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Designing and testing microtransit routes to improve social inclusion: A pilot study in a suburban area

Alessandro Emilio Capodici [a], Martina Citrano [a], Gabriele D'Orso [a], Marco Migliore [a,b,*], Leonardo Minaudo [a,b], Riccardo D'Angelo [c]

[a] Department of Engineering, University of Palermo, Palermo, Italy
[b] Sustainable Mobility Center (Centro Nazionale per la Mobilità Sostenibile - CNMS), Italy
[c] Edisonweb s.r.l., Mirabella Imbaccari, Italy

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ABSTRACT

Suburbs are often characterized by a scarcity of mobility options to access services. Introducing microtransit is a promising way to improve public transport in suburbs, ensuring greater social inclusion and connecting isolated areas to main transit hubs. The paper aims to develop a multi-step GIS-based methodology for designing semi-flexible stop-based microtransit, having fixed routes and flexible routes (detours) and operating with real-time ride bookings (zero lead time). We considered a suburban area in Palermo, Italy, as study area. The identification of fixed and flexible routes was based on the forecasted passenger flows, through the estimate and the assignment of the daily origin-destination matrix for microtransit, also considering safety, spatial, and technical constraints. A small-scale pilot was carried out between November and December 2022 to test microtransit routes and the reliability of a mobile application to operate the service. A customer satisfaction and a willingness-to-pay survey were addressed to the users. The small-scale pilot showed that microtransit could improve public transportation in suburbs, being more accessible and reducing waiting times at stops. Particularly, the result of the design process led to a semi-flexible service accessible by 90 % of the resident population and with waiting times of less than 15 min in 76 % of the rides, lower than those currently experienced by bus users (20 min).

1. Introduction

Suburban areas are often characterized by low travel demand conditions, especially during off-peak hours and weekends, posing a challenge for fixed-route bus services, subject to fiscal constraints (Mishra et al., 2020). For these reasons, public transport companies tend to allocate their financial resources in the city center, where the transport demand is generally higher (Wang, Liu, & Zhang, 2022). Consequently, public transit often operates with gaps in timetables or underutilized capacities in suburban areas (Baier et al., 2024).

Thus, people living in suburban areas are often forced to use private vehicles or experienced high waiting times at stops or long walk to reach them due to unreliable, not widespread and low-frequency public transport services (Ribeiro et al., 2021; Velaga et al., 2012). If non drivers, people living in suburban areas experience difficulties with reaching desired destinations and essential services like healthcare facilities or food shops (Kamruzzaman & Hine, 2011). This becomes extremely problematic, especially for elderly people, people with disabilities or low-income people: the low quality of conventional public transport services is one of the main causes of social exclusion in suburbs (Busco et al., 2023; Ward & Walsh, 2023).

In Italy, for example, the share of elderly people (80 years and above) has nearly doubled between 2001 (4.2 %) and 2020 (7.4 %), according to the data collected by the Italian National Statistical Institute (ISTAT). Conversely, the situation is different for the youth population, whose share in the EU population has decreased over the past two decades. In Italy, in 2020, 13 % of the population was under 15 years old, compared to 14.3 % in 2001. For young aged 15 to 19, the share was 4.8 % in 2020, down from 5.3 % in 2001 (Eurostat, 2021).

Thus, with the growing number of older people, there is an increased need to provide alternative transportation options for the aging population (Rahman et al., 2016). The lack of infrastructure and services

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* Corresponding author at: Department of Engineering, University of Palermo, Palermo, Italy.
E-mail addresses: alessandro.capodici@unipa.it (A.E. Capodici), martina.citrano@unipa.it (M. Citrano), gabriele.dorso@unipa.it (G. D'Orso), marco.migliore@unipa.it (M. Migliore), leonardo.minaudo@unipa.it (L. Minaudo), riccardo.dangelo@edisonweb.com (R. D'Angelo).

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tailored to the elderly can lead to social isolation and limited access to main amenities. Thus, developing a more widespread and inclusive public transportation system that considers the needs of different social groups is crucial to ensure equitable participation in urban life (Wang, 2007).

Shared mobility services can provide either point-to-point or first−/last-mile transportation in suburban areas for people unable or unwilling to drive (van Kuijk et al., 2022; Yen et al., 2023a; Ren et al., 2023). Among these services, microtransit is a publicly or privately operated on-demand transit service offering shared rides within a service area using vans, minivans, or minibuses (SAE International, 2021; Yen et al., 2023b). Mainly targeting disadvantaged groups such as older people and low-income people (Knierim & Schlüter, 2021; Liezenga et al., 2024), microtransit can reduce waiting times at stops (Pan & Shaheen, 2025), meeting the needs of elderly people who cannot stand for a long time (Wang, 2007). Moreover, the use of compact vehicles can create new opportunities to enhance accessibility in suburban areas and promote effective social inclusion. These vehicles make it possible to extend the coverage to all those areas with inaccessible infrastructures for conventional buses (D'Orso et al., 2023). As feeder systems to transit hubs, microtransit can also expand access to downtown job opportunities, making them reachable to low-income people living in suburban areas.

Passengers can request minibus or van rides on their smartphone using a mobile application. However, the operator's scheduling software uses its algorithms to manage the dispatching procedure, optimize the vehicle's route in real time, and manage economic transitions.

The adoption of technology can cause a new challenge for elderly residing in suburban areas. However, if some policies are put in place, technology has the potential to mitigate social issues arising from an aging population and improve individual quality of life (Cho & Park, 2023).

