restrictions.

19.Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	64	N/A

Form Dot F 1700.7 (8-72) Reproduction of completed page authorized

About the UC Institute of Transportation Studies

The University of California Institute of Transportation Studies (UC ITS) is a network of faculty, research and administrative staff, and students dedicated to advancing the state of the art in transportation engineering, planning, and policy for the people of California. Established by the Legislature in 1947, ITS has branches at UC Berkeley, UC Davis, UC Irvine, and UCLA.

The California Resilient and Innovative Mobility Initiative

The California Resilient and Innovative Mobility Initiative (RIMI) serves as a living laboratory—bringing together university experts from across the four UC ITS campuses, policymakers, public agencies, industry stakeholders, and community leaders—to inform the state transportation system's immediate COVID-19 response and recovery needs, while establishing a long-term vision and pathway for directing innovative mobility to develop sustainable and resilient transportation in California. RIMI is organized around three core research pillars: Carbon Neutral Transportation, Emerging Transportation Technology, and Public Transit and Shared Mobility. Equity and high-road jobs serve as cross-cutting themes that are integrated across the three pillars.

Acknowledgments

This study was made possible with funding received by the University of California Institute of Transportation Studies from the State of California through a one-time General Fund allocation in the 2021 State Budget Act for the Resilient and Innovative Mobility Initiative. The authors would like to thank the State of California for its support of university-based research, and especially for the funding received for this project.

Institute of Transportation Studies | UNIVERSITY OF CALIFORNIA

Job Access, Agency Cost, and VMT Impacts of Offering Microtransit Alongside Fixed-route Transit

Michael F. Hyland, Ph.D., Assistant Professor[1]
Susan Pike, Ph.D., Professional Researcher[2]
Siwei Hu, Ph.D. Candidate[1]
Jacob Julius Berkel, Undergraduate Student[1]
Yan Xing, Ph.D., Postdoctoral Researcher[2]
Ritun Saha, Ph.D. Student[1]
Geoffrey Hans Vander Veen, Undergraduate Student[1]
Dingtong Yang, Ph.D., Postdoctoral Researcher[1]

[1]Department of Civil and Environmental Engineering, University of California, Irvine
[2]Institute for Transportation Studies, University of California, Davis

April 2025

California Resilient and Innovative Mobility Initiative

Report No.: RIMI-4I | DOI: 10.7922/G2DN43DQ

Table of Contents

Table of Contents

List of Tables

List of Figures

Executive Summary

Executive Summary

Public transit ridership has been declining over the last decade in major American cities. Especially since the COVID-19 pandemic, public transit services have been struggling to attract riders. The integration of traditional fixed-route transit (FRT) and the more flexible microtransit service has been touted as a means to attract riders to public transit, improve mobility and sustainable transportation outcomes (e.g., reduce greenhouse gasses and local pollutants), and provide better accessibility to disadvantaged travelers. However, there are few successful real-world examples of, and guidelines for, integrating the two forms of transit. In this report, we define microtransit as a publicly owned shared-ride passenger mobility service with flexible vehicle routes and on-demand ride scheduling, where the vehicles are typically 6-10-person vans or small buses. This service can be integrated with fixed-route buses and rail to extend the efficiency and accessibility of transit service. Pickup/drop-off stops are often limited to designated locations, known as “virtual stops,” but microtransit can also operate as a curb-to-curb service. Ride requests and payment are typically arranged through an app.

To better understand the challenges facing transit agencies operating microtransit services and working to integrate microtransit with existing fixed-route systems, we interviewed several California transit agencies that are currently operating or recently operated microtransit programs. We also developed an agent-based simulation modeling framework to evaluate different integrated fixed-route and microtransit system designs.

Key findings from the interviews are:

- Stated goals for introducing microtransit include promoting an alternative to the private vehicle, reducing vehicle miles traveled (VMT), and complementing fixed-route transit by offering service in the off-peak hours and in areas where fixed-route transit does not operate.
- There is significant diversity in the structure of service regions and flexibility of customer pickup and drop-off locations across cities. Some cities operate microtransit in one large service region, while others have up to nine separate zones within which trips must start and end. Also, some cities offer door-to-door service to customers, while others require travelers to walk to and from virtual stops to receive microtransit service.
- Integrating microtransit and fixed-route transit remains a challenge for several agencies. While some offer fare discounts or free transfers between both services, agencies struggle to coordinate their respective schedules.
- Costs and funding sources remain a major concern among several agencies. One agency estimates that the hourly cost to operate a microtransit vehicle is $50. Another city estimates that the subsidy per microtransit ride is close to $80.

Our proposed agent- and simulation-based modeling framework captures the supply of and demand for integrated fixed-route transit and microtransit systems. The model reflects travelers’ mode and route choice behavior. Moreover, it captures the pick-up and drop-off dynamics of microtransit services in response to travelers' spatial-temporal demand patterns. The modeling framework includes a binary logit mode choice model for determining the share of auto and transit trips, where "transit" includes any of the following modes or a combination thereof: fixed-route transit, microtransit, and walking. We utilize an algorithm to determine the best transit-based path through a supernetwork with pedestrian/walking, fixed-route transit, and microtransit layers, where "best" is determined through a combination of travel time components (e.g., walking, waiting, and in-vehicle time) and monetary costs. We use FleetPy, an open-source Mobility-on-Demand (MOD) simulation tool, to model the dynamic and stochastic aspects of microtransit service[1]. This tool simulates how the fleet of microtransit vehicles would behave or operate in a real-world scenario provided a set of traveler requests for the microtransit service.

In this study, we consider four key system design parameters, namely, fixed-route headways (headway or transit frequency is the time difference between two consecutive fixed-route transit vehicle's arrival at a stop location) and microtransit fleet size, operating hours, and number/location of virtual stops. Moreover, the key performance metrics we consider include subsidy per transit trip, mode share, accessible jobs within 15 minutes, and VMT. We developed case studies for downtown San Diego and Lemon Grove, a small city in San Diego County, neither of which currently offers microtransit service.

Our results show that introducing microtransit service decreases fixed-route ridership; however, microtransit decreases auto mode share and increases destination accessibility. The increase in accessibility is particularly large in the Lemon Grove region, where most houses are not located near existing transit lines. Nevertheless, achieving these results requires significant subsidies. Our model results show that the subsidy ranges from $5 to $20 per microtransit trip and $3 to $16 per microtransit mile, depending on the microtransit fleet size and the service region. Additionally, according to our results, a small fleet size, high fixed-route service frequency, and limiting operations to the peak period improve the financial sustainability of microtransit service.

[1] FleetPy models the decisions of a fleet operator. The fleet operator needs to assign vehicles to customer requests, and sequence customer pickups and drop-offs. The customer requests arrive dynamically over the course of the day, and the operator does not have prior information about the location or timing of the requests, therefore the fleet operator is making decisions in a stochastic environment.

Contents

Introduction

Ridership on public transit has declined in the United States in the past decade (Erhardt et al. 2022; Lee and Lee 2022). We define public transit as a government-owned passenger transportation service using buses, trains, vans, etc.

Figure 1 shows public transit ridership from quarter 1 of 1990 to quarter 1 of 2023 in U.S. and Canadian cities, as collected by the American Public Transportation Association (Dickens, 2023). Bus ridership consistently declined from 2008 to 2020, while rail ridership—including heavy rail, light rail, and commuter rail—experienced a steady increase since 1995. However, public transit ridership from all modes has seen a serious decline since the COVID-19 pandemic in quarter 1 of 2020; since then, many North American public transit agencies have struggled to regain their pre-pandemic ridership. In fact, by quarter 1 of 2023, ridership had only reached 84 percent of the level seen in quarter 4 of 2019. Researchers have identified several reasons for declining transit ridership, including the rise of ride-hailing services (Erhardt et al. 2022), lower gasoline prices (Lee and Lee 2022), as well as neighborhood changes in high-density neighborhoods (Lee and Lee 2022).

Traditional transit systems that rely exclusively on fixed-route and fixed-schedule transit networks struggle to provide high-quality service to transit-dependent travelers. This is especially true for moderate- to low-population density areas where jobs, food, and shopping locations are spatially dispersed. Moreover, operating transit services in these areas is quite expensive for transit agencies (Guerra and Cervero 2011).

Unlike traditional fixed-route transit vehicles that follow a pre-defined path and schedule, microtransit provides flexible on-demand service for travelers (Hansen et al. 2021; Veve and Chiabaut 2022; Ghimire et al. 2024). In this report, we define microtransit as a government-owned shared-ride passenger mobility service with flexible vehicle routes and on-demand ride scheduling, where the vehicles are typically 6-10-person vans or small buses. Among other uses, microtransit can provide first-mile/last-mile service to those who may not be close to a transit stop. Like cabs or a Transportation Network Company (TNC) such as Uber, some microtransit offerings provide curb-to-curb service, while other microtransit offerings limit pickups and drop-offs to designated locations, known as “virtual stops.” Ride requests and payments are typically arranged through a mobile phone app, but many microtransit services also permit web-based and phone requests and payments.

Various public transit agencies in California have implemented microtransit pilot projects, including Metro Micro from the Los Angeles County Metropolitan Transportation Authority, SmaRT Ride from the Sacramento Regional Transit District, and Van Go! from the San Joaquin Regional Transit District. Public transit providers regard microtransit as a complement to traditional fixed-route service, especially in moderate- to low-density areas. Researchers argue that integrating microtransit and fixed-route systems could attract more riders to transit generally, as well as improve mobility, accessibility, and sustainability of the transportation system (Shaheen and Cohen 2019).

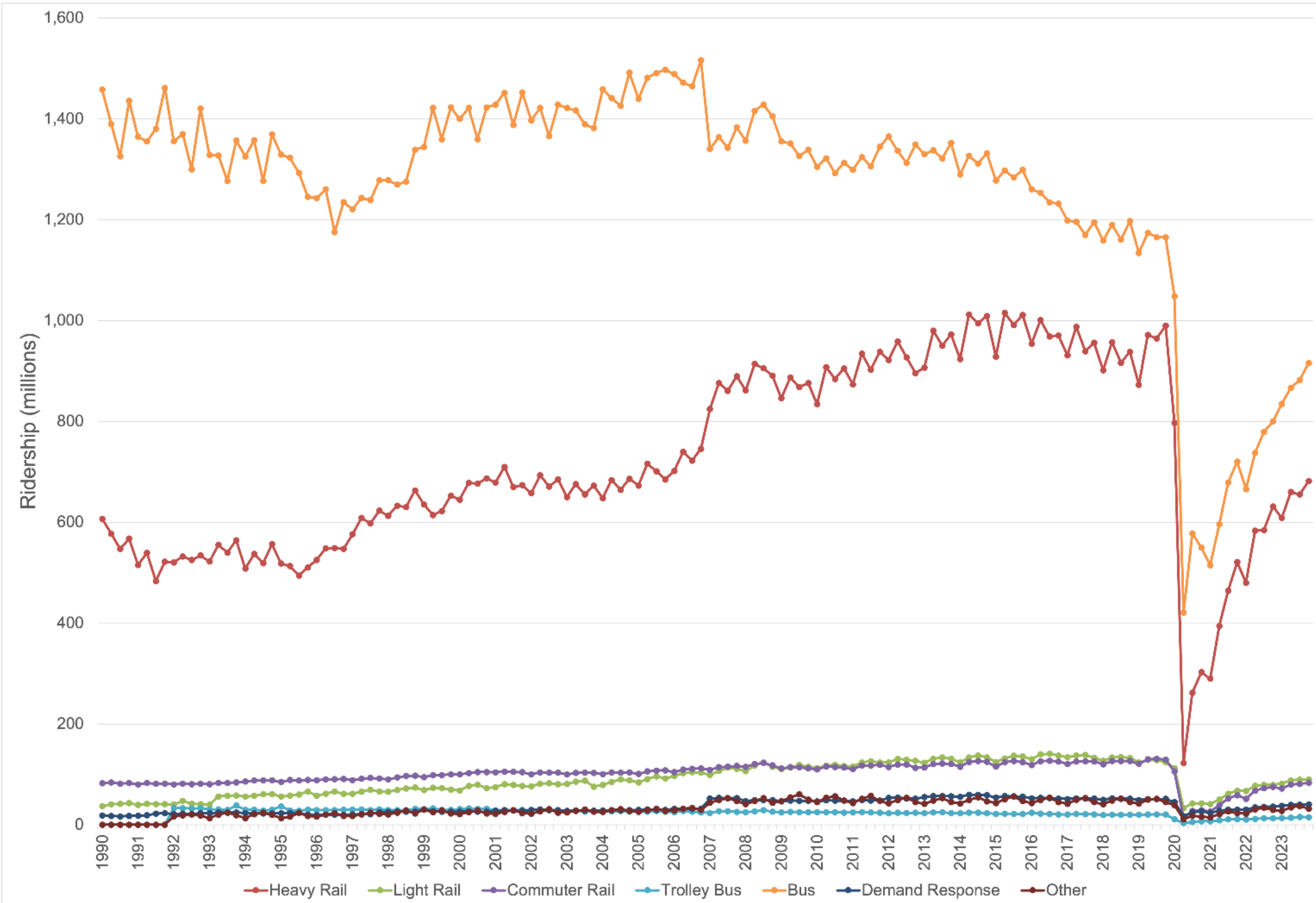


Figure 1. Trends in Ridership by Transit Mode between 1990 and 2023 in the U.S. and Canada

However, there are few successful real-world examples or helpful guidelines for integrating fixed-route transit and microtransit. To fill this research gap, we first interviewed a sample of California transit agencies that have operated microtransit programs to identify issues and challenges they faced when implementing microtransit. We evaluated whether their microtransit programs met their own goals, assessed how integrated services have evolved over time, and explored how these services can play a role in transit recovery, particularly following the COVID-19 pandemic.

With the information we gathered, we developed an integrated multi-modal fixed-route and microtransit simulation model to evaluate different network and operational designs. Provided with a set of travelers and trips they plan to complete within a pre-defined service region for a day, our model simulates how travelers behave in terms of choosing among modes and routes to complete their trips, given the key attributes of the modes and routes available. The model outputs the experiences of travelers who use the multi-modal transportation system, and we calculate key performance metrics such as accessibility to jobs, user wait times for transit modes, VMT by mode, out-of-pocket cost, total subsidy, and subsidy per transit trip. We use our model to study the impacts of different fixed route transit headways, microtransit fleet sizes, operating hours, and virtual stop[2] coverage on these key performance metrics. We focus on two subregions of San Diego: downtown San Diego and Lemon Grove, a small city in San Diego County, neither of which currently offers microtransit service. In these case study regions, we consider personal vehicles, fixed-route transit, microtransit, and walking to be modal options for travelers.

This report is structured as follows: Section 2 presents the results of our interviews with transit agencies regarding the challenges and issues related to microtransit service. Section 3 summarizes what is known about integrating fixed-route and microtransit services, describes the critical design elements used in constructing our proposed simulation model of an integrated fixed-route and microtransit system, and presents the modeling framework. Section 4 describes the metrics used to evaluate the performance of the integrated system. Section 5 describes the two case studies—downtown San Diego and Lemon Grove—neither of which currently has microtransit service, and the various scenarios that were modeled based on combinations of the critical design parameters. Section 6 displays and discusses the model results. This report concludes with a summary of the study and future research directions in Section 7.

[2] "Virtual stops" are designated locations for customers to be picked up or dropped off by microtransit vehicles.

Understanding Key Challenges Facing Transit Agencies

The decision to implement microtransit comes with several tradeoffs for any municipality, transit agency, or other entity planning to offer this service. While we know what some of these tradeoffs are, the development of microtransit is evolving quickly. New service models have emerged, and providers offer everything from backend software support to full turn-key one-stop-shop service (including user interfaces through apps, scheduling and routing software, vehicles, drivers, or any combination of these services and products). Agencies must decide whether and how much to partner with external providers. At the same time, many aspects of the service itself vary from agency to agency to best serve the needs of a particular locality or community. For example, at what times of day should microtransit operate? How many vehicles should be employed at a time? Should the system be zone-based, serve one large area, or specific corridors? The modeling component of this study informs agencies about how different decisions in the program's design relate to specific outcomes of interest, including passenger wait times, passenger boardings per hour, access to jobs, and the subsidy per user of the service.

Our research team interviewed six agencies and municipalities that have implemented or are considering implementing microtransit. The interviews were informal and generally open-ended. We were primarily interested in identifying the considerations that went into the planning and design of microtransit services and any tradeoffs between features or service structures made by agencies in that process. We also asked about which evaluation criteria were most important to transit agencies when designing microtransit. Each interviewee represents a unique area, and that is reflected in the specific tradeoffs and considerations made in their microtransit planning. Interview participants' information is kept confidential. Below, we present an overview of each interviewee's comments on a selection of considerations related to the planning and implementation of microtransit.

Goals

We began by discussing the goals of microtransit programs and the central considerations in service design. One city we spoke with stated that their objectives included promoting an alternative to private vehicles and potentially reducing VMT. Their microtransit service was implemented as a part of their climate action plan. Another program reported wanting to use a fleet with Zero Emission Vehicles (ZEVs). Another city reported they have some climate and electrification goals, and they currently use hybrids but are trying to go to ZEVs. Unfortunately, the design they want is not yet on the market in the United States. Over time, they want to maintain the image of being a smaller and faster service than buses, as well as one that can pass through neighborhoods more easily.

Another interviewee highlighted the goal of having an alternative to driving. They wanted to be innovative in their community when they began considering microtransit. They also hoped to provide service during off-peak hours. The bus network in their area serves employment hubs and has limited service on evenings and weekends. Microtransit could fill the remaining service gaps.

Another city told us that one of their goals when they launched their microtransit service was to have all riders picked up within 15 to 20 minutes from the time a ride was requested. That was their main metric of success.

A transit agency we spoke with said they had a local competitive grant, which dictated the direction of their program. According to the grant terms, specific zones throughout the region were identified for investment, and as such, the budget from the grant was set aside to serve those specific areas. These zones drew resources away from some other zones that needed more resources, given their current demand levels.

Another city we spoke with reported that they wanted to launch a microtransit service because the area's fixed-route services were more focused on intercity trips and not based in their locality.

One agency had "a really different form of microtransit," one that serves a small rural community about 10 miles away from a small town. "It is not so much a stopgap or first/last mile service as it is providing a service to communities where there may not be a fixed route option." In this case, they considered the conditions under which microtransit serves transportation needs in and of itself versus connecting to or integrating with traditional transit service. The agency previously operated a lifeline service. The interviewee noted that people "needed better access to mobility, but also [there was] not the demand to warrant service. There weren't enough people to make the big bus efficient," especially given the small size of the communities. Now, the agency offers microtransit six days a week, and it runs eight hours a day with solid ridership.

Some of the services were designed to include specific communities or locations where it would be especially beneficial. For example, one provider noted, "we have a little area that is outside of [another small town] that is very connected to [that small town]. The housing authority out there—they have a strong tie to [the small town]—and when we had the local service, there was a stop in that little area that helped connect that community to [that small town] and the amenities that are there." As a result, the microtransit service also connects the small area with nearby affordable housing.

One interviewee reported tradeoffs in terms of wait times: "we may set a 10- or 30-minute wait time; [the riders] don't want to see a 10-minute trip take 75 minutes." The agency suggested 1.5 times the trip length as a standard.

A Regional Transportation District we spoke with discussed objectives, including addressing the needs of marginalized communities in their county. They pointed out that providing a demand-responsive transit alternative could address gaps in transit coverage in unincorporated areas. They also commented that sometimes microtransit is implemented with the goal of innovation for innovation's sake.

Coverage Design, Stops, and Zones

Microtransit may operate within a specified region, provide transport between specific locations or areas, cover an entire community, or serve a designated corridor. All these models are present among our interviewees. In this section, we present their perspectives on the coverage of each microtransit service.

One system has operation zones because there are very few destinations in the gaps between them. They function as two endpoints, but "people are using the service similarly to how they were using the fixed route service before; they took it in and had two or three trips within [the larger town] in the day. We are seeing how the microtransit service is not just a commute between the two places but gives them more access…they can get to medical [treatment]." This county also offers another service between a second small town, and all trips must start or end in that town, or the riders would be able to take the service quite far away on other, long intercity trips that would make the vehicle unavailable for other riders.

One expanding service has been point-to-point, but they will begin expanding their area and incorporating unscheduled stops into the new areas, starting with all their transit stops. Another service has had virtual stops throughout most service zones, and these are set by a third-party provider whose algorithm supports the service (though everything else is done in-house).

A city we spoke with started microtransit as a curb-to-curb service that could go anywhere within the city limits. They considered designating zones but decided against that option. It is not being seriously considered going forward.

The system that uses zones started with two since they could not offer full coverage at the beginning. However, as they developed more zones, the decision of which streets to include and where the boundaries should be drawn was very subjective. They also knew that some potential boundaries would be unacceptable to the community, so they had to guarantee certain areas would be covered. They also had plans at the outset for how many vehicles there would be, which then affected the size of a reasonable service area for each zone. "Part of the day there will be one bus—it can't cover something 10 miles long, like 50 square miles." The available resources have had a serious influence on the size of service zones.

One large transit agency we spoke with discussed the difficulty of designing the service around destinations like a university or a mall, which attract a lot of riders but few who are residents of the area. "Also, the number of employees [there] does not necessarily reflect the number of riders that the destination attracts. This is the same for transit stations—no one lives there, there are no jobs, and yet many people arrive. You can add hotspots to the models, but it is an assumed outcome that you are then entering in…and getting feedback on." This agency was pointing out how some existing models are not helpful if they require so many inputs or assumptions that you don't get a lot of new information as an output. This interviewee suggested that they may be doing it backward regarding what the models might do. They start with a budget, or the resources more generally, and an idea of the boundaries and service hours. It is then a guess-and-check approach with the zone design to see what the wait times are going to be and how many riders there will be per hour.

The large transit agency we interviewed noted that they prefer virtual stops. This helps prevent drivers from going deep into neighborhoods. It seems to improve travel times, and they noted that the one curb-to-curb zone takes up more labor resources. The software they use automates the identification of virtual stops; they have about 3000 to 4000 pins in each 15-square-mile zone. Typically, there are four pins at an intersection, with some exceptions. The software provider can semi-curate the positions before assignment, i.e., remove points where a vehicle cannot physically do so, or doing so would be unsafe. The agency can also edit points as they see fit. They note that some edits are worth doing: “the automated thing will do it right in the intersection, not right in the middle; on a corner, but 10-15 feet from a crosswalk, but you can go in there and see 100 feet from the crosswalk there is a bus bench, a pad, and a safe place for a bus to turn out rather than 10 feet from a crosswalk on a 40-mph intersection.” They also noted that not all bus stops are good places for microtransit to pick up or drop off passengers since they don't want smaller vehicles waiting and getting in the way of a large bus that needs to access the stop.

Other notable points about establishing zone boundaries included one provider making sure to include a hospital in one zone and others including areas that are low density or that have low transit demand. Most microtransit services also aim to make sure each zone contains a variety of destinations, such as community colleges or commercial spaces, since a purely residential zone would not help people connect to places they need to go. Other considerations included whether there are safe crossings or good streets for people to wait on or, “would the bus be coming down a farm road to pick them up – is this any safer?”

Relation to Fixed Route Transit

One of our interviewees discussed how they see a public preference for microtransit service, but that just may be because of cuts to fixed-route service made during the COVID pandemic and not necessarily reflect a real preference for microtransit.

During some interviews, interviewees talked about how microtransit is helpful since it can serve areas “off the main drag” or where it is not safe or convenient to operate a 40-foot bus, not only due to the area’s density but also because of tighter corridors.

Another example of microtransit’s strengths is in the smaller communities covered by the service. Often, these places do not have good sidewalks and thus may not have good pathways connecting to traditional transit. It can be difficult to find a place to put an Americans with Disabilities Act (ADA)-accessible bus route.

One of our interviewees talked about timing microtransit service operations so they would be coordinated with the fixed-route service; the ability to do this informed which vendor they would select. This would mean that some microtransit trips that access fixed-route buses would be timed and prioritized based on when a bus leaves; however, they did say they are waiting to see how it works. They also noted, “I see this service as an important component of mass transit, and we should remember we are mass transit.”

One city we spoke with said their microtransit service's hours of operation were extended over time so that the service now runs until 11 pm. Though they did not explicitly talk about how this relates to fixed-route transit, the later operating hours allow riders to access a form of transit when other services are less frequent. They pointed out how this helps people with alternative work schedules. This city does not operate the bus system in their area, and they don't coordinate with it beyond offering a free transfer for microtransit riders. There are ongoing talks about achieving better integration, including developing an app integrating the two services. They are still using the initial transfers they received in 2018 and 2022 from the bus provider. They have tried to promote the service at different times, but it is not used often. There are calls from "customers that they keep getting [told] rides [are] unavailable. I can't tell if they are frequent rider, and now that ridership is getting to an all-time high—you are getting that sometimes and that makes you upset…"

One transit agency reported that they are concerned with fiscal considerations related to the number of transfers and whether they compete with or cannibalize fixed-route ridership. They also noted that the considerations for microtransit's relationship to fixed-route transit were subjective—they did want to feed the traditional bus service—but this came into conflict with concerns about better coverage. There were several cases where the microtransit service area overlaps, in one case completely, with the bus service. However, microtransit serves shorter trips within the zones, and if it does not overlap with fixed-route service areas, some places will have inadequate or difficult-to-access service. They pointed out that "although that zone is almost 100 percent overlapped or redundant with the fixed route, every corner of that zone and many sectors in the middle of it have areas where the walking distance to the fixed route stop is more than a 1/3 mile, or more than a half mile." And they went on to say, "there are seniors here that need it, or a low-income neighborhood here; show me where you could cut it and almost any place you would cut it, I can say there is a use case there that we can legitimately say there is a user that has poor access to fixed route." In the downtown area, the overlap of microtransit and traditional bus service is partly due to the public image that they have both bus and microtransit. Bus coverage varies widely between different zones. This example suggests that there are some cases where the traditional and demand-responsive transit can operate in the same area at the same time without directly competing nor explicitly providing first/last mile connections. I.e., the two services each serve particular travel needs within the same area.

In some areas, the fixed routes do not provide direct access to specific places, or they require a transfer. Offering microtransit service removes the transfer and provides direct access to key locations. In the case of the RTD, none of the fixed routes were changed in any way based on the demand-responsive transit. They did offer discount transfers, but they were not well utilized. This topic was not explicitly covered in the other interviews, though we do not expect that any of the other providers changed their fixed-route services in order to enable microtransit. Similarly, no interviewees talked about replacing fixed-route services with microtransit.

Relation to Paratransit

Some interviewees discussed how microtransit relates to paratransit, though, by and large, it was not seen as a service that would replace paratransit. One transit agency pointed out that the real comparison is between microtransit and paratransit rather than fixed-route transit. However, the service areas are different; paratransit goes everywhere, with average trip lengths of about eight miles versus two to three miles for microtransit. The Regional Transit District we spoke with uses the same app for microtransit and paratransit.

Demand and Use

Important considerations for agencies and municipalities planning or operating microtransit services include who will use it and how frequently it will be used. We spoke with our interviewees about the demand for their service, how it is used, and what groups are using it.

The service connecting smaller communities to a larger town told us:

> We haven't run into a demand issue. And [the small community] is 700 to 800 person population and because of the way the service is, I have found basically you have the community members in [the small community], the person who is the breadwinner there uses the vehicle to go to a job and so basically what happens is you are cutting a really small population in half right off the bat, so I don't think we've really run into an issue with demand being a problem. In this community, passengers clump in the morning going out and, in the evening, coming back.... Some use the service throughout the day.

For this service, there is no issue with people being able to get rides, and they aim to be in the range of two to five or six riders per hour. However, there are tradeoffs between the vehicle capacity and the level of demand that can be served, the comfort of the ride, and wheelchair accessibility.

One interviewee told us they do not serve commute trips since they operate only eight hours per day. Most people use it for services unavailable in the small community, such as medical visits and grocery shopping. Microtransit services that have earlier start times and/or later ending times can serve commute trips.

One city offers microtransit in one small, disadvantaged area that serves about 4,000 free rides per month. It started with funds from the air district and was linked to a community recreation center. Now, they can get people anywhere for free, assuming a ride starts or ends in that zone.

A transit agency interviewee spoke about the lack of demographic information about users. The provider's app does collect a small amount of information from users, primarily from credit cards entered into the system. Other interviewees did not raise this issue, though without conducting surveys of riders, it is difficult to collect very detailed information about who is using the service.

One city said they may reevaluate their fares since the service is highly utilized, and the fare revenue is one funding source. They may be able to increase fares but maintain ridership, thereby covering a larger share of the costs through fare revenue. They meet 90-95 percent of their ride requests. However, as they were still coming out of the pandemic at the time of the interview, it was hard to estimate ridership. They do take into account "annual considerations like when does school start…or the holidays… We know from past years we might take a couple of vehicles off the road." This city has used zones to evaluate use from a geographic perspective.

The RTD reported they have about 1.5 passengers per vehicle-hour—which makes sense since they serve more rural areas, which have lower demand. They note that right-sizing the fleet is the "key to future success." Unfortunately, people often expect the service to imitate Uber, and so they complain. At the same time, though, they do not want the service to be taken away.

Costs and Funding

Interviewees were concerned with costs and the funding sources for the microtransit programs. Some are still operating as pilot programs or with renewed special funding sources. All the interviewees talked about the challenge of balancing the need for more vehicles, which incurs much higher costs, and the ability to meet demand.

One city we spoke with reported that microtransit is included within the city budget. One agency reported that their fixed routes cost about $45 an hour to run, and microtransit is $50 or $52 (for two different areas). The costs are comparable because drivers, insurance, and maintenance costs are not based on the bus size.

Another city reported that it was one of the first to implement microtransit, so there was not a lot of information on how to design the service. This also means they did not have much information in terms of costs and service. They went through a lot to try to make something work within specific funding requirements that may not apply to the private companies they could partner with. They also noted that there is a lot of flexibility that comes with using the provider for everything since they are a large organization with better resources. They don't have to wait two to six months if they want to switch to lower-emission vehicle options. It also makes maintenance more flexible.

A transit agency we spoke with had done a rough budget; they had a total of $1-2 million per year and were planning to spend a few hundred thousand per zone. They decided to start with a couple of zones and then roll out additional zones over time. Passengers book a ride through an app, but then the payment is made directly to the transit agency through already available means: passes, cash, etc. The regular fare is the same as that of the bus service, as are discounted fares.

The RTD we spoke with had an initial three-year pilot program, and they are subsidizing rides at $80 to $85 per trip. This is higher than others, but they have lower ridership and fares of $4 for the first five miles and $0.50 after that, which is much higher than many other microtransit operations. The interviewee did not discuss why their costs are so high, though it could be particular to the vendor they work with or the types of trips they serve. We note that the trips they serve tend to have longer distances and times, and this limits the number of trips/passengers per hour.

Vehicles and Employees

Another consideration when implementing microtransit is what types of vehicles to use and what employment arrangements to have with drivers. One city we spoke with is considering microtransit and looking at the current transit services as a starting point to determine what microtransit employment strategy would make the most sense for the community.

In another area, drivers/operators are all essentially shift workers, and the service operates like a TNC, such as Uber. In another location, employees are hired through a third-party contractor but are paid the same as those for the fixed-route service, and still others are transit agency employees.

One city's provider was responsible for everything. They also pointed out that since the provider works like a TNC, they are not allowed to own their own vehicles, so they have a third-party fleet service that provides the vehicles through a lease. In this case, the provider also employs the drivers, and the city pays a fee, but the provider does the hiring and background checks. They use smaller vehicles, such as hybrids, that seat five passengers and keep the front seat next to the driver empty. The wheelchair-accessible vehicles have less room, though.

Learning and Sharing

We asked our interviewees if they spoke with others as they designed and implemented their microtransit service. One city noted that they spoke with their county and the county transit service.

One city we spoke with pointed out how they had heard the rates that are paid to drivers. They noted the challenges that arise from keeping fares low and figuring out how to make it sustainable. A city we spoke with was one of the first in the country to offer microtransit, so they didn't have data from other locations available to help in their planning. A transit agency we spoke to told us they spoke to microtransit service providers in Antioch, CA, which mainly offers connections to BART, who indicated they average only about seven boardings per hour, but that is because they operate in a very small area, just a few square miles.

Tools and Models

One city explored expanding its service's footprint, but that is always a challenge. For instance, while new large developments often include bus stops, it isn't always clear how to connect them to microtransit. The city is also considering some projects that will have no parking and how microtransit will benefit those kinds of developments.

One transit agency reported that the available software required too much information to make any predictions that they prefer not to use the software.

When we asked one representative if there were performance metrics the transit agency would want to see, they replied:

> I'd be happy with ridership and wait times. For me those are the biggies. Like when I got the...tool for me it was like is this realistic? Can I reproduce what we're doing today? I have known boundaries and known resources—let's program that in and see what it says ridership will be? If you can't reproduce today, then you know, you can't do anything. And yeah, it is always like a tug of war—resources, riders and wait times and everything after that is like second order.

Considering the interviews, the key metrics that stand out as important include the passenger wait times, the ability to meet demand, and the costs of the service. Our interviewees also consistently noted that they see microtransit as a service that improves access to key locations that might be otherwise inaccessible or unduly difficult for particular use-cases (elderly, disabled, etc.). The interviews conducted as part of this study were not designed to identify best practices overall but rather to uncover tradeoffs and any quantifiable goals that microtransit providers are aiming for, largely to inform part 2 of this study, the simulation modeling.

Methodology

In this section, we present the proposed integrated fixed-route and microtransit modeling framework. Our proposed model captures the supply and demand equilibration in an integrated fixed-route transit and microtransit system. On the one hand, it reflects travelers' mode and route choice behavior. On the other hand, it captures the pick-up and drop-off dynamics of microtransit services in response to travelers' spatial-temporal demand patterns.

Before presenting the model, we first state key problem assumptions, state the underlying problem we are addressing, and discuss the microtransit and fixed-route transit design variables that we analyzed in this study. The next section presents the key performance metrics that we use to evaluate alternative integrated fixed-route transit and microtransit system designs.

Assumptions

In this study, we have made the following assumptions:

1. Following Vansteenwegen et al. (2022)'s taxonomy, we model a microtransit service that is a dynamic-online, many-to-many, fully-flexible, and stop-based service. Dynamic-online means the schedule of the microtransit service can change dynamically during operation according to requests received in real-time. Many-to-many means that passengers can be picked up and dropped off at multiple locations, unlike the many-to-one feeder systems where all travelers share a common destination. Fully-flexible means schedules and routes of microtransit services are determined from scratch without any pre-determined patterns. Stop-based means passengers must walk to virtual stops to be picked up and dropped off.
2. Arrivals of fixed-route transit users at transit stops follow a uniform distribution. As a result, the waiting times of fixed-route transit users are half of the route headways. We do not aim to model coordination between fixed-route transit and microtransit, as we view this as an operational-level problem rather than a design-level problem.
3. Fixed-route transit, auto, and walking networks and network attributes are assumed to be constant, i.e., the level of service of these three modes is independent of the number of travelers using them.
4. Conversely, the microtransit network depends on the spatial and temporal demand for microtransit.
5. All modes are available to all travelers.
6. For travelers, the transit modes and auto mode are independent, i.e., there is no integrated path between auto and transit. This assumption precludes park-and-ride and kiss-and-ride options.