Operating with flexible routes and without a fixed schedule, microtransit could expand access to transit hubs or replace traditional bus lines in low density areas, leading to an increasing number of people switching from private cars to public transport. This could be achieved only by providing a comfortable and easy-to-use service that is flexible in time and travel routes like a car.

Microtransit services can include either: (1) fixed route or dynamic services (flexible routes) and (2) fixed schedule or dispatch (on-demand) operations (Shaheen et al., 2020). Some services can be defined as semi-flexible when a standard bus route and timetable is predetermined, but buses can deviate from these standards based on the demand (Vansteenwegen et al., 2022). Microtransit can operates with pre-booking when users must make bookings in advance; with zero lead time, if last minute bookings are possible, and requests may come in real-time; or with mixed lead times when operator allows passengers to make bookings in advance as well as last minute (Vansteenwegen et al., 2022).

The paper aims to develop a methodology for designing semi-flexible on-demand stop-based microtransit with real-time bookings (zero lead time) in suburban areas. As a semi-flexible on-demand service, fixed routes and detours, i.e., routes that vehicles run only where there is an actual request from users, must be identified. Moreover, being a stop-based service, rider's pick-up and drop-off (PUDO) locations, i.e., specific stops distributed throughout the service area, should be defined. Some PUDOs are stops of the fixed routes that vehicles must drop by (but they must not stop if there are no users waiting for the service), known as checkpoints, while other PUDOs are along the flexible routes (detours), being optional stops. Therefore, from the operator's perspective, there is the opportunity to avoid unnecessary stops along the fixed route and potentially shorten the travel time.

The methodological approach should be different from the ones to follow for the design of ride-hailing, door-to-door or walking-enabled shared-ride services (Wang, Hyland, et al., 2022; Wang, Liu, & Zhang, 2022). Door-to-door and ride-hailing services' operational problems do not incorporate the PUDO location selection subproblem because the PUDO locations are the traveller's exact origin and destination. Moreover, the ride-hailing service does not need to optimize routes by considering multiple origins and destinations at the same time, as it serves different users individually. Otherwise, the semi-flexible service is defined by some fixed routes and optional detours and characterized by some PUDO locations. Thus, the methodology involves the subproblem of the PUDO location. Moreover, there is also a substantial difference for a methodological perspective between the semi-flexible service and the walking-enabled shared-ride services, since the latter, although based on PUDOs, used a dynamic walking approach (Yan et al., 2024), involving travellers being picked up and dropped off at alternative locations - convenient for the vehicle operator - that are within a few blocks from their origin and destination locations. These PUDO locations are determined from time to time based on requested origins and destinations. On the other hand, the semi-flexible service we wanted to design had some pre-defined PUDO locations.

In order to describe the methodology, a case study was presented. The suburban neighborhoods of Partanna Mondello and Tommaso Natale in Palermo, Italy, were considered as a study area. A pilot study was conducted to test the designed microtransit routes, assessing in-vehicle time and waiting time at stops.

The remainder of the paper is organized as follows: Section 2 gives a brief overview of the methods for designing microtransit services; a multi-step GIS-based methodology is described in Section 3 presenting how it has been applied to our case study; Section 4 presents the pilot study and its results. Finally, our conclusions are drawn in Section 5.

2. Background

Transportation technologies do not offer "one-size-fits-all" solutions; this is evident from the failure rates observed in demand-responsive transport services deployed worldwide.

However, emerging technologies such as microtransit require effective design techniques and decision-support tools, that should be generalized yet adaptable to different contexts (Rath et al., 2023). Moreover, these services are complex, aiming to combine the accessibility and affordability of conventional public transport services with the flexibility of ridesharing services; thus, many are the factors that must be considered in the design process. Itani et al. (2024), for instance, conducted a thorough analysis of the integration between conventional public transport networks and on-demand services, identifying three key parameters to design the service: key area characteristics (i.e., demographics and population attributes), area size (based on maximum waiting time), and accessibility-based decision-making (i.e., spatial accessibility and demand size). However, they explored these characteristics from a qualitative perspective. Moreover, these factors were often considered separately, developing design techniques that dealt with only one aspect of the complex problem that microtransit service design is.

The development of on-demand services in areas with low transit demand should include a careful selection of the service type based on the area characteristics. Offering only first-mile/last-mile service showed to be not attractive in high-income zones and areas with a low ratio of population to employment density, as users tend to do low intra-zonal trips and personal vehicles are highly used (Zuniga-Garcia et al., 2022).

Rossetti et al. (2023) stated that identifying potential markets or consumer segments is the first step to design and develop successful microtransit services. Using discrete choice experiments, they found that people with graduate degrees and transit users have a higher interest in microtransit, while women and elderly people generally showed a lower level of interest.

A microtransit user preference analysis could be useful for transit agencies to understand how to design the service in order to meet the needs of users or improve the service quality and increase their market uptake. For example, Alsaleh et al. (2023) found that the number of unassigned trips, the in-vehicle time, and the main travel mode before the introduction of the service significantly affect the use of microtransit.

Many of the studies about the design of microtransit services describe how to solve routing problems, emphasizing the importance of dynamic routing planning. For example, Bruni et al. (2014) developed a designing technique aiming to the route robustness, i.e. the ability to feasibly accommodate late requests that lead to mild detours on the routes. Fu and Chow (2022) went beyond the traditional dispatching and routing problem proposing a mixed integer linear programming model to solve pickup and delivery problems with vehicle-synchronized en-route transfers for microtransit.