The microtransit system is not necessarily intended to feed travelers to the fixed-route system. Travelers are free to choose only one or more than one mode to travel between their respective origins and destinations.

Problem Statement

The problem we are trying to solve is defined as follows:

Given:

- a fixed set of travelers with specific origins, destinations, departure times, and individual attributes
- a multi-modal network with walking, fixed-route transit, microtransit, and auto modes, which are available to all travelers
- system design inputs - fleet size, virtual stop coverage, microtransit operating hours, fixed-route transit headways, etc.

Determine the mode and (potentially multi-modal) path choice for each traveler, as well as the performance of the microtransit service. Given the mode and path for each traveler, as well as the performance of the microtransit service, we can calculate a wide range of performance metrics, including the subsidy per transit user, employment accessibility, VMT, and mode share.

Microtransit and Fixed-route Transit Design Parameters

This study aims to analyze the impact of four microtransit and fixed-route transit design parameters on traveler experiences and the performance of the transportation system. The four parameters include: 1) fleet size, 2) virtual stop coverage, 3) operating hours for microtransit, and 4) fixed-route headway.

Modeling Framework

Figure 2 gives an overview of our modeling framework. The modeling framework takes design parameters (i.e., fleet size, virtual stop coverage, operating hours for microtransit, and fixed-route headways) as inputs and outputs the mode share (and performance metrics) at mode choice equilibrium under various design parameter combinations. The modeling framework consists of two main components: a supply module and a demand module.

The supply module is shown at the bottom of Figure 2, consisting of two different networks for two modes: transit mode and auto mode. The transit mode is modeled using a transit supernetwork with microtransit, fixed route transit, and walking network layers, as well as connecting links between those layers, representing the waiting times for microtransit and fixed-route services. We consider the link travel time for walking, fixed-route, and auto modes to be constant. Similarly, the waiting time for fixed-route transit is fixed for individual lines based on the headway design parameter. However, we assume that the link travel time and waiting time for microtransit vary as a function of the spatial and temporal distribution of microtransit demand.

The demand module is shown at the top of Figure 2, which consists of a generalized cost calculation part that takes the modal performance metrics as inputs to calculate the generalized cost for the transit mode and the auto mode. The demand module also includes a binary logit mode choice model, which takes the generalized costs from the previous part to calculate the mode choice probability of travelers. The demand module outputs the sets of travelers for the transit mode (fixed-route, microtransit, and walking) and the auto mode.

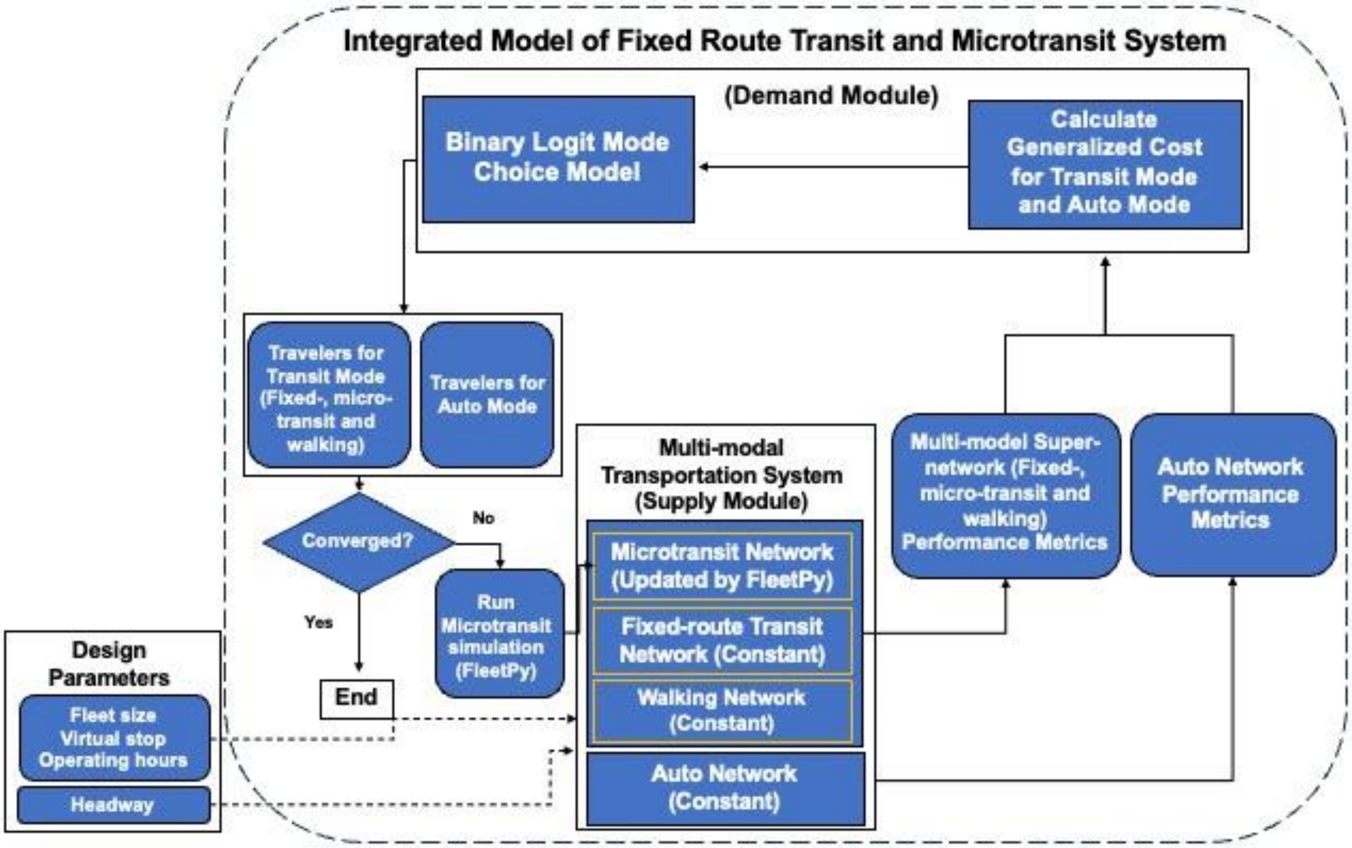


Figure 2. Overview of integrated fixed-route transit and microtransit modeling framework

After the demand module outputs the travelers for the transit and auto modes, the integrated system checks the convergence to determine whether the mode choice equilibrium is reached. If the system has not yet converged, we run FleetPy again to simulate microtransit service and compute microtransit performance metrics. The system will use microtransit users' waiting time and in-vehicle travel time to update the microtransit waiting and driving links in the transit supernetwork. Once the model converges, it outputs the experiences of each user and the microtransit system performance.

We present the technical specifications of the demand module, supply module, and convergence criteria in the Appendix.

Evaluating System Performance

This section describes the performance metrics we use to evaluate integrated fixed-route transit and microtransit system designs. In addition to the metrics presented below, we also calculate and record extensive information about traveler experiences and the performance of the microtransit service. For example, like prior research, we calculate and store travelers' waiting time (Pinto et al. 2020; Bertsimas, Ng, and Yan 2020) and the number of rejected requests[3] (Pinto et al. 2020).

Performance Metrics

Operating Cost

The operating cost includes both fixed-route transit and microtransit, although we can separate the costs of each individual service. Using publicly available information, we make cost component assumptions for (i) hourly labor cost for one fixed-route driver, (ii) hourly labor cost for one microtransit driver, (iii) per-mile fixed-route fuel costs, and (iv) per-mile microtransit fuel costs. Given these cost components and the number of microtransit and fixed-route transit vehicles and operating hours, as well as miles driven by each vehicle type, we can calculate the operating cost for the entire integrated microtransit and fixed-route transit system.

Revenue

Revenue is the fare ($) collected from the passengers. For fixed-route transit, the revenue is generated from the $2.5 flat transit fare, which aligns with the transit fare in the San Diego area. The revenue in the microtransit service comes from the microtransit fare, which is assumed to be $1.97/mile in this study.

Subsidy per Rider

When the microtransit service has higher operating costs than revenue, the service is not profitable and needs a subsidy to operate. The subsidy is defined as the difference between operating costs and revenues.

Mode Share

Mode share for a particular mode is the percentage of travelers choosing said mode among all other modes.

[3] Travelers request microtransit rides through a mobile phone app, web app, or phone call. The microtransit operator tries to assign this request to a microtransit vehicle. If it is not possible for the operator to match the request to a vehicle within a pre-specified wait time, then the request is rejected. These are called rejected requests.

Accessibility

In this study, we use the number of jobs travelers can visit within 15 minutes in the transit supernetwork (i.e., not including auto mode) as the measure of accessibility.

Vehicle Miles Travelled

Vehicle miles traveled (VMT) is the total distance traveled by all the vehicles. We differentiate VMT by mode as well.

Transit Line Usage

Transit line usage is defined as the total number of people using that line during the study period.

Case Study Network Models and Scenarios

This section describes the model transportation networks constructed for San Diego and Lemon Grove and the different scenarios that we created to evaluate the impact of adding microtransit service.

Transportation Networks

Figure 3 displays the downtown San Diego multi-modal network with auto network and transit supernetwork. The red lines represent the fixed-route transit routes, and the yellow lines represent roads. We use graphical representations (i.e., nodes and links) to model the fixed route transit network, microtransit network, and walking network. The links in these three separate networks represent the travel time required to travel from one node to the next. We connect these networks using links representing the wait time for microtransit vehicles and fixed-route transit vehicles, essentially implementing the transfer from one mode to the other. This combined graphical representation is called a supernetwork. The transit supernetwork includes walking, microtransit, and fixed-route transit layers. The walking layer is based on the auto network, assuming a walking speed of 2.8 miles/hr. To transport a traveler between their origin and destination locations via microtransit often involves a detour to pickup or drop-off other travelers. To create link travel times in the microtransit layer, we multiply the auto travel times by a detour ratio, which is the ratio of simulated travel time or distance in FleetPy and the shortest path auto travel time. Therefore, walking, microtransit, and auto networks are three separate networks that all have the same topology but different speeds and travel times. The downtown San Diego fixed route transit network has 20 transit lines (including bus and rail), 162 nodes, and 320 directed links.

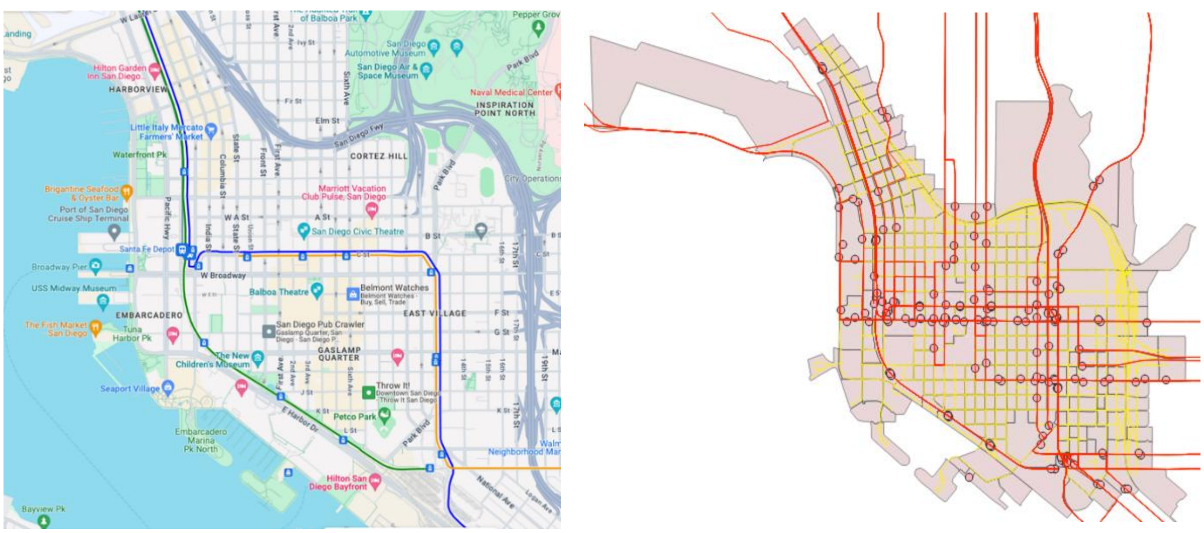


Figure 3. The Multi-modal Network of Downtown San Diego

Figure 4 illustrates the city of Lemon Grove's multi-modal network with auto network and transit network. The auto network has 1,099 nodes and 2,816 directed links. The transit network has six transit lines, 74 nodes, and 130 directed links.

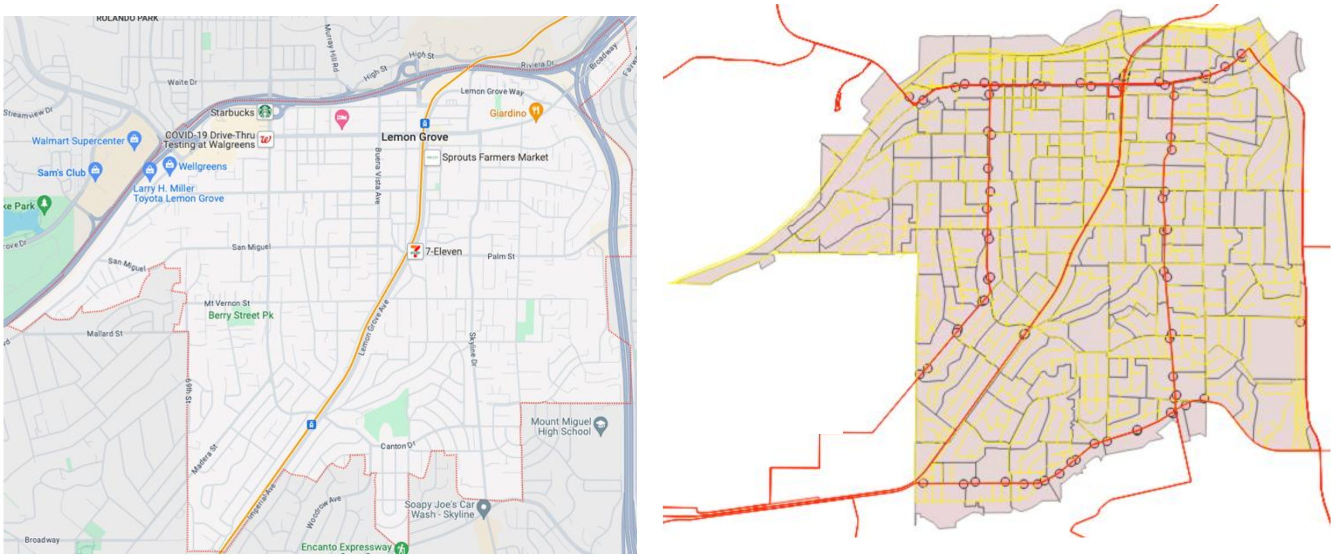


Figure 4. The Multi-modal Network of Downtown Lemon Grove

The auto network is obtained from the San Diego Association of Governments (SANDAG) GIS portal, while the transit network is obtained from the General Transit Feed Specification (GTSF) dataset. A sample of the supernetwork with all the link types is shown in Table 1.

Table 1. Supply input: a sample of the Supernetwork's attributes

From node	To node	Distance (meter)	Travel time (sec)	Link type
698	3	8.69	5.43	0 (walking)
3	698	8.69	5.43	0 (walking)
782	734	283.99	21.17	1 (fixed-route transit)
734	782	283.99	21.17	1 (fixed-route transit)
294	782	0	1800	2 (fixed-route transit waiting)
782	294	0	0	2 (fixed-route transit waiting)
1570	875	8.69	0.77	4 (microtransit)
875	1570	8.69	0.77	4 (microtransit)
698	1570	0	180	5 (microtransit waiting)
1570	698	0	0	5 (microtransit waiting)

Demand Data

To determine the number of trips generated during a typical day in each study area, we used travel demand data from ActivitySim,[4] an open-source activity-based travel demand modeling platform. ActivitySim estimates travel demand for a typical workday. There are 46,241 trips across an average day from 5 am to 11:59 pm in downtown San Diego and 21,074 trips for the city of Lemon Grove. Figure 5 illustrates the hourly number of trips for downtown San Diego and Lemon Grove. Since the earliest trip departs at 5 am in ActivitySim, the x axis in Figure 5 starts at 5 am.

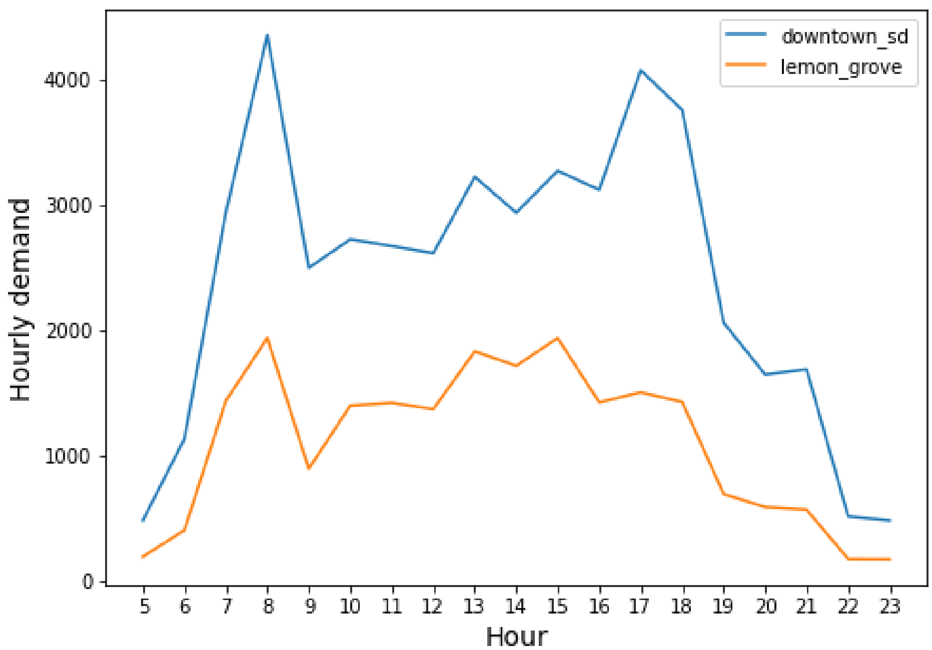


Figure 5. Travel Demand Patterns for downtown San Diego and city of Lemon Grove by Hour

[4] https://activitysim.github.io

Figure 6 shows the spatial distribution of trip origins for downtown San Diego and the Lemon Grove networks.