The problem of identifying candidate stop locations as potential PUDO points was addressed by Jin and Xia (2021), considering the demand, facility and operational cost, and transportation cost (the walking distance that residents must face to reach the stop).

To identify demand responsive tailored bus routes to be added for a specific event, social media data were used by Sala et al. (2021), enhancing predictions of demand to attend a music festival.

In many works, simulations are used to design the service and assess its performance before introducing it in an area. Yoon et al. (2022) provided a new simulation sandbox for semiflexible transit and on-demand microtransit. On the other hand, Inturri et al. (2019) used an agent-based model fed with GIS data to explore different system configurations and vehicle dispatching strategies. Similarly, Calabrò et al. (2023) adopted an Ant Colony Optimization (ACO) algorithm implemented within an agent-based model. The objective was to enhance access to urban railway stations through feeder services.

Furthermore, Bürstlein et al. (2021) simulated the effectiveness of an on-demand first-mile service in Markham, Toronto, using *PTV MaaS Modeller* in combination with a macroscopic-scale simulation conducted with *PTV Visum*. In particular, the authors analyzed two different types of vehicles- cars and vans- during morning peak-hours.

Several researchers studied how to design microtransit services integrated in public transportation systems to solve the first-mile problem. Thorhauge et al. (2022) analyzed the preferences for autonomous shuttle buses, and their potential contribute to improve modal share for public transport if they were used as first/last-mile transport. Shen et al. (2018), for example, performed an agent-based supply-side simulation to assess the performance of an integrated system, considering shared autonomous vehicles, different fleet sizes and ridesharing preferences. By modeling various scenarios with different Shared Autonomous Vehicle (SAV) capacities, the simulation conducted by Huang et al. (2022) examined the impact of SAVs on first/last-mile connectivity, considering them as a flexible transport mode integrated with railway stations.

The study conducted by Chen et al. (2020) also explored the integration of Shared Autonomous Vehicles as a first-mile solution for connecting to metro stations, focusing on optimizing vehicle distribution and enhancing ride-sharing strategies. Luo et al. (2021) developed a method to design intermodal networks considering mobility on-demand transit and micromobility services for the first/last mile connections to it, identifying the near-optimal transfer hub locations.

Finally, Bonner and Miller-Hooks (2023) emphasized the role of equity in the optimal design of microtransit zones.

To the best of our knowledge, this paper is one of the few discussing an approach to designing an on-demand semi-flexible service with real-time bookings (zero lead time). Indeed, many studies have focused on door-to-door (fully flexible) services or DRT stop-based services that require pre-booking time. The novelty of our approach was developing a methodology to design microtransit services in many of their aspects: we considered the assessment of the demand and the user's preferences to identify potential routes; we considered accessibility, safety, and technical constraints to identify the candidate pick-up and drop-off locations, putting ourselves in the perspective of the users but also the developer of the navigation applications; we estimated the size of the fleet and tested two mobile applications to manage the dynamic routing in real time and satisfy users' requests, considering the developed microtransit routes. Furthermore, our methodology is not based on a simulation approach, which is typically used for designing this type of service. Rather, we considered an origin-destination (O—D) matrix for microtransit derived from the administration of a Stated Preference (SP) survey conducted among residents of the study area. This decision was made since we aimed to provide public transport companies and local authorities with a straightforward GIS-based method for conducting a preliminary design of a semi-flexible service, taking into account some fundamental constraints (road characteristics, safety, accessibility, app-based limitations) and assessing the users' desire lines based on forecasted passenger flows. Additionally, some GIS software, such as QGIS, is open-source and free, unlike many simulation software.

Another contribution derives from the pilot. We analyzed the reliability of the estimation of waiting and in-vehicle time that the mobile application makes in real time and shows to the user during the booking of a ride. This is an important aspect to consider since it may greatly affect user satisfaction. Indeed, if the mobile application estimates the waiting and in-vehicle times incorrectly, especially underestimating them, the users can experience higher times than the ones they consider when choosing between the travel options shown in the ride booking system.

3. Methods

The method follows the steps reported in Fig. 1. We used QGIS (version 3.10) - an open-source Geographic Information System (GIS) - and AequilibraE (version 0.6.2), a QGIS plugin for transportation modeling.

The first step is the identification of the study area and its potential to host a microtransit service. In this phase, the study area is delimited, divided into Traffic Analysis Zones (TAZs), and the demographic and land use characteristics and the existing public transport supply are analyzed. The second step is the construction of the road network in GIS software, using OpenStreetMap data. The third step, starting from the road network of the study area, involves the construction of the microtransit network considering technical and spatial constraints. The fourth step consists in the estimation of the microtransit demand through a calibrated 4-step model based on the results of a combined Revealed Preference (RP)/SP survey conducted among the residents of the study area. The result of this step is the daily microtransit O—D matrix, depending on some assumptions on the walking time to stops, the waiting time and the commercial speed of the microtransit vehicles. The fifth step is the traffic assignment: an AoN assignment of the daily microtransit O—D matrix is performed using AequilibraE. The sixth step involves the use of the algorithm described in subsection 3.6 to identify the fixed routes and the optional detours, based on the potential passenger flows and the limitation of the waiting and in-vehicle times. The seventh step is the fleet sizing, considering the potential demand to serve and the defined routes. The eighth step is the identification of pick-up and drop-off locations considering accessibility, safety, and technical constraints. Finally, it should be verified that the assumed parameters in terms of walking time to stop, waiting time and microtransit vehicles' commercial speed for estimating the O—D matrix (mode choice model input parameters) are met. If not, the routes and PUDOs must be re-estimated, and the procedure must be iterated from step 4 until convergence (see the loop represented in Fig. 1).