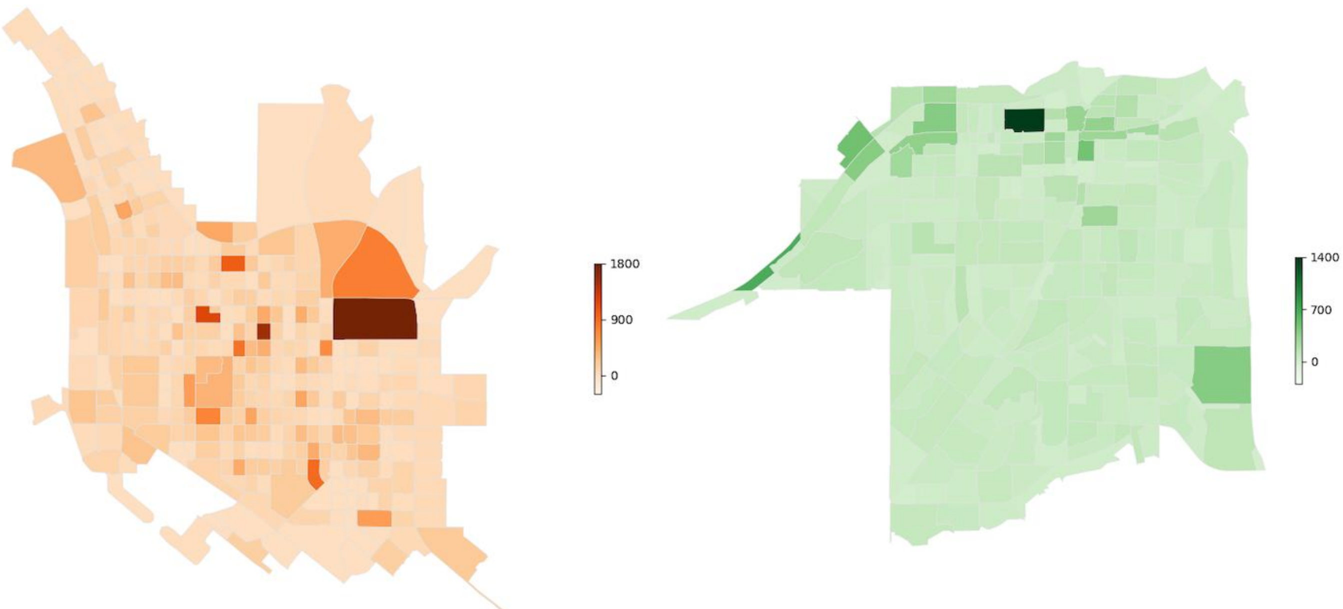


Figure 6. Travel Demand Patterns (Number of Originating Trips) for downtown San Diego and city of Lemon Grove by MGRA (Master Geographic Reference Areas)

Scenarios

As mentioned previously, we analyze four design parameters for both downtown San Diego and Lemon Grove. Below are the design parameters and the design parameter values we consider.

- Fixed route headways (15 and 30 mins)
- Virtual stops (75% virtual stops coverage and 100% virtual stops coverage)
- Fleet size (10, 15, and 20 vehicles)
- Operating periods
    - AM (5-10am) & PM (3-8pm) (operating hours: 10hr)
    - AM (5-10am), MD (10am-3pm), PM (3-8pm) (operating hours: 15hr)

For virtual stop coverage, we analyzed two scenarios, 75 percent and 100 percent. A 75 percent virtual stop coverage means that 75 percent of walking nodes are selected as virtual stops for passenger pickups and drop-offs for microtransit service, while 100 percent virtual stop coverage means microtransit could pick up or drop off passengers from all walking nodes.

As shown in Table 2, we ran 12 microtransit-only scenarios with different combinations of virtual stop coverage and fleet sizes. In addition, we also ran two fixed-route-only scenarios (headway 15 minutes and 30 minutes) and

24 scenarios with both microtransit and fixed route service under different combinations of the four parameters described above. We ran 38 scenarios in total.

We assume the fixed route transit flat fare is $2.5 and the microtransit distance-based fare is $1.97.

Table 2. Testing scenarios

Scenario ID	Transit Mode	headway (min)	Virtual stop (%)	Fleet size	Operating Periods
1	Micro only	0	75	10	['AM', 'PM']
2	Micro only	0	75	10	['AM', 'MD', 'PM']
3	Micro only	0	75	15	['AM', 'PM']
4	Micro only	0	75	15	['AM', 'MD', 'PM']
5	Micro only	0	75	20	['AM', 'PM']
6	Micro only	0	75	20	['AM', 'MD', 'PM']
7	Micro only	0	100	10	['AM', 'PM']
8	Micro only	0	100	10	['AM', 'MD', 'PM']
9	Micro only	0	100	15	['AM', 'PM']
10	Micro only	0	100	15	['AM', 'MD', 'PM']
11	Micro only	0	100	20	['AM', 'PM']
12	Micro only	0	100	20	['AM', 'MD', 'PM']
13	Fixed only	15	0	0	0
14	Micro+Fixed	15	75	10	['AM', 'PM']
15	Micro+Fixed	15	75	10	['AM', 'MD', 'PM']
16	Micro+Fixed	15	75	15	['AM', 'PM']
17	Micro+Fixed	15	75	15	['AM', 'MD', 'PM']
18	Micro+Fixed	15	75	20	['AM', 'PM']
19	Micro+Fixed	15	75	20	['AM', 'MD', 'PM']
20	Micro+Fixed	15	100	10	['AM', 'PM']
21	Micro+Fixed	15	100	10	['AM', 'MD', 'PM']
22	Micro+Fixed	15	100	15	['AM', 'PM']
23	Micro+Fixed	15	100	15	['AM', 'MD', 'PM']
24	Micro+Fixed	15	100	20	['AM', 'PM']
25	Micro+Fixed	15	100	20	['AM', 'MD', 'PM']
26	Fixed only	30	0	0	0
27	Micro+Fixed	30	75	10	['AM', 'PM']
28	Micro+Fixed	30	75	10	['AM', 'MD', 'PM']
29	Micro+Fixed	30	75	15	['AM', 'PM']
30	Micro+Fixed	30	75	15	['AM', 'MD', 'PM']

Scenario ID	Transit Mode	headway (min)	Virtual stop (%)	Fleet size	Operating Periods
31	Micro+Fixed	30	75	20	['AM', 'PM']
32	Micro+Fixed	30	75	20	['AM', 'MD', 'PM']
33	Micro+Fixed	30	100	10	['AM', 'PM']
34	Micro+Fixed	30	100	10	['AM', 'MD', 'PM']
35	Micro+Fixed	30	100	15	['AM', 'PM']
36	Micro+Fixed	30	100	15	['AM', 'MD', 'PM']
37	Micro+Fixed	30	100	20	['AM', 'PM']
38	Micro+Fixed	30	100	20	['AM', 'MD', 'PM']

Modelling Results

In this section, we describe the results of our simulations. We examine the system impacts by varying our four design parameters: microtransit fleet size, virtual stop density and operating hours, and fixed-route headways.

Impact of Microtransit Fleet Size

Figure 7 illustrates the impact of fleet size and transit frequency on performance metrics in downtown San Diego, while Figure 8 illustrates their impacts in Lemon Grove. Figure 7(a) and Figure 8(a) show that as fleet sizes increase, the required transit subsidy per transit user increases, which means that the cost of adding microtransit vehicles outweighs the expected total revenue. Transit subsidy per transit user is a ratio of the total subsidy (cost-revenue) for both fixed-route and microtransit services and the total number of person trips that include fixed route or microtransit.

Figure 7(a) shows that for downtown San Diego, when the transit agency opens its microtransit service (fleet size greater than zero), the 15-minute transit headway has the lowest transit subsidy per user compared with no fixed route transit and 30-minute transit headway. For downtown San Diego, when there is no microtransit service, the subsidy per user for a 30-minute transit headway is negative, which means the fixed route service has a net profit. This surprising finding stems from the small service region and the fact that we only consider the operating costs in the downtown San Diego region. Conversely, in Lemon Grove, fixed-route transit service without microtransit requires a large subsidy. Note that Lemon Grove needs a higher transit subsidy per user than downtown San Diego because Lemon Grove has fewer users, generating less revenue.

Figure 7(b) and Figure 8(b) show a similar trend, with the number of accessible jobs within 15 minutes increasing as the microtransit fleet sizes increase. We use the number of accessible jobs within 15 minutes in the transit supernetwork (walking, fixed-route transit, and microtransit) as a metric for accessibility. When there is no microtransit service (fleet size = 0 veh), downtown San Diego has relatively high accessibility because it has a convenient fixed-route transit network with high coverage. Hence, while adding microtransit does increase accessibility in downtown San Diego, the impact is not dramatic. Conversely, as Lemon Grove has very low accessibility in the no-microtransit case, Lemon Grove's accessibility triples with a microtransit service.

Figure 7(c) and Figure 8(c) show a similar trend: as the microtransit fleet size increases, microtransit mode share increases, while the mode shares for fixed-route, walking, and auto decrease. Microtransit mode share in Lemon Grove ranges from 6 to 12 percent in different testing scenarios, while the microtransit mode share in downtown San Diego ranges from 3 to 9 percent. This difference implies that microtransit service might be more popular in low transit coverage areas than in high transit coverage areas.

Figure 7(d) and Figure 8(d) show a similar trend: as the vehicle fleet sizes increase, the total vehicle miles traveled (VMT) remains at the same level while auto VMT decreases. This finding implies that microtransit is unlikely to decrease total VMT despite decreasing auto VMT. Hence, the environmental sustainability benefits of microtransit are limited or non-existent in our two case study regions.

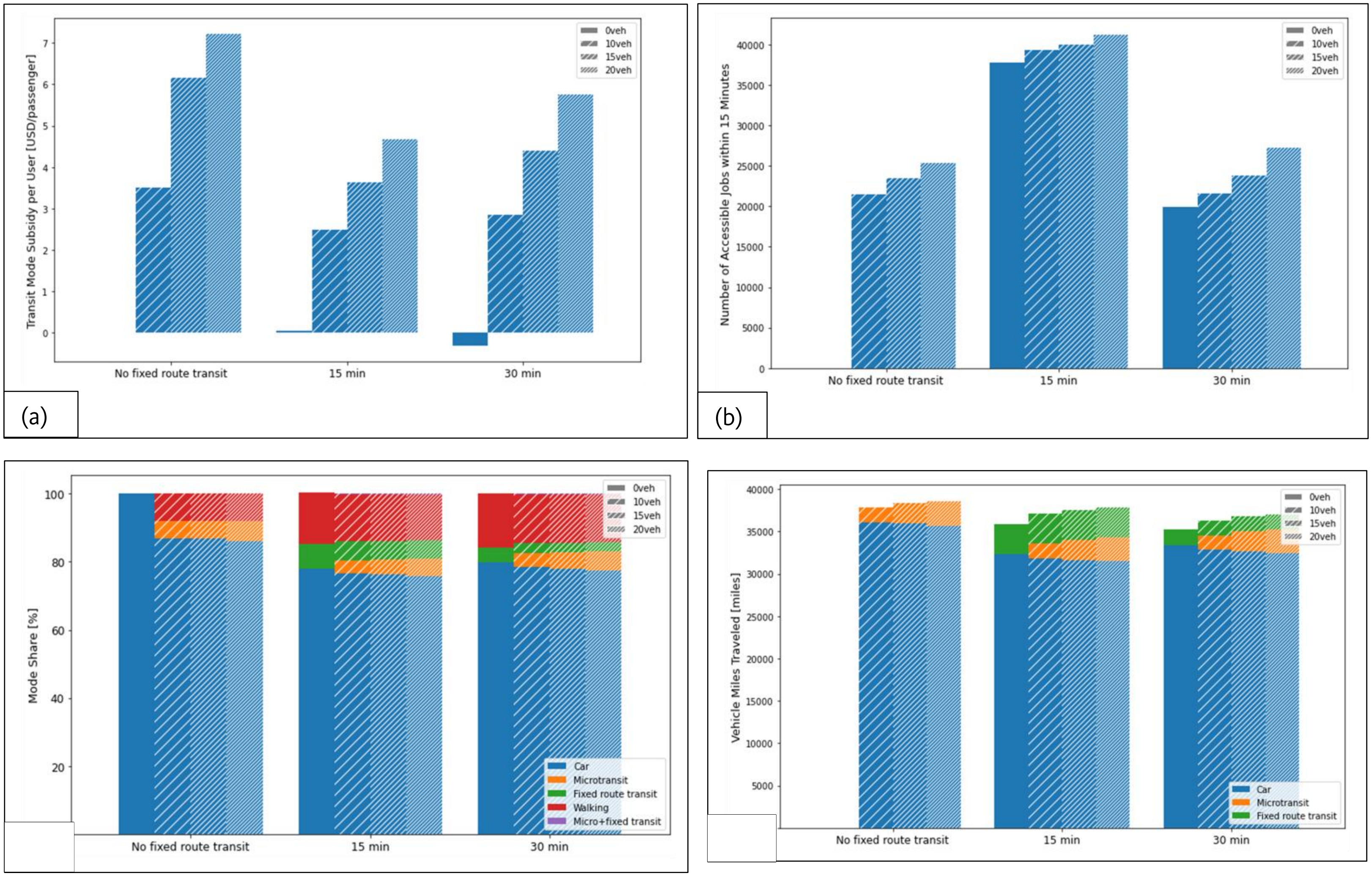


Figure 7. Impacts of different fleet size and transit frequencies for downtown San Diego network
(virtual stop=75%, operating period=[“AM”,”PM”])

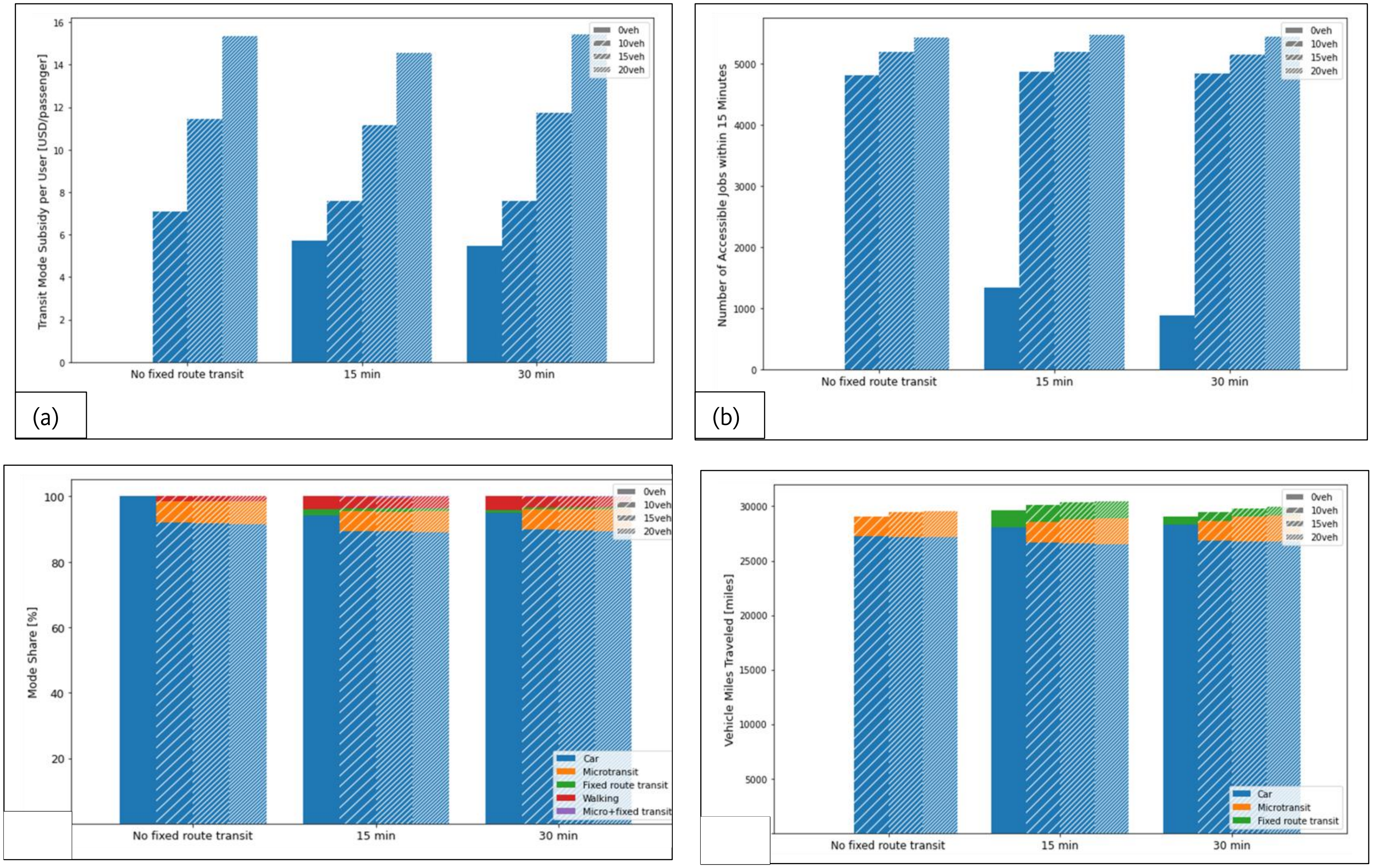


Figure 8. Impacts of different fleet size and transit frequencies for Lemon Grove network
(virtual stop=75%, operating period=[“AM”,”PM”])

Impacts of Microtransit Virtual Stop Density

Figure 9 illustrates the impacts of different virtual stops and transit frequencies for downtown San Diego, while Figure 10 illustrates their impacts for Lemon Grove.

Figure 9(a) and Figure 10(a) show that as coverage of virtual stops increases from 75 percent to 100 percent of network nodes, transit mode subsidy per user decreases in both downtown San Diego and Lemon Grove. The reason is that increasing virtual stop coverage does not increase operating costs, but it does increase ridership and, therefore, revenue from microtransit services. The increase in microtransit ridership stems from the decrease in the required walking distance between microtransit users' trip origin and their pickup location.

Figure 9(b) and Figure 10(b) show virtual stop coverage does not have a significant impact on job accessibility in the downtown San Diego network. Conversely, increasing virtual stop coverage does increase accessibility in the Lemon Grove network, where transit coverage is low.

Figure 9(c) and Figure 10(c) show that as virtual stop coverage increases, the microtransit mode share will increase, with the impact being bigger in Lemon Grove.

Figure 9(d) and Figure 10(d) show that increasing virtual stop coverage will lead to a small increase in microtransit VMT, but it does not necessarily increase the total VMT of all modes.

While this project provides an important first-order analysis of virtual stop coverage's impact on key performance metrics, the research methodology has room for improvement. First, and foremost, the network graph for microtransit vehicles does not incorporate turn penalties. As such, some of the primary benefits of limiting virtual stops to key corridors in the real-world are not reflected in our study. Second, we randomly select nodes in the 75% virtual stop coverage case rather than strategically determining optimal virtual stop locations based on spatial demand patterns.

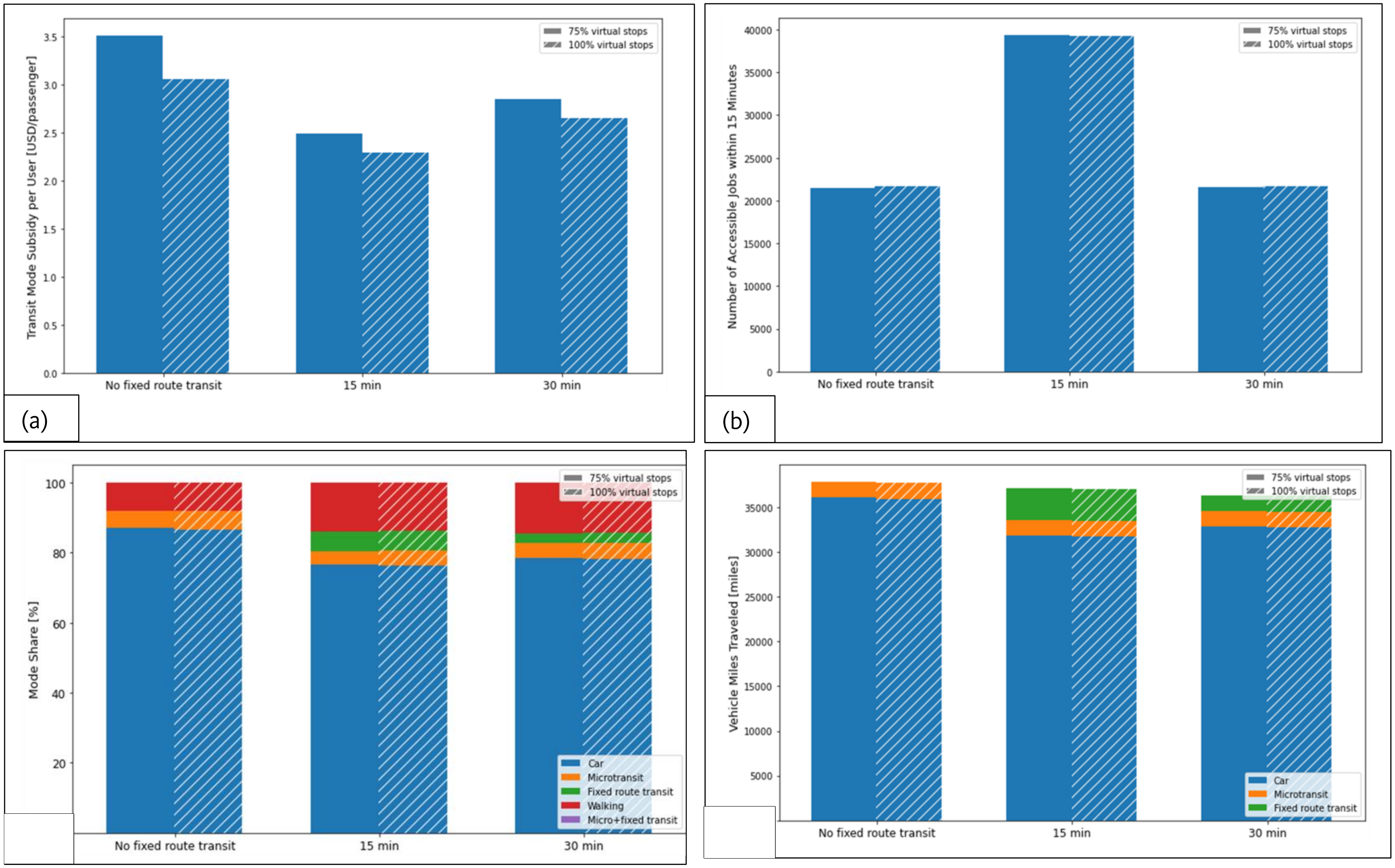


Figure 9. Impacts of different virtual stop and transit frequencies for downtown San Diego network
(fleet size=10 veh, operating period=["AM","PM"])

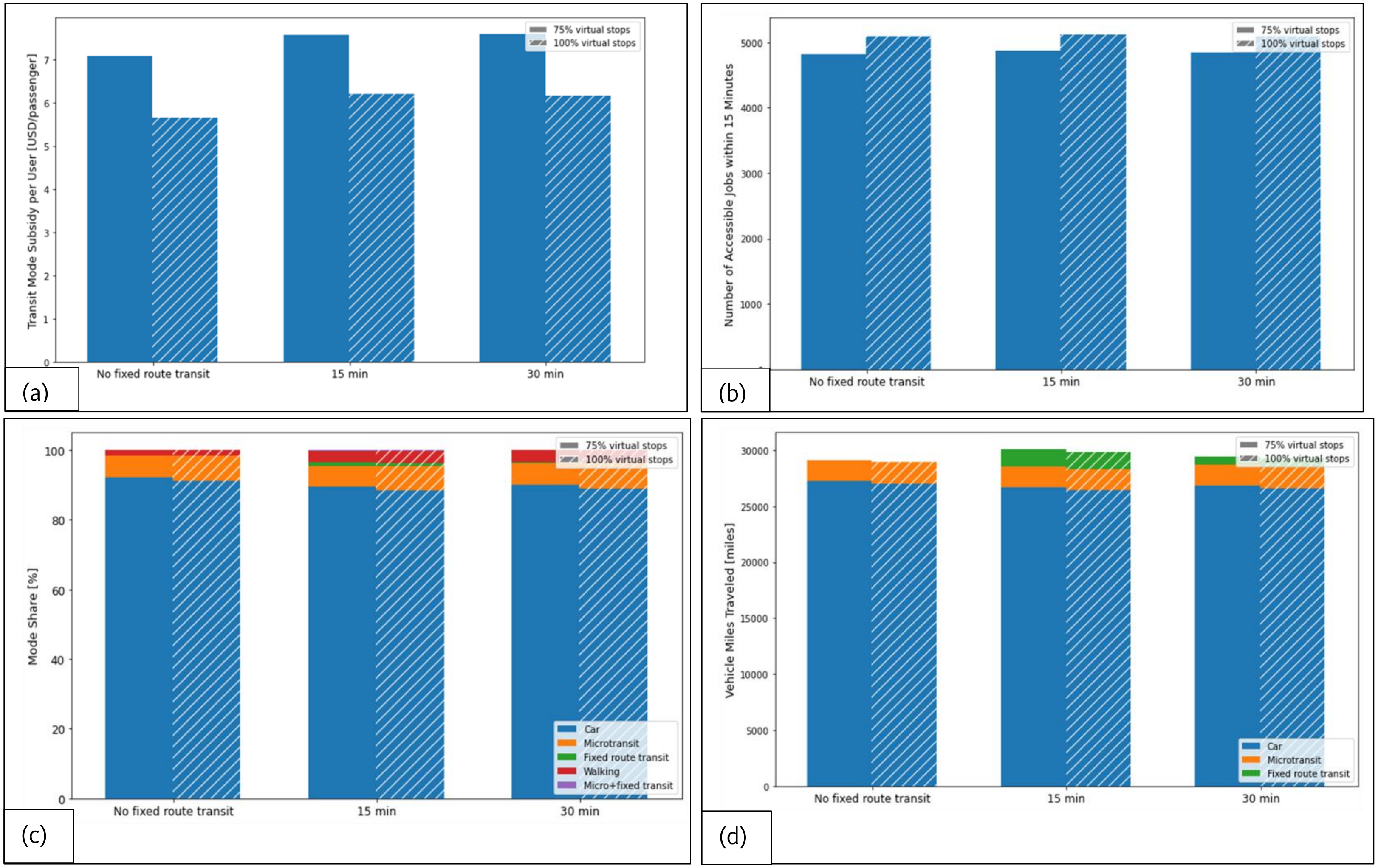


Figure 10. Impacts of different virtual stops and transit frequencies for Lemon Grove network
(fleet size=10 veh, operating period=[“AM”,”PM”])

Impacts of Microtransit Operating Hours

Figure 11 illustrates the impacts of different microtransit operating periods and transit frequencies for downtown San Diego, while Figure 12 illustrates their impacts for Lemon Grove. Figure 11(a) shows that as operating periods increase from [AM, PM] (10 hours) to [AM, MD, PM] (15 hours), transit subsidy per transit user increases in downtown San Diego. However, Figure 12(a) shows a different trend in that the same increase in operating periods leads to a decrease in subsidy per user in Lemon Grove. The difference implies that in high transit coverage areas like downtown San Diego, it would require less subsidy per user for shorter periods (e.g., only during the morning and evening peak periods), while for low transit coverage areas, it would require more subsidy per user for shorter periods.

Figure 11(c) and Figure 12(c) show that as operating periods increase, the mode share for microtransit increases in both downtown San Diego and Lemon Grove, but Lemon Grove has a higher increase. Unsurprisingly, as the operating periods increase, the mode share for fixed-route transit decreases. For microtransit-only scenarios, increasing operating periods will increase the walking mode share because some auto users will shift to microtransit, which includes walking to the stop, and thus, the walking mode share increases.

Figure 11(d) and Figure 12(d) show that as operating periods increase, microtransit VMT will increase. Moreover, total VMT slightly decreases as operating periods increase under microtransit-only scenarios. However, consistent with the analysis of prior design parameters, operating periods do not have a big impact on total VMT and environmental sustainability.

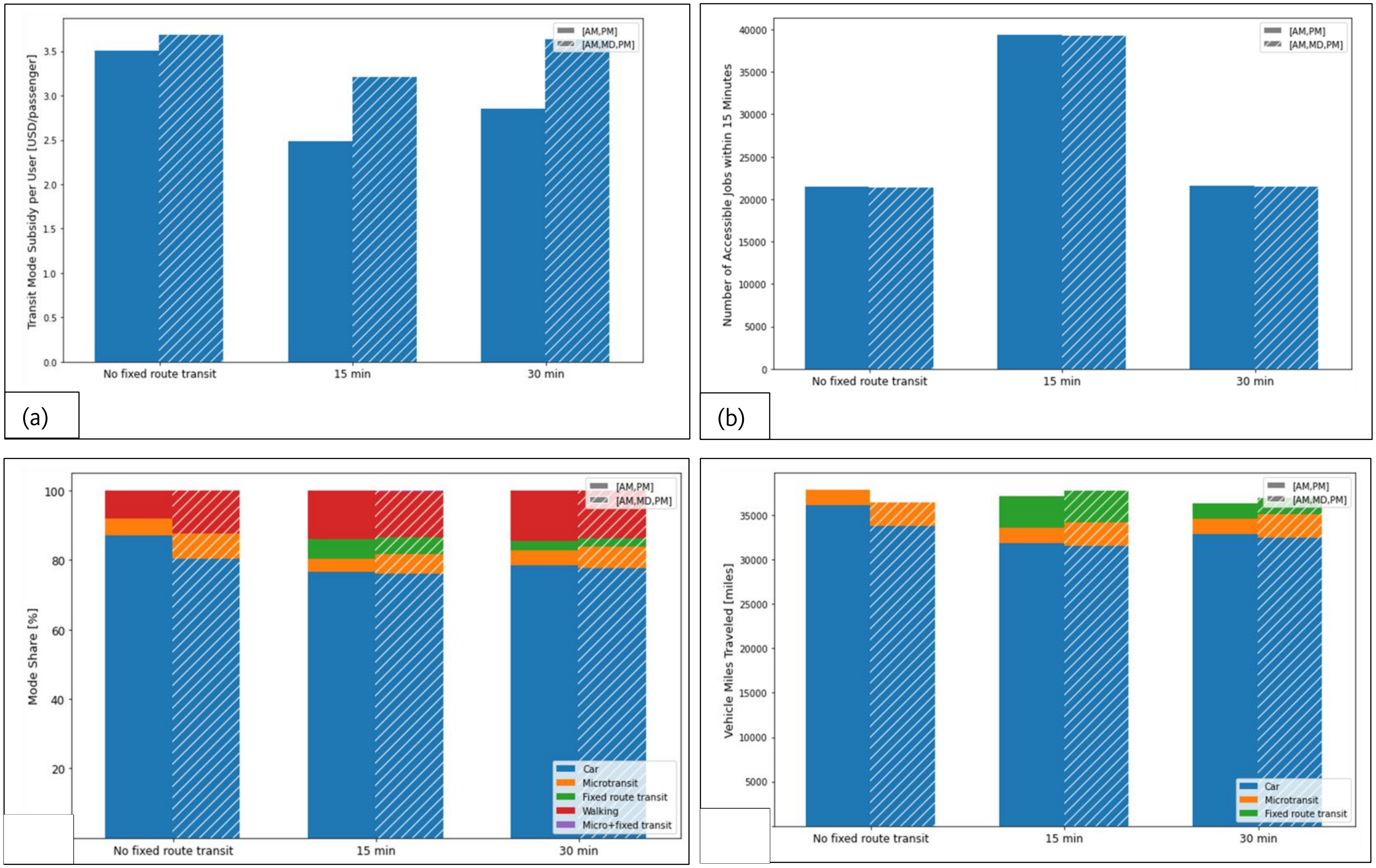


Figure 11. Impacts of different operating periods and transit frequencies for downtown San Diego network
(virtual stop=75%, fleet size=10 vehicles)

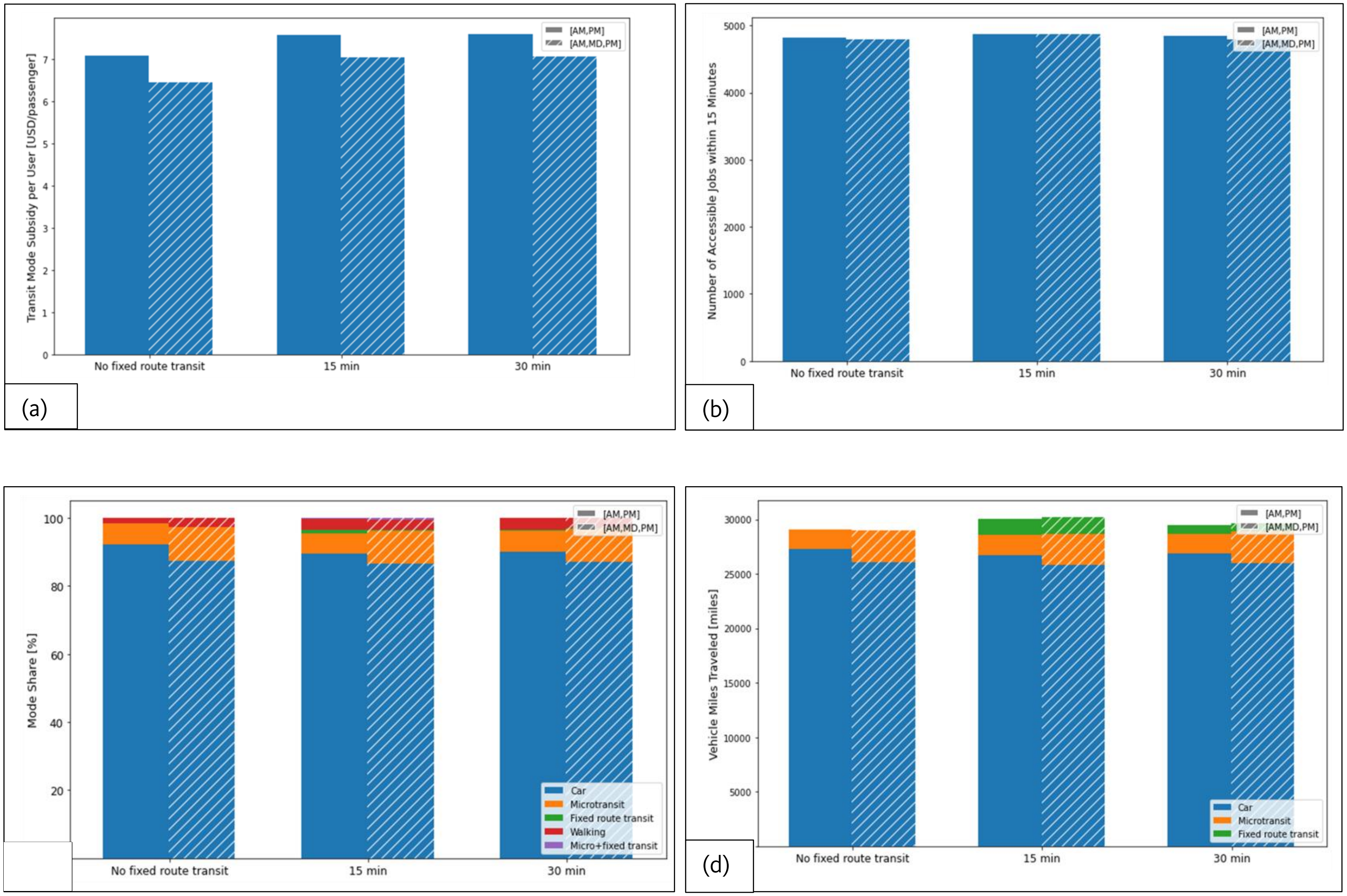


Figure 12. Impacts of different operating periods and transit frequencies for Lemon Grove network
(virtual stop=75%, fleet size=10 vehicles)

Spatial Analysis of Job Accessibility Impacts

Figure 13 shows the number of jobs that can be reached within 15 minutes for travelers originating from each zone for San Diego. These zones are called master geographic reference areas, or MGRAs; they are similar in size to census blocks. The upper panel, Figure 13 (a) and Figure 13 (b), show the number of accessible jobs for the fixed-route-only scenario under 15-minute and 30-minute headway scenarios, respectively. As expected, shorter headways produce increases in job accessibility. Comparing the upper panel with the lower panel where microtransit operates alongside fixed-route transit (Figure 13 (c) and Figure 13 (d)), the results indicate that adding microtransit service increases job accessibility in the region, particularly in outlying areas.