Each step of the methodology is presented through the description of the case study.

3.1. *The study area*

The study area encompasses the neighborhoods of Tommaso Natale and Partanna Mondello, located in the northern part of the city, and the small seaside villages of Mondello and Addaura. Therefore, the study

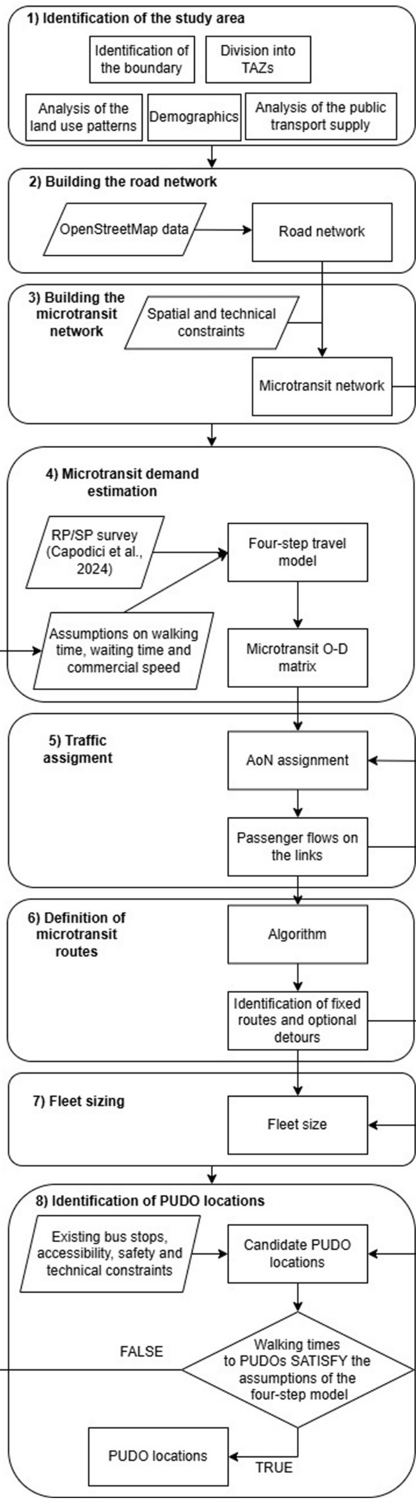

Fig. 1. Methodological framework.

area covers about 10.5 km^2. This area is mostly residential, characterized by a discontinuous urban fabric and few traffic attractors such as a shopping mall, some restaurants, beaches, and sports centers. The study area has a total population of 28,664 people (ISTAT, 2021). Fig. 2 shows the population pyramid depicting the distribution of various age groups for each gender in the study area. Many of the residents belong to vulnerable groups: almost 30 % of residents are people aged over 60 and only 47 % of residents aged between 15 and 64 are employed (ISAT, 2021).

Regarding the public transport services, the railway connects the study area with the city center operating with a frequency of 1 train per hour. There are also 7 bus lines, operated by the municipal transportation company AMAT S.p.A (Fig. 3). We analyzed the performance of the bus service in the study area, measuring frequencies and waiting times at stops (Table 1). We found that some bus lines have low frequency and low reliability; thus, many users face high waiting times at stops, up to 20 min. Therefore, these poor-quality public transport services forces residents to use their private vehicles for their trips.

The on-demand service is intended to be integrated with the existing public transport services, providing a first-mile/last-mile solution connecting people to the main high-capacity and high-frequency transit hubs. We hypothesized that the service would operate during the off-peak hours in the morning and in the afternoon with 22-seater minibuses serving mainly non-commuting trips.

From the user's perspective, customers can book a ride online and in real-time, choosing their pick-up and drop-off points from a set of potential stops. These stops may be checkpoints or optional stops located along a detour. After sending a request, a customer receives several transport options to choose from, characterized by different waiting times and in-vehicle times shown in the mobile application. The transport options displayed by the mobile app depend on the spatial position of the minibuses in the study area, prioritising those that could be more convenient in terms of time due to proximity. Once the customer selects the preferred transport option, the request is assigned to the corresponding minibus, which picks up customers from the selected stops and takes them to their destination stops. The minibus travels along the assigned fixed route, stopping at the checkpoints and making detours only if there are travel requests.

Thus, as for routing and vehicle dispatching, once a ride request occurs, the closest vehicle that can satisfy the request (also based on available seats) goes to serve the request itself. If the request comes from a PUDO located in an optional detour, the vehicle closest to that detour and that does not have to go back to travel along it, goes to satisfy the request. Moreover, routing is also affected by the ride booking system. Indeed, as already said, the mobile application shows each user different travel options in terms of waiting time, in-vehicle time and PUDOs. The vehicle is then selected by the user. Thus, vehicle dispatching is defined by the users themselves according to their preferences. As a real-time system, the mobile application offers optimised options based on the active vehicles, considering the approach described above. The system does not show the user travel options involving vehicles that have already reached their maximum capacity.

Subsequently, in order to develop a travel demand model, the study area was divided into 136 TAZs, using the ISTAT census blocks (Fig. 4). A centroid was assigned to each TAZ, to represent the concentration of population and employment within the TAZ.

3.2. Building the road network

To identify potential routes for microtransit vehicles, the road network graph was built in QGIS. Using AequilibraE plugin, the OpenStreetMap (OSM) road network was imported. The plugin generated link and node layers representing respectively all the roads and the road intersections with their geometric and functional features within the study area. Each node has the node number, x- and y-coordinates as attributes. Each link has a set of data attributes (the link number, the starting and ending nodes' numbers, direction, distance, functional classification, allowable transport modes, etc.) associated with it. The road network had 1482 links and 1168 nodes.

3.3. Building the microtransit network

Not all roads in the study area are passable by microtransit vehicles. Considering that the service to be designed involves the use of a fleet of minibuses, road width, for example, becomes a constraint to be taken

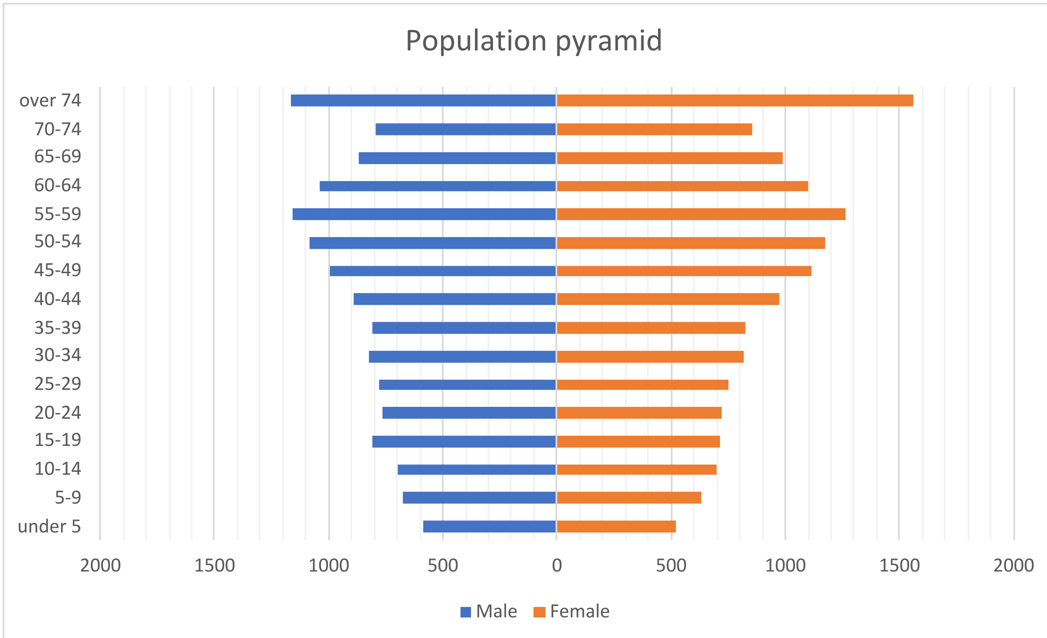

Fig. 2. Population pyramid depicting the distribution of various age groups for each gender in the study area.

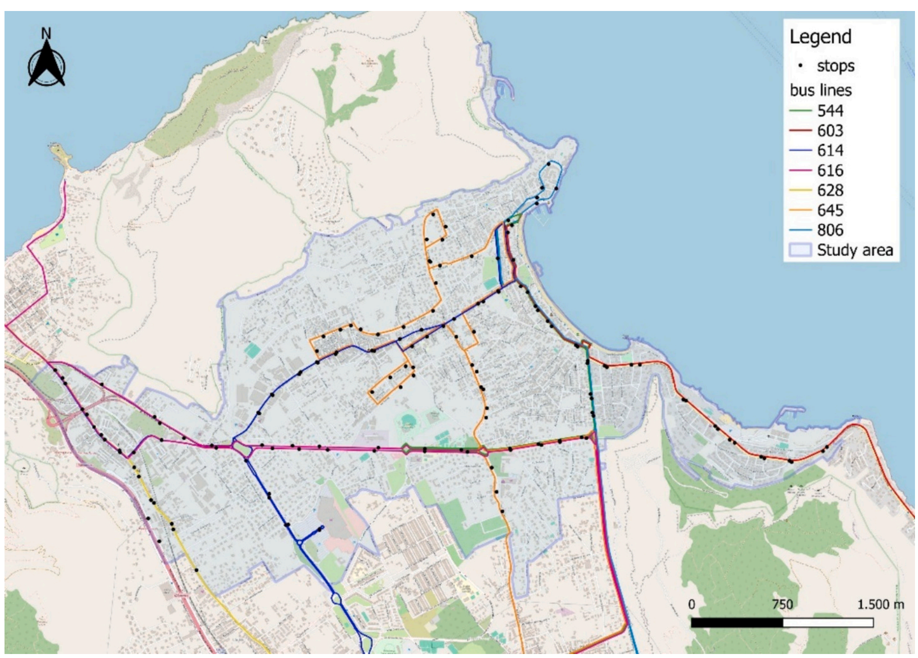

Fig. 3. Existing bus lines and stops in the study area.

Table 1
Observed frequencies and waiting times for the study area's bus lines.