Figure 13 parallels Figure 14, except Figure 14 focuses on Lemon Grove. The main difference between the two figures is that in Lemon Grove, adding microtransit service alongside fixed-route service dramatically increases job accessibility.

Figure 13. Job accessibility within 15 minutes for downtown San Diego
(fleet size: 10 vehicle, operating period: [AM, PM], virtual stop: 75%)

Travel Distance by Mode

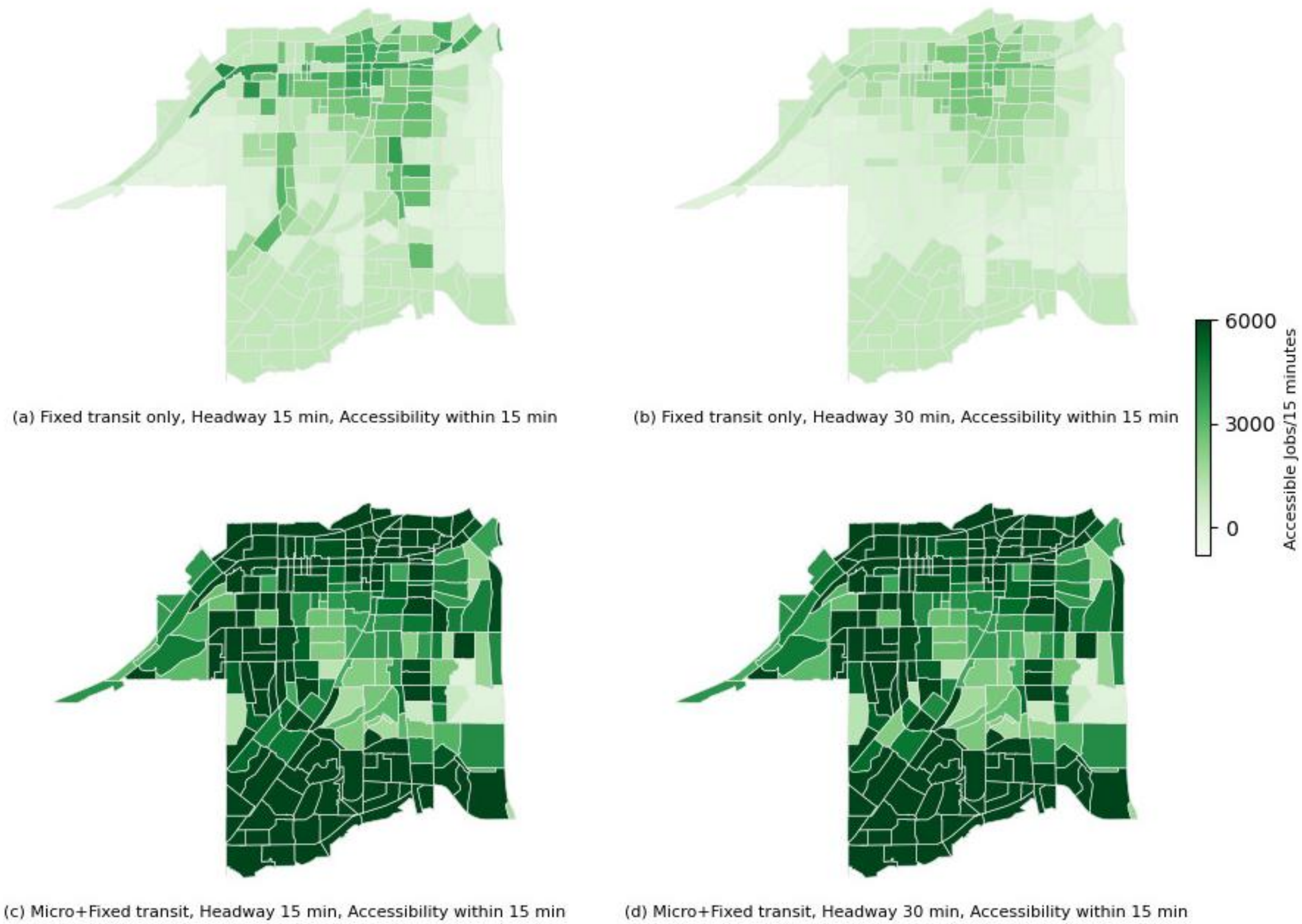


Figure 14. Job accessibility within 15 minutes for Lemon Grove
(fleet size: 10 vehicles, operating period: [AM, PM], virtual stop: 75%)

Figure 15 shows the individual travel distance distribution by mode for downtown San Diego (left) and Lemon Grove (right). The blue bins represent the distribution of travelers' total travel distance from their origins to their destinations. The orange, green, red, and purple bins represent the trip length distribution for car, microtransit, walking, and fixed-route modes. For the downtown San Diego network, 95 percent of trips have distances ranging from 0 to 1.84 miles, while for the Lemon Grove network, 95 percent of the trips have distances ranging from 0 to 2.67 miles. It shows that the Lemon Grove area is geographically larger than downtown San Diego.

For both car and micro-transit modes, Lemon Grove has a higher mode share than downtown San Diego. For walking, the trip length for downtown San Diego ranges from 0 to 0.5 miles, while for the Lemon Grove network, the walking trip length distribution is skewed towards 0. The mode share for fixed-route transit in downtown San Diego is small, while Lemon Grove only has very few fixed-route transit trips due to its low coverage. Walking could serve short-distance trips (average trip length 0.53 miles in San Diego and 0.56 miles in Lemon Grove). Microtransit could serve short-to-middle distance trips (average trip length 0.79 miles in San Diego and 1.14 miles in Lemon Grove), while fixed-route transit could serve middle-distance trips (average trip length 0.94 miles in San Diego and 1.22 miles in Lemon Grove). However, the automobile could serve trips of all distances.

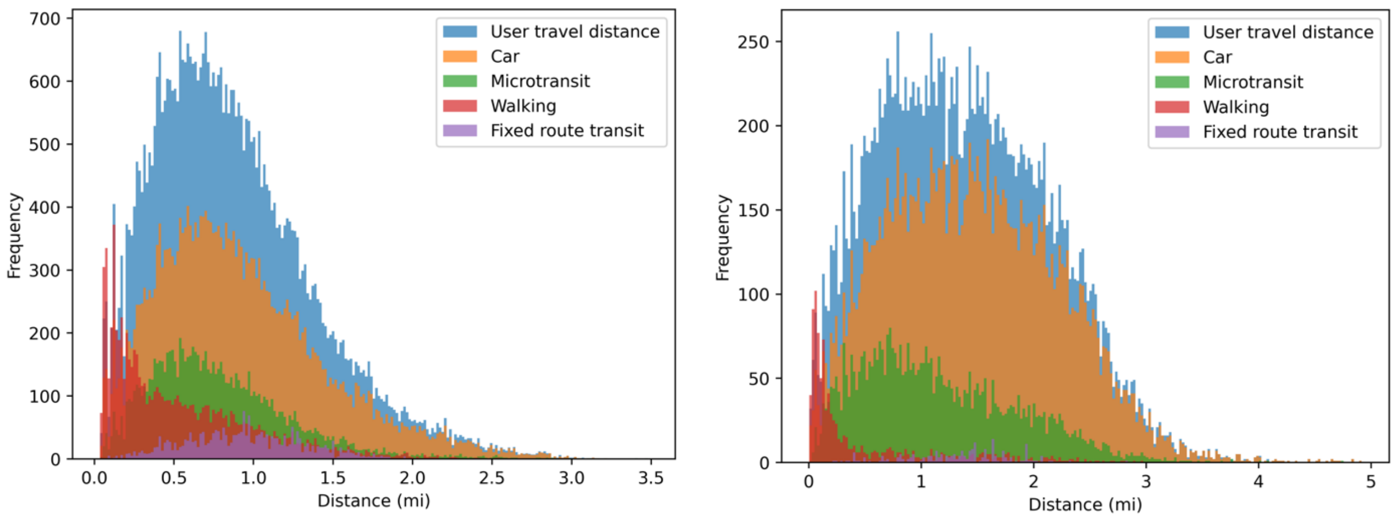
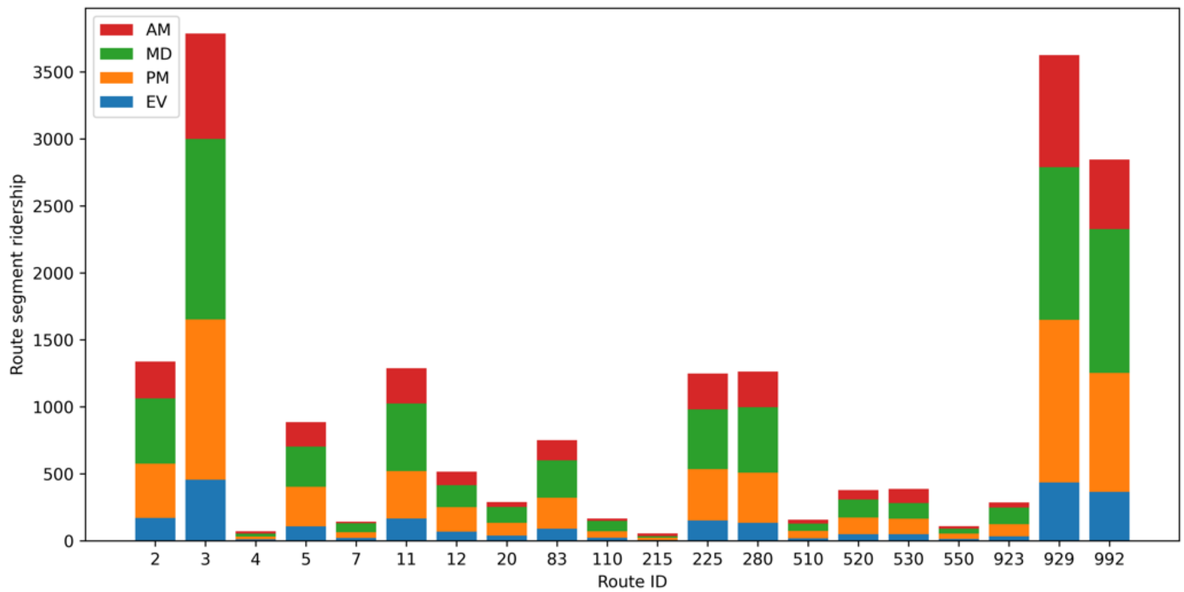


Figure 15: Individual travel distance by mode for downtown San Diego (left) and Lemon Grove (right) (fleet size=10 veh, operating hour=15h, headway=15min, virtual stop=100%)

Transit Line Usage

Figure 16 shows the transit line usage of downtown San Diego (upper) and Lemon Grove (lower) for scenario 13 (headway = 15 minutes, virtual stop =75%, fleet size = 10 vehicles, operating period = [AM, PM]). Each transit link's usage is calculated first as the number of travelers using that transit link. Transit link usages aggregated by route ID are shown in Figure 17. In terms of time of day, the midday (MD) period (orange bins) has a large share of link usage because microtransit doesn't operate in the MD period. As a result, travelers are more likely to use fixed-route transit during the MD period. In the downtown San Diego region, route 4, route 215, and route 550 have lower transit ridership, which means these routes are unproductive routes. In the Lemon Grove region, route 520 and route 4 have lower transit ridership. Therefore, the proposed model is useful in identifying transit line usage and identifying unproductive lines, which could inform system planning.



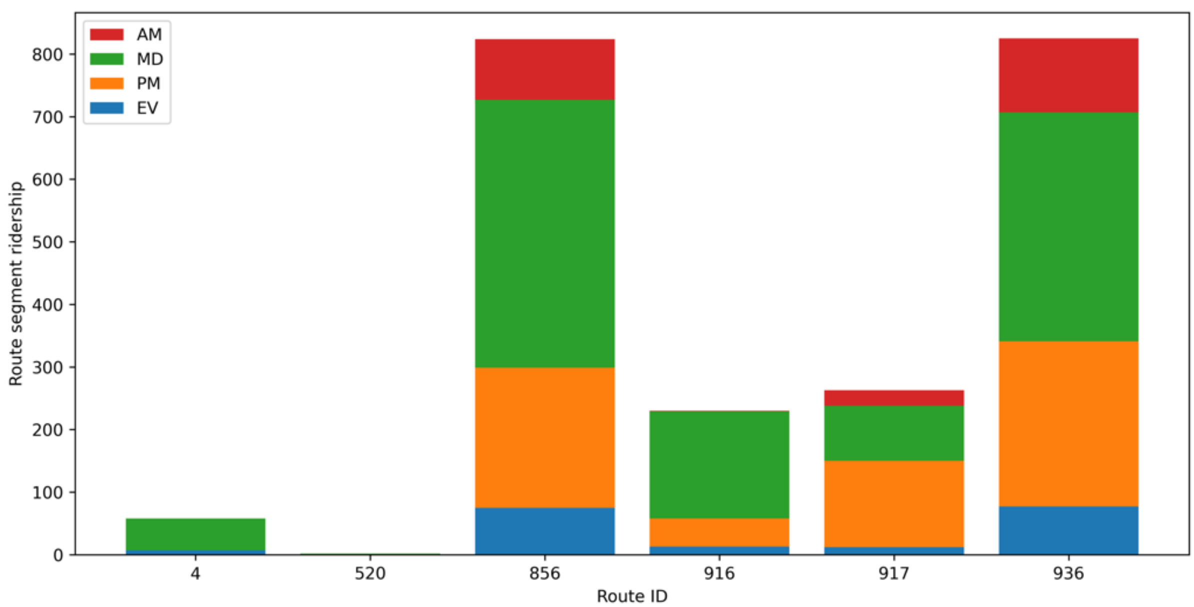


Figure 16. Transit line usage classified by route ID for downtown San Diego (upper) and Lemon Grove (lower) (scenario 13)

Figure 17 illustrates simulated transit line usage in downtown San Diego (upper) and Lemon Grove (lower). The transit links in the center of downtown San Diego are heavily used, while the transit links in the northern, eastern, and western parts of Lemon Grove are heavily used. The transit links in downtown San Diego are thicker than those in Lemon Grove because downtown San Diego to illustrate it has much higher ridership than Lemon Grove.