Bus line	Observed Frequency [bus/h]	Observed Waiting time [min]	Average passengers per h
544	3	10	35
603	1,5	20	6
614	3	10	59
616	1,5	20	23
628	3	10	35
645	2,5	12	41
806	3,5	8,6	68

into account. In fact, minibuses must have the space to circulate and stop safely, without excessively impeding the traffic flows. In contrast, many of the roads in the study area are narrow local two-way streets, where the simultaneous presence of a minibus in one direction and a vehicle in the opposite direction could lead to difficult maneuvers to get through. A minibus that needs to pick up passengers could cause road congestion even on narrow local one-way roads, as other vehicles are unable to pass it.

Thus, the following spatial and technical constraints were considered to determine the admissible links that make up the potential micro-transit network:

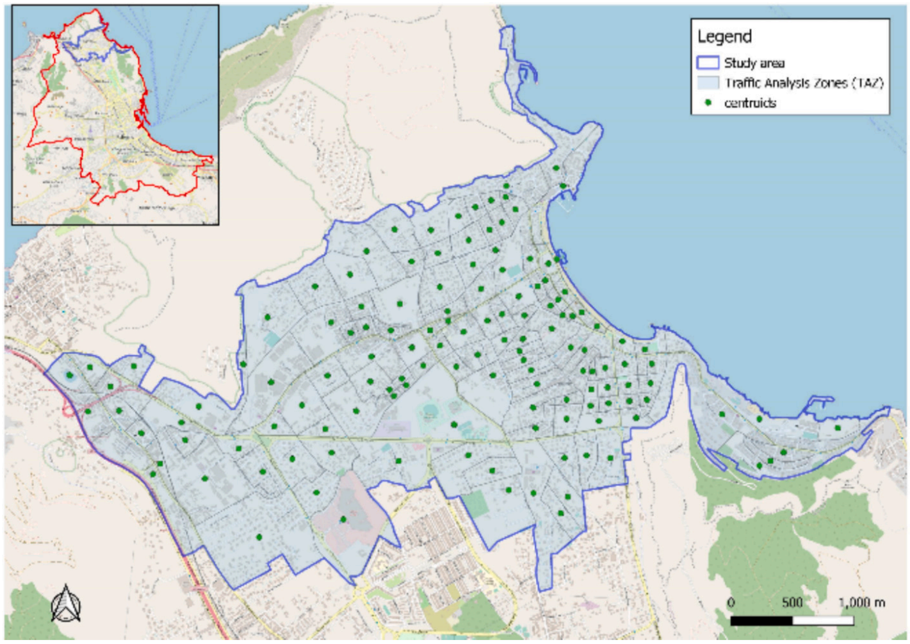

Fig. 4. Division of the study area into Traffic Analysis Zones and identification of centroids.

- road width: only roads with sufficient width to allow minibuses circulating without impeding the traffic flows were considered among the possible microtransit routes.
- space for safe stops: only roads with sufficient space to stop the vehicle and pick up and drop off passengers without impeding traffic were considered among the possible microtransit routes.
- slope: we excluded from the microtransit network roads with a slope greater than 5 %; in this way, stops along microtransit routes can be reached also by elderly people and wheelchair users.
- traffic direction: we excluded from the microtransit network cul de sacs where it is not easy to make a U-turn and all one-way streets that lead to roads with safety or width issues.
- road surface conditions: we excluded from the microtransit network all the roads that had degradation in the road pavement such as potholes, upheaval, or cracks.
- road types: we excluded pedestrian-only streets and private roads from the microtransit network.

Thus, we dropped all the links that did not satisfy these constraints from the OSM road network, such as private roads, only-pedestrian streets and roads with space or safety issues, finding the potential microtransit routes. The microtransit network is composed of 846 links and 670 nodes (Fig. 5).

Using AequilibraE plugin, the centroids were properly connected to

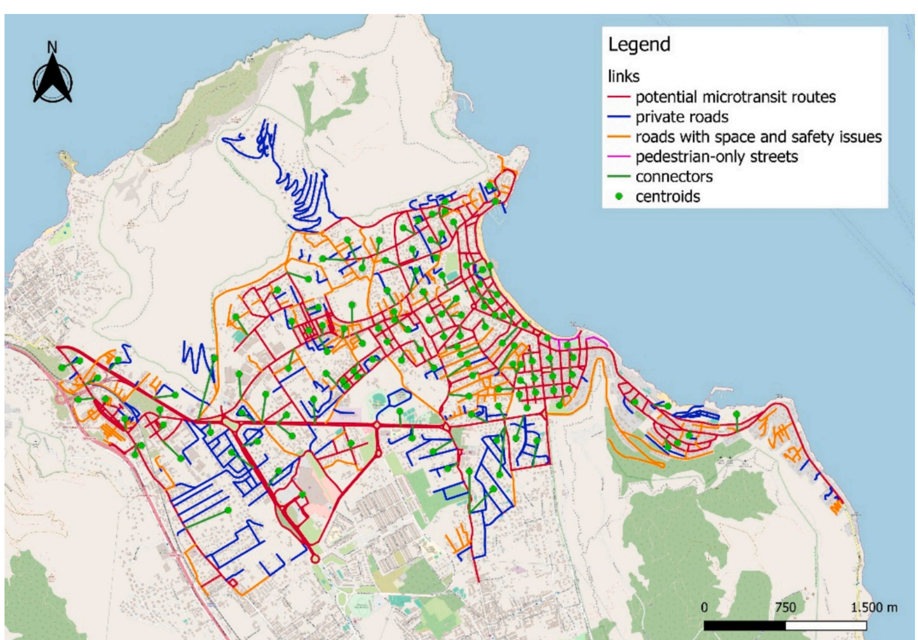

Fig. 5. Identification of potential flexible and fixed routes for microtransit (red lines). Roads that cannot be travelled by microtransit: private roads (blue lines), pedestrian-only roads (purple lines), and roads with space and safety issues (orange lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the microtransit network through centroid connectors.