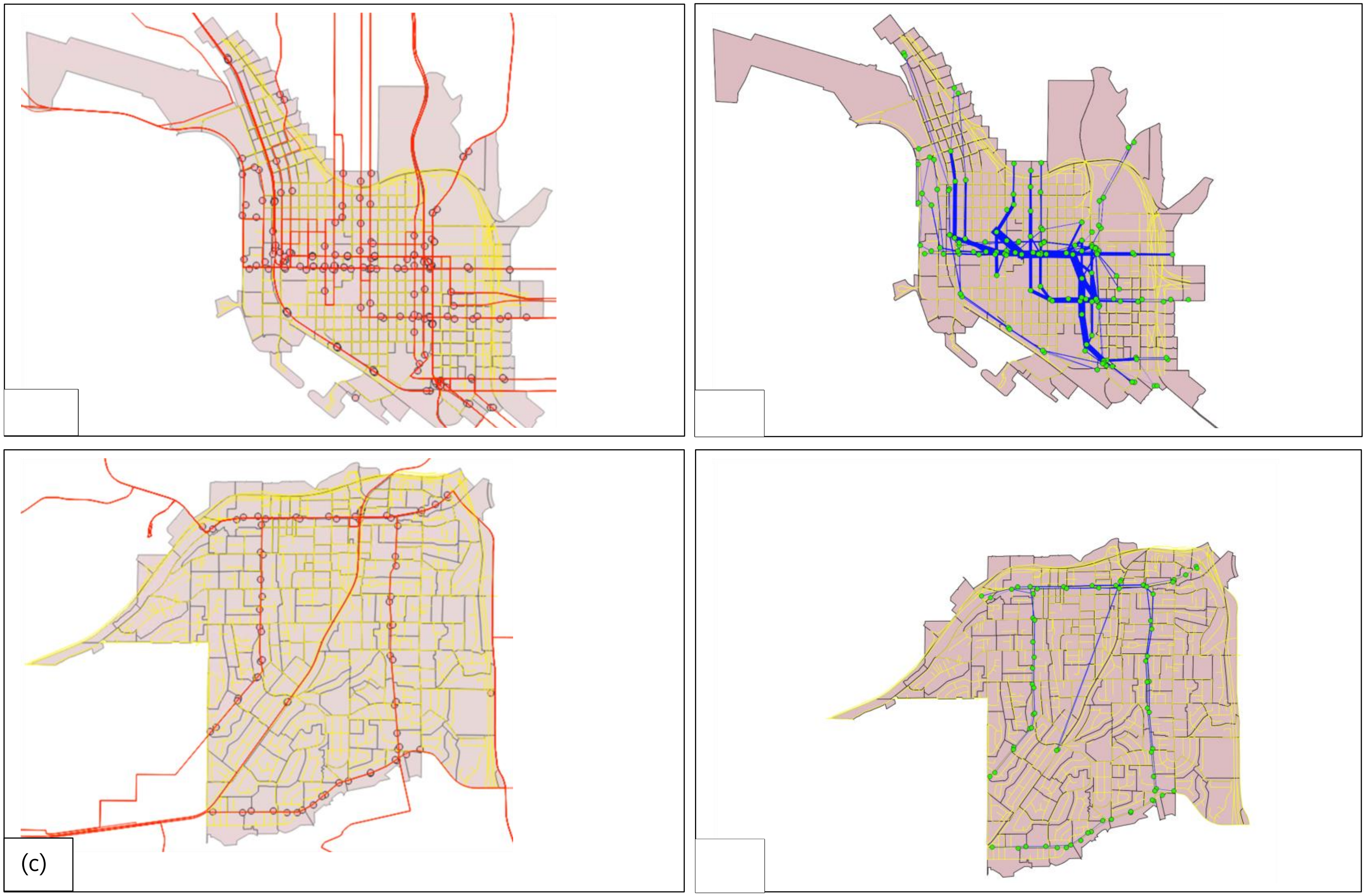


Figure 17. Transit line usage in downtown San Diego (upper) and Lemon Grove network (lower)
(fleet size=10 veh, virtual stop=75%, operating period=["AM","PM"])

Conclusion

Major American cities have witnessed a decline in public transit ridership during the last decade. Especially since the COVID-19 pandemic, transit operators have been struggling to provide good service quality to transit-dependent travelers and to attract new travelers to transit in moderate- to low-density areas. The integration of traditional fixed-route transit and microtransit is seen as a potential mechanism to increase ridership and improve mobility and accessibility. However, there are very few successful real-world examples of—and guidelines for—integrating fixed-route and microtransit.

In this project, we surveyed representatives from a sample of the recent microtransit programs in California to identify issues and challenges facing transit agencies when implementing microtransit services. Following this outreach and assessment, we developed an integrated fixed-route and microtransit simulation model that accounts for travelers' diversity to evaluate the impact of different design parameters on key performance metrics.

We used the model to study the impact of four different design parameters—fixed-route headways, microtransit fleet size, operating hours, and virtual stop coverages—on road networks in downtown San Diego and Lemon Grove, a small city in San Diego County. We evaluated the integrated systems by calculating the effect of introducing microtransit on transit mode subsidies per user, number of accessible jobs within 15 minutes (a metric for accessibility), mode share, and modal VMT.

Simulation results show that integrating microtransit with fixed-route transit will not necessarily increase public transit ridership. In fact, it will decrease fixed-route ridership. However, it will reduce auto mode share and auto VMT, as well as increase job accessibility, particularly in areas like Lemon Grove with poor transit coverage.

The proposed model could also be used to provide estimates of transit line usage, which could provide information for transit agencies to identify unproductive lines.

For future research, we plan to develop an algorithm to calibrate the mode and route choice models for the study region. We also plan to evaluate different fare structures for microtransit and fixed-route transit. For example, if a traveler uses a microtransit service, he or she could receive a free transfer to a fixed-route service.

References

Alonso-Mora, Javier, Samitha Samaranayake, Alex Wallar, Emilio Frazzoli, and Daniela Rus. 2017. "On-Demand High-Capacity Ride-Sharing via Dynamic Trip-Vehicle Assignment." *Proceedings of the National Academy of Sciences of the United States of America* 114 (3): 462–67. https://doi.org/10.1073/pnas.1611675114.

Basu, Rounaq, Andrea Araldo, Arun Prakash Akkinepally, Bat Hen Nahmias Biran, Kalaki Basak, Ravi Seshadri, Neeraj Deshmukh, Nishant Kumar, Carlos Lima Azevedo, and Moshe Ben-Akiva. 2018. "Automated Mobility-on-Demand vs. Mass Transit: A Multi-Modal Activity-Driven Agent-Based Simulation Approach." *Transportation Research Record* 2672 (8): 608–18. https://doi.org/10.1177/0361198118758630.

Bertsimas, Dimitris, Yee Sian Ng, and Julia Yan. 2020. "Joint Frequency-Setting and Pricing Optimization on Multimodal Transit Networks at Scale." *Transportation Science* 54 (3): 839–53. https://doi.org/10.1287/trsc.2019.0959.

Dickens, Matthew. 2023. *Ridership Report*. American Public Transportation Association, December 2023. https://www.apta.com/research-technical-resources/transit-statistics/ridership-report/

Dijkstra, Edsger W. 1959. "A Note on Two Problems in Connexion with Graphs." *Numerische Mathematik 1, 269-271 (1959).*

Engelhardt, Roman, Florian Dandl, Arslan-Ali Syed, Yunfei Zhang, Fabian Fehn, Fynn Wolf, and Klaus Bogenberger. 2022. "FleetPy: A Modular Open-Source Simulation Tool for Mobility On-Demand Services." http://arxiv.org/abs/2207.14246.

Erhardt, Gregory D., Jawad Mahmud Hoque, Vedant Goyal, Simon Berrebi, Candace Brakewood, and Kari E. Watkins. 2022. "Why Has Public Transit Ridership Declined in the United States?" *Transportation Research Part A: Policy and Practice* 161 (July): 68–87. https://doi.org/10.1016/j.tra.2022.04.006.

Frei, Charlotte, Michael Hyland, and Hani S. Mahmassani. 2017. "Flexing Service Schedules: Assessing the Potential for Demand-Adaptive Hybrid Transit via a Stated Preference Approach." *Transportation Research Part C: Emerging Technologies* 76: 71–89. https://doi.org/10.1016/j.trc.2016.12.017.

Ghimire, Subid, Eleni Bardaka, Kai Monast, Juan Wang, and Waugh Wright. 2024. "Policy, Management, and Operation Practices in U.S. Microtransit Systems." *Transport Policy* 145 (January): 259–78. https://doi.org/10.1016/j.tranpol.2023.10.011.

Guerra, Erick, and Robert Cervero. 2011. "Cost of a Ride." *Journal of the American Planning Association* 77 (3): 267–90. https://doi.org/10.1080/01944363.2011.589767.

Hansen, Todd, Michael Walk, Shuman Tan, and Ahmadreza Mahmoudzadeh. 2021. "Performance Measurement and Evaluation Framework of Public Microtransit Service." *Transportation Research Record* 2675 (12): 201–13. https://doi.org/10.1177/03611981211028622.

Lee, Yongsung, and Bumsoo Lee. 2022. "What's Eating Public Transit in the United States? Reasons for Declining Transit Ridership in the 2010s." *Transportation Research Part A: Policy and Practice* 157 (March): 126–43. https://doi.org/10.1016/j.tra.2022.01.002.

Liu, Yang, Prateek Bansal, Ricardo Daziano, and Samitha Samaranayake. 2019. "A Framework to Integrate Mode Choice in the Design of Mobility-on-Demand Systems." *Transportation Research Part C: Emerging Technologies* 105 (August): 648–65. https://doi.org/10.1016/j.trc.2018.09.022.

Luo, Qi, Samitha Samaranayake, and Siddhartha Banerjee. 2021. "Multimodal Mobility Systems: Joint Optimization of Transit Network Design and Pricing." *ICCPS 2021 - Proceedings of the 2021 ACM/IEEE 12th International Conference on Cyber-Physical Systems (with CPS-IoT Week 2021)*, 121–31. https://doi.org/10.1145/3450267.3450540.

Merriam-Webster Dictionary. 2024. "Mass Transit." Merriam-Webster (webpage). Last Updated August 23, 2024. https://www.merriam-webster.com/dictionary/mass%20transit.

Pinto, Helen K.R.F., Michael F. Hyland, Hani S. Mahmassani, and I. Ömer Verbas. 2020. "Joint Design of Multimodal Transit Networks and Shared Autonomous Mobility Fleets." *Transportation Research Part C: Emerging Technologies* 113 (December 2018): 2–20. https://doi.org/10.1016/j.trc.2019.06.010.

Shaheen, Susan, and Adam Cohen. 2019. "Shared Ride Services in North America: Definitions, Impacts, and the Future of Pooling." *Transport Reviews* 39(4):1-16. https://doi.org/10.1080/01441647.2018.1497728.

TUM-VT/FleetPy. 2024. (webpage). https://github.com/TUM-VT/FleetPy.

Veve, Cyril, and Nicolas Chiabaut. 2022. "Demand-Driven Optimization Method for Microtransit Services." *Transportation Research Record* 2676 (3): 58–70. https://doi.org/10.1177/03611981211049143.

Appendix

Model Specifications

Notation

The notation used in this report is shown in **Table A - 1.**

Table A - 1. Notation table

Variables	Meaning
$U_{i,m}$	Utility of traveler i selecting mode m
$V_{i,m}$	Deterministic component of utility of traveler i selecting mode m
$\varepsilon_{i,m}$	Stochastic component of utility of traveler i selecting mode m
$\widetilde{w}_{i,\mathrm{T}}$	Walking time of traveler i using transit mode T (min)
$w_{i,M}$	Waiting time of traveler i using microtransit mode M (min)
$w_{i,F}$	Waiting time of traveler i using fixed-route transit mode F (min)
$t_{i,M}^{ivt}$	In-vehicle-travel (ivt) time of traveler i using microtransit mode M(min)
$t_{i,F}^{ivt}$	In-vehicle-travel (ivt) time of traveler i using fixed-route transit mode F (min)
$F_{i,M}$	Fare of traveler i using transit mode T (microtransit and fixed-route transit) ($)
$n_{i,F}^{t}$	Number of transfers for traveler i using fixed-route transit mode F
$t_{i,D}^{ivt}$	In-vehicle-travel (ivt) time of traveler i using drive-alone mode D (min)
$c_{i,D}^{g}$	Gasoline cost for traveler i using drive-alone mode D ($)
$\Pr_i(m \vert \mathcal{M})$	Probability of traveler i choosing mode m from mode choice set $\mathcal{M}$
$\Psi_{i,m}^{n}$	Traveler i's probability of choosing mode m at iteration n
ϵ	Convergence threshold
η	Perception threshold for mode change
C_l^F	Daily operating cost for line l in the fixed-route transit system ($)
T_l	Operating hours for line l in the fixed-route transit system (hr)
h_l	Headway for line l in the fixed-route transit system (min)
D_l	Line duration for line l in the fixed-route transit system (min)
L_l	Route total length for route l (mile)
C_F^d	Hourly operating cost for one vehicle in fixed-route transit system ($)
C_F	Daily operating cost for the entire fixed-route transit system ($)
C_M	Daily operating cost for the entire microtransit system ($)
T_M	Daily operating hours for microtransit service ($)
S^f	Fleet size for microtransit service

Variables	Meaning
C_M^d	Hourly operating cost for microtransit service ($)
VMT_M	Microtransit's vehicle miles traveled (mile)
G_M	Microtransit's per-mile gasoline cost ($)
ω	Coefficient generation minimum threshold
Sets	
$\mathcal{M}$	Set of the available modes

Demand Module: Binary Logit Mode Choice Model

As mentioned above, the demand module consists of a generalized cost calculation part, as well as a binary logit mode choice model part. This section describes the mode choice model first. Let $\mathcal{M}$ be the set of available modes, where $\mathcal{M} = \{T, D\}$ (T for transit mode with walking, fixed-route transit (FRT) and microtransit legs, D for drive-alone auto mode), and the selected mode m ($m \epsilon \mathcal{M}$) is either one of transit or auto mode. We assume transit mode and auto mode are independent of each other. Let $U_{i,m}$ be the utility for traveler i selecting mode m, consisting of a deterministic term, $V_{i,m}$, which could be estimated through observable attributes and a stochastic term, $\varepsilon_{i,m}$, which accounts for attributes that are unobservable to modelers. Equation (1) displays such a utility function:

$$U_{i,m} = V_{i,m} + \varepsilon_{i,m} \tag{1}$$

For transit mode (represented by T), this study assumes that the deterministic term, $V_{i,T}$, is expressed as in Equation (2):

$$V_{i,T} = \beta_{0,T} + \beta_{1,T}\widetilde{w}_{i,T} + \beta_{2,T}w_{i,M} + \beta_{3,T}w_{i,F} + \beta_{4,T}t_{i,M}^{ivt} + \beta_{5,T}t_{i,F}^{ivt} + \beta_{6,T}F_{i,T} + \beta_{7,T}n_{i,F}^{t} \tag{2}$$

where $\widetilde{w}_{i,M}$, $w_{i,M}$, $w_{i,F}$, $t_{i,M}^{ivt}$, $t_{i,F}^{ivt}$, $F_{i,T}$, $n_{i,F}^{t}$ are the walking time, microtransit waiting time, fixed-route transit waiting time, microtransit in-vehicle-travel time, fixed-route transit in-vehicle-travel time, transit fare (microtransit and fixed-route transit), and number of transfers in the fixed-route transit network. $\beta_{n,T}$ ($n = 0, \dots, 7$) represents the coefficients of the variables in the transit mode. $\beta_{0,T}$ represent the alternative specific constant (ASC) for the transit mode, while $\beta_{n,T}$ ($n = 1, \dots, 7$) represent the coefficients for walking time, microtransit waiting time, fixed-route transit waiting time, microtransit in-vehicle-travel time, fixed-route transit in-vehicle-travel time, transit fare (microtransit and fixed-route transit), and number of transfers in the transit supernetwork for transit mode T.

For private auto drive-alone mode (represented by D), this study assumes that the deterministic part, $V_{i,D}$, could be expressed as Equation (3):

$$V_{i,D} = \beta_{0,D} + \beta_{1,D}t_{i,D}^{ivt} + \beta_{2,D}c_{i,D}^{g} \tag{3}$$

where $t_{i,D}^{ivt}$, $c_{i,D}^{g}$ are in-vehicle-travel time, and gasoline cost for traveler i using drive-alone mode D. $\beta_{n,D}$ ($n = 0,1,2$) represents the alternative specific constant (ASC) for drive-alone auto mode, as well as the coefficients for in-vehicle-travel time, and gasoline cost for drive-alone auto mode D.

By assuming the stochastic term $\varepsilon_{i,m}$ follows an independent and identical Gumbel distribution, we can derive the binary logit mode choice model, where the probability of traveler i choosing mode m is displayed in Equation (4):

$$\Pr{}_i(m|\mathcal{M}) = \frac{e^{V_{i,m}}}{\sum_{m' \epsilon \mathcal{M}} e^{V_{i,m'}}} \tag{4}$$

Multi-modal Least Generalized Cost Path-finding Algorithm

We consider heterogeneous travelers in this study, which means each traveler has different $\beta_{n,T}$'s and $\beta_{n,D}$'s. This means that even if two travelers share the same origin-destination (OD) pair, they might not share the same least generalized cost path because they might evaluate the same disutility (e.g., waiting time) differently. Therefore, we calculate the least generalized cost path for each traveler for both transit and auto mode.

We developed a multi-modal least generalized cost path-finding algorithm to calculate the deterministic term for transit mode, $V_{i,T}$, in Equation (2) and the deterministic term for auto mode, $V_{i,D}$, in Equation (3). The multi-modal least generalized cost path-finding algorithm is illustrated in Figure A - 1. The path-finding algorithm is modified from Dijkstra's label-setting shortest path algorithm (Dijkstra 1959) with binary heap implementation. The modification is as follows: as the path-finding algorithm traverses each link, it calculates the $\beta_{n,T} \cdot x_{n,T}$ on

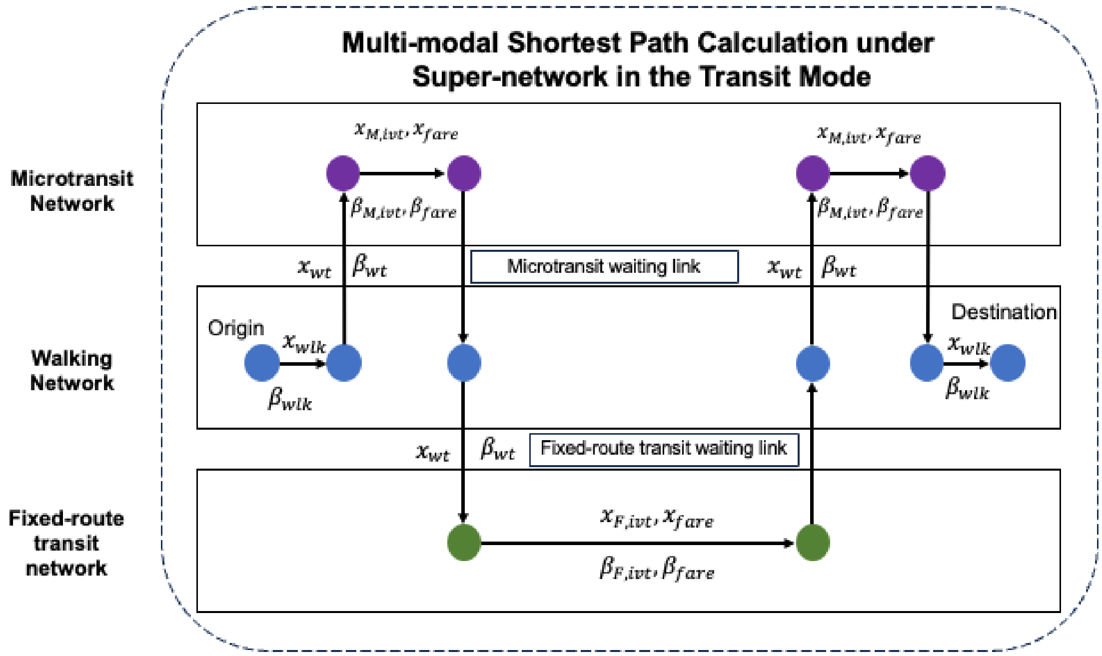


Figure A - 1. An illustration of the multi-modal least generalized cost path-finding algorithm.

the current link and sums up the $(\beta_{n,T} \cdot x_{n,T})$'s from a traveler's origin to the current link automatically. When the least generalized cost path-finding algorithm reaches the traveler's destination, it gives the least generalized cost path for such traveler given his or her OD pair.

We calculate the least generalized cost paths for transit mode and auto mode, which become the input of Equation (2), and could be used to calculate a traveler's probabilities for choosing transit mode and auto mode.

Supply Module: Multi-modal Transportation System

This section describes the supply component of the modeling framework, which is a multi-modal transportation system that includes both constant and dynamic parts. We assume the walking, fixed-route transit, and auto network to be constant while the microtransit network is updated by the microtransit service simulation (V-T/FleetPy 2024).

Constant Networks: Walking, Fixed-Route Transit, and Roadway Networks

We assume that the walking, fixed-route transit, and auto networks are constant, which means there is no congestion effect in those networks. However, even if the networks are constant, two travelers from the same OD pair could still have two different least cost paths because of the differences in their preference coefficients - β's.

Microtransit Service Simulation (FleetPy)

We use FleetPy, a modular open-source MoD service simulator, to model the microtransit service (Engelhardt et al. 2022). FleetPy includes simulation, routing, demand, infrastructure, and fleet control modules. For the routing module, routes are computed using the Dijkstra algorithm (Engelhardt et al. 2022). The fleet control module uses an immediate response method for passenger-vehicle matching and the algorithm proposed by Alonso-Mora et al. (2017) for vehicles' repositioning after they drop off their passengers. Readers can refer to the following references for the details of FleetPy and its GitHub webpage (Engelhardt et al. 2022; TUM-VT/FleetPy. 2024). ceWe assume that microtransit vehicles pick up passengers at virtual stops, and passengers will walk from their origins to virtual stops and from virtual stops to their destinations. Once a microtransit vehicle picks up its passenger, it will drive to the virtual stop that is closest to the passenger's destination. Ride-pooling is allowed in FleetPy. After running the microtransit simulation, the red links in Figure A - 2 (i.e., microtransit travel links and microtransit waiting links) are updated according to users' waiting times and in-vehicle travel times from FleetPy.

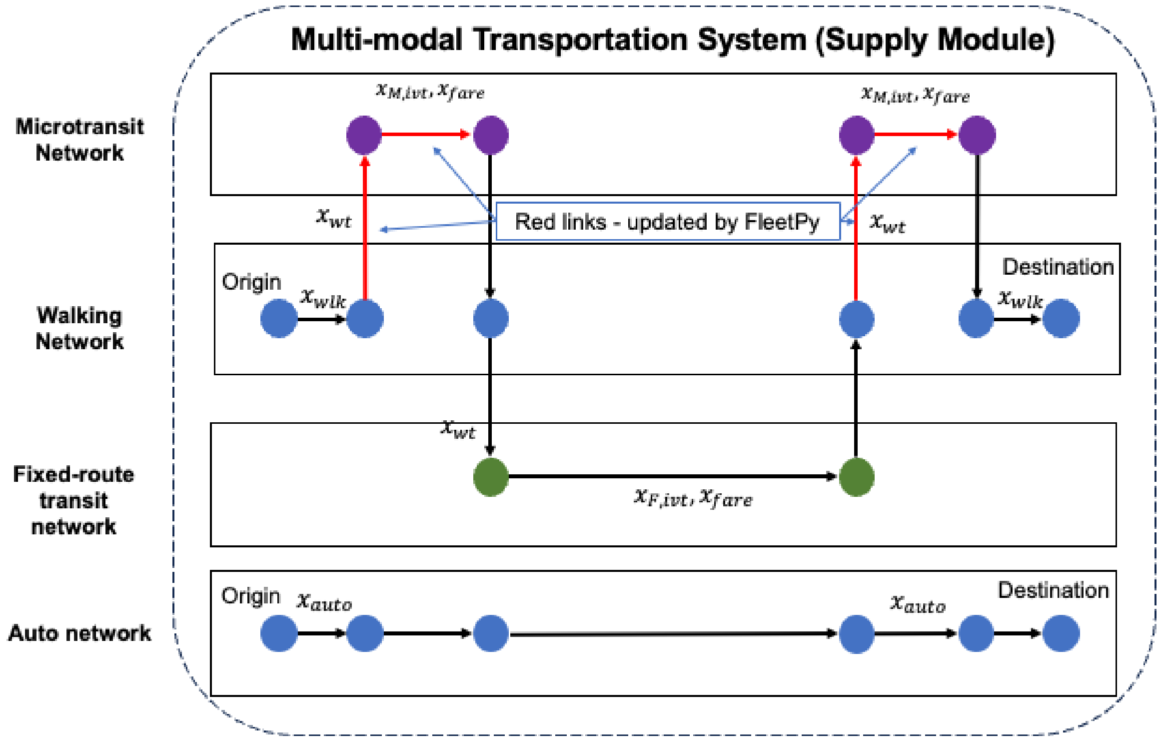


Figure A - 2. An illustration of the multi-modal transportation system (supply module)

Perception Threshold for Mode Change

We assume that travelers have a perception threshold for mode change. The perception threshold is formulated as follows:

- if the difference of traveler i's probability of choosing mode T in iteration n and iteration $n-1$, $\left|\Psi_{i,T}^{n} - \Psi_{i,T}^{n-1}\right|$, is greater than the mode change threshold η, namely $\left|\Psi_{i,T}^{n} - \Psi_{i,T}^{n-1}\right| > \eta$, then the model generates a new random number for the binary choice model. A new random number might lead to a different mode choice result in iteration n than it is in iteration $n-1$;
- if $\left|\Psi_{i,T}^{n} - \Psi_{i,T}^{n-1}\right|$, is smaller than or equal to the mode change threshold η, namely $\left|\Psi_{i,T}^{n} - \Psi_{i,T}^{n-1}\right| \leq \eta$, then traveler i will keep his mode choice in the previous iteration.

We set the mode change threshold η to be 0.05 in this study, which means if the change in traveler's mode choice probability for transit mode or auto mode is less than 0.05, then travelers will stick to their modes in the previous iteration.

Demand Profiles

Table A - 2 shows a sample of travelers' demand profiles, including their trip IDs, origins, destinations, departure times, and their individual attributes.

Table A - 2. Demand input: a sample of travelers' demand profile

Depart time	O	D	ID	$\beta_{D,0}$	$\beta_{D,ivt}$	$\beta_{D,gas}$	$\beta_{T,0}$	$\beta_{T,wk}$	$\beta_{M,wt}$	$\beta_{F,wt}$	$\beta_{M,ivt}$	$\beta_{F,ivt}$	$\beta_{F,trfr}$	$\beta_{T,fr}$
18006	384	498	0	0	0.16	1.19	0	0.22	0.12	0.07	0.15	0.12	0.53	0.10
18011	186	297	1	0	0.13	0.62	0.06	0.09	0.11	0.08	0.10	0.05	0.51	0.18
18014	423	161	2	0	0.14	0.71	0.07	0.17	0.08	0.07	0.09	0.10	0.50	0.14

Convergence Criterion

We use the squared percentage difference of the mode choice probability between two consecutive iterations of all modes among all travelers as the convergence criterion, as shown in Equation (5):

$$\sum_{i \in I} \sum_{m' \epsilon \mathcal{M}} \frac{\left(\Psi_{i,m'}^{n} - \Psi_{i,m'}^{n-1}\right)^2}{\Psi_{i,m'}^{n-1}} \leq \epsilon \quad (5)$$

Where $\Psi_{i,m'}^{n}$ is traveler i's probability of choosing mode m' at iteration n, and ϵ is the convergence threshold, which is set to be 0.01 in this study. The convergence criterion measures the discrepancy in the probability of choosing the same mode in two consecutive iterations.

Convergence Analysis

We ran each scenario multiple times until the results began to converge. As Figure A-3 shows, the proposed model converges under all the scenarios in both downtown San Diego and Lemon Grove networks. For the downtown San Diego network, all scenarios converge within seven iterations, while for the Lemon Grove network, all scenarios converge within four iterations.

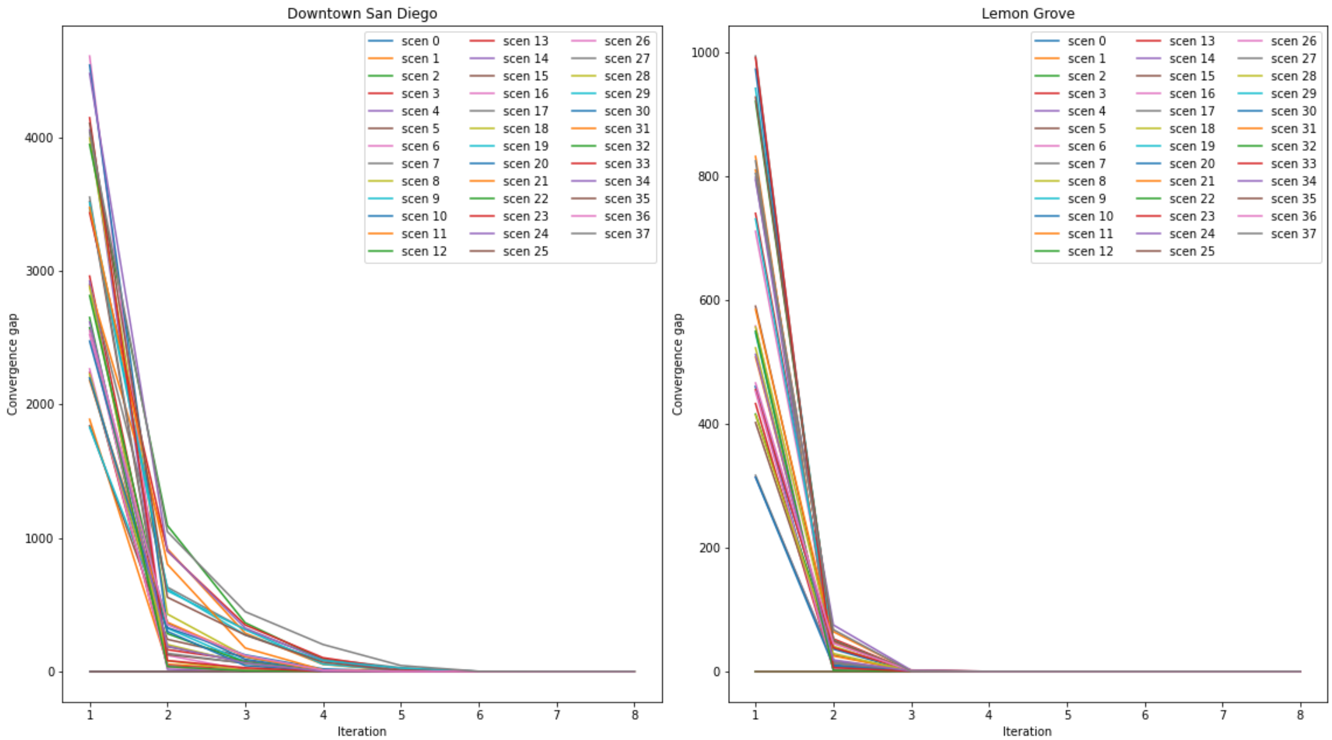


Figure A - 3. Convergence patterns for downtown San Diego and city of Lemon Grove among all scenarios

Performance Metrics

This section describes the performance metrics used in this study in terms of monetary investment and benefits. From the monetary investment perspective, this section will describe how the operating cost, revenue, and transit mode subsidy per user are calculated. From the benefit perspective, this study analyzes mode share, vehicle miles traveled (VMT), and accessibility. This section describes the cost structure first and how the accessibility is calculated in this study.

Table A - 3. Performance metrics in this study

Performance Metrics	Units
Operating cost	US Dollar
Revenue	US Dollar
Subsidy	US Dollar
Mode share	%
Vehicle miles traveled (VMT)	mile
Accessibility (number of accessible jobs within 15 minutes)	1

Cost and Revenue for Fixed-Route Transit and Microtransit

This section presents how the costs of the fixed-route transit and microtransit are calculated. In terms of fixed-route transit, for a single transit route, l, the daily operating cost, C_l^F, is calculated as in Equation (6):

$$C_l^F = 2 \times \frac{D_l}{h_l} T_l C_F^d + 2 \times \frac{L_l}{h_l} T_l G_F \tag{6}$$

where T_l, h_l, D_l, L_l are operating hours, headway, route duration, and route total length for route l. The operating hours, T_l, is set to be 19 hours from 5 am to 11:59 pm in this study. C_F^d is fixed-route transit hourly labor cost and G_F is the fixed-route transit per-mile gasoline cost. Number 2 in Equation (6) means the transit route l operates in two directions. The first term in Equation (6) represents the labor cost, and the second term represents the gasoline cost for the fixed-route transit.

The fixed-route transit system's daily operating cost, C_F, is calculated as in Equation (7), which sums over all the lines l:

$$C_F = \sum_l C_l^F \tag{7}$$

For fixed-route transit, the revenue comes from the \$2.50 flat transit fare, which aligns with the transit fare in the San Diego area.[5]

Microtransit operating daily cost, C_M, is calculated as in Equation (8):

$$C_M = T_M S^f C_M^d + VMT_M G_M \tag{8}$$

where T_M, S^f, C_M^d are the operating hours, fleet size, and hourly labor cost for microtransit service, while VMT_M and G_M are the microtransit's VMT and per-mile gasoline cost. The first term in Equation (8) represents the labor cost, and the second term represents the gasoline cost for microtransit service. The revenue in the microtransit service comes from the microtransit fare, which we assume to be \$1.97/mile.

Binary Mode Choice Model

For the individual coefficients in the binary mode choice model (β's in Table A - 4), we adopt the coefficients of the estimated multinomial logit model from Frei, Hyland, and Mahmassani (2017). Since they were estimated for the Chicago region, we manually adjusted the coefficients to match downtown San Diego's mode split according to the study area's census track mode share from the American Community Survey.[6] The β's in Equation (2) are generated from a normal distribution with a given mean and standard deviation. Since each β

---

[5] San Diego Metropolitan Transit System (MTS) Fare Chart: https://www.sdmts.com/fares/fare-chart

[6] Means of Transportation to Work from American Community Survey data: https://data.census.gov/table?q=Means%20of%20Transportation&g=1400000US06073005101,06073005102,06073005103,06073005201,06073005202,06073005301,06073005302,06073005401,06073005402,06073005403,06073005601,06073005801,06073005802&y=2022

should be non-negative, we add a minimum threshold ω (either 0, 0.01 or 0.05) in the generation process to make sure all the β's are positive (i.e., $\beta = \max(\tilde{\beta}, \omega)$). The mean, standard deviation, and threshold for each coefficient in San Diego and Lemon Grove are presented in Table A - 4.

Table A - 4. Coefficients used to generate β's in this paper

Coefficients	Meaning	Mean (San Diego)	Standard Deviation (San Diego)	Mean (Lemon Grove)	Standard (Lemon Grove)	Minimum threshold
$\beta_{D,0}$	Alternative specific constraint for auto mode D	0	0	0	0	0
$\beta_{D,ivt}$	Coefficient for in-vehicle travel time for auto mode D	0.184	0.047	0.198	0.047	0.01
$\beta_{D,gas}$	Coefficient for gasoline cost for drive-alone mode D	0.994	0.377	0.579	0.377	0.05
$\beta_{T,0}$	Alternative specific constraint for transit mode T	0.022	0.04	0.292	0.04	0
$\beta_{T,wk}$	Coefficient for walking time	0.213	0.140	0.329	0.140	0.01
$\beta_{M,wt}$	Coefficient for microtransit waiting time	0.104	0.022	0.094	0.022	0.01
$\beta_{F,wt}$	Coefficient for fixed-route transit waiting time	0.069	0.022	0.082	0.022	0.01
$\beta_{M,ivt}$	Coefficient for microtransit in-vehicle travel time	0.104	0.022	0.104	0.022	0.01
$\beta_{F,ivt}$	Coefficient for fixed-route transit in-vehicle travel time	0.102	0.029	0.106	0.029	0.01
$\beta_{F,trfr}$	Coefficient for fixed-route transit transfer penalty	0.504	0.022	0.504	0.022	0.01
$\beta_{T,fr}$	Coefficient for fare in fixed-route transit and microtransit	0.554	0.377	0.554	0.377	0.05