3.4. Microtransit demand estimation

The microtransit demand was estimated through a four-step travel model (Ortúzar & Willumsen, 2011), considering only non-commuting trips. In fact, the microtransit service to be designed operates during off-peak hours, serving mainly non-commuting trips. In addition, the flexibility in time and routes of microtransit and the possibility of having extra time due to detours beyond the travel time of the direct route are aspects leading microtransit to better serving non-commuting trips without time constraints rather than commuting trips with time constraints.

The four-step travel model consists of a trip generation model, a trip distribution model, a mode choice model and a route assignment model.

The four-step travel model was based on the results of a combined RP/SP survey conducted in the study area in November and December 2021 (Capodici et al., 2025). A single questionnaire was designed and divided into three sections; the first section was about the socioeconomic characteristics of the respondents; the second section was the RP survey about the respondents' mobility habits; and the last section was the SP survey with some discrete choice experiments to be submitted to the respondents. We selected and trained some students from the University of Palermo as survey administrators. Personal interviews were conducted during off-peak hours stopping respondents near the main points of interest in the study area. We considered only people over the age of 14 as respondents.

Potential participants, randomly selected among residents who were making their trips, were approached and asked if they were willing to complete a survey about the introduction of a new transportation mode in the area, lasting about five minutes. If willing to participate, the interviewer read the questions to the participants and recorded their responses on the survey form.

The first step of the four-step travel demand modeling is trip generation. Trip generation predicts the total number of trips by trip purpose, generated by each zone of a study area. The number of non-commuting trips generated by the TAZs was estimated based on the number of residents – distinguished by socioeconomic factors like age – and different trip generation rates. The trip generation rates were calculated as the average of the rates detected by the RP section of the survey and recorded by the Audimob survey. Indeed, in the RP section, we asked respondents to recall how many trips they did the day before the interview. For each of these trips, respondents had to indicate the place of origin, the destination, the mode of transportation used and the trip purpose. In this way, we distinguished non-commuting trips from commuting trips and calculated an average trip generation rate for each socioeconomic group.

The Audimob Generation Model estimates the number of trips generated by different socio-demographic groups (age groups) on an average weekday, for different trip purposes (work, study, non-commuting trips), for all Italian municipalities. More detailed information on the generation model can be found in Capodici et al. (2024).

As for the distribution model, we divided respondents into two groups (people aged 15–59 and aged over 60) and estimated the main destinations of the trips from the data recorded in the RP survey. Both respondents aged 15–29 and over 60 made their trips mainly towards areas outside the study area (63 % for those aged 15–29 and 51 % for those aged 60 years and over), thus, for them, microtransit can be used as feeder system to main transportation hubs (Fig. 6). However, many of these trips cannot be made using public transportation because the areas are not served by public transport services (27 % for people aged 15–29 and 11 % for people aged over 60). In this case, microtransit is useless. Moreover, the commercial areas Politeama and Strasburgo, located outside the study area in the central part of the city, were the main destinations for both groups (Fig. 7).

We used the distribution of trip destinations to estimate the number

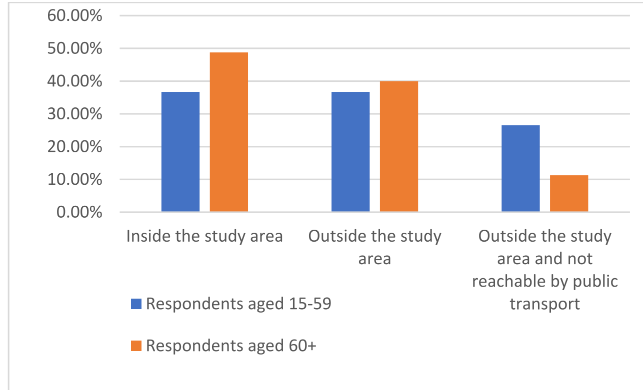

Fig. 6. Distribution of the trip destinations by group of respondents.

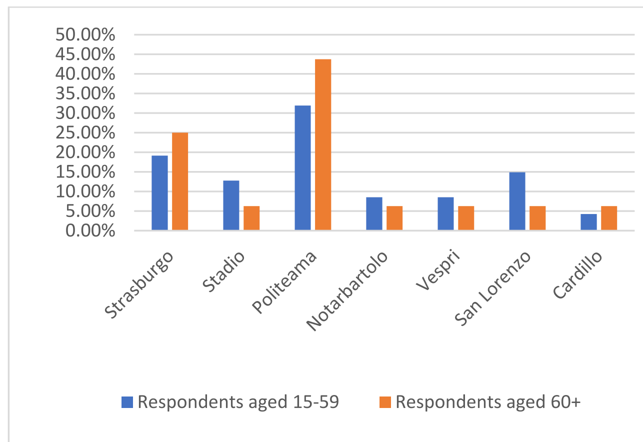

Fig. 7. Distribution of trip destinations outside the study area by group of respondents.

of non-commuting trips generated by each TAZ and attracted by the study area and by the urban areas outside the study area.

For the non-commuting trips inside the study area, a gravity model was applied, considering TAZ attractiveness as function of the number of employees in the retail and service sectors (related to points of interests from which non-commuting trips may derive such as shops, supermarkets, post offices, banks, healthcare facilities), leading to the estimation of the non-commuting trips for each O—D pair. We also considered the distribution of trip destinations outside the study area to estimate the non-commuting trips generated by each TAZ and attracted by these destinations (Strasburgo, Stadio, Politeama, Notarbartolo, Vespri, San Lorenzo, and Cardillo).

Finally, thanks to the results of the SP survey (number of SP observations = 565) it was possible to calibrate a mode choice model, estimating the probability of choosing microtransit by each category of users. In fact, the SP section of the questionnaire includes four discrete choice experiments, in which respondents were given four hypothetical scenarios and asked to choose which mode of transportation they would use among private car, motorcycle, microtransit, and walking. Microtransit was described as a first-mile/last-mile shuttle, with PUDO stops within a 10-min walk from the houses, connecting to a high-capacity or high-regularity transit node, and with a fare similar to a bus's.

We considered the following attributes: in-vehicle time and parking search time for private car; for walking, it is assumed that in-vehicle time equals travel time; for motorcycles, total travel time was considered to be equal to in-vehicle time; and for microtransit, travel time was considered to be composed of three components: walking time to access to a pick-up location (varying between two levels), the waiting time at pick-up location (varying between two levels) due not only to the time the vehicle takes to arrive but also to the possibility of trip requests occurring that could cause a time-loss, and the in-vehicle time (varying between two levels). Regarding costs, we considered the cost of fuel (fixed) and the cost of parking (varying between two levels) for the car mode; the cost of fuel (fixed) for the motorcycle mode; and a cost varying between two levels for the microtransit mode. We also consider a binary variable to identify the presence of transfers in the scenario (considering the integration of microtransit with the railway line or high-frequency bus lines). We considered the following socioeconomic variables: age, gender, number of cars per family members, driving license possession and level of education.

The results of the discrete choice experiments were elaborated by a statistical software developing a Multinomial Logit model.

By applying the probabilities to choose microtransit to the non-commuting trips estimated in the distribution model, it was possible to estimate the daily microtransit O—D matrix to be assigned to the graph. In order to estimate the O—D matrix, a waiting time at stop of 10 min and a commercial speed of 20 km/h for microtransit were assumed. The O—D matrix results from a thorough analysis of the choice probabilities for microtransit service among various socio-economic categories. In this context, key variables such as age, educational attainment, gender, and ticket price were taken into account. We classified the population according to gender (male/female), age (15–29; 30–44; 45–59; 60–74; older than 74) and educational attainment (primary school certificate, junior high school diploma, high school diploma, and degree). Thanks to the calibration of a mode choice model, we calculated different choice probabilities for microtransit for these different socio-economic groups (considering all the combinations of the socio-economic characteristics considered: e.g., males aged 15–29 with a degree), considering also the effect of the service fare.

The integration of these factors allowed for the assessment of demand elasticity, which measures users' responsiveness to socio-economic conditions within the study area. Specifically, a fare of €2 for microtransit was identified as providing the optimal balance between user needs and the financial sustainability of the service. This fare was selected according to simulations that indicated its potential to maximize service attractiveness, thereby promoting increased usage among users. However, it is essential to highlight that this fare requires financial subsidies from public administration. In fact, local authorities already provide subsidies to public transport to ensure the accessibility and sustainability of mobility services. Thus, we estimated the daily microtransit O—D matrices for the different socio-economic groups considering a fare of 2€. The daily microtransit O—D matrix was calculated as the sum of the daily microtransit O—D matrices for the different socio-economic groups.

Finally, the daily O—D matrix represents the average number of passengers that could use microtransit during off-peak hours for non-commuting trips.

3.5. Traffic assignment

To define the microtransit routes, the daily O—D matrix has been assigned to the graph assuming that the microtransit network is uncongested. An "All or Nothing" (AoN) assignment based on the Dijkstra algorithm was performed through the AEquilibraE plugin in QGIS. Thanks to the assignment, it was possible to obtain the desired paths between the O—D pairs and the passenger flow per direction on each link.

As Fig. 8 shows, most of the flow is assigned to the two main roads of the study area (Viale dell'Olimpo and Via Partanna Mondello), with values of about 1600 daily passengers in both directions. Smaller but not negligible flows have been assigned to Via Tommaso Natale (585), Viale Venere (375), Via Caduti sul Lavoro (347), Via Mattei (281), Lungomare Cristoforo Colombo (273), Via Diomede (252), and Via Lanza di Scalea (226), which connect users to the main traffic attractors of the area.

3.6. Definition of microtransit routes and fleet sizing

We identified the users' desire lines and superimposed the fixed routes on the road segments with the highest flows. Specifically, we used an algorithm to identify the fixed routes, based on the following steps (Fig. 9): 1) an all-or-nothing assignment of the O—D matrix to the graph is performed via Djikstra's algorithm, finding the flow value for each arc of the graph; 2) two PUDOs (A and B) are predefined considering two strategic points: these are two nodes where I have a high-quality public transport service (in our case, a bus line and a train station); they are two crucial trip attractors and generators that we want to include as stops on the fixed lines so that the on-demand service can act as a feeder and users can transfer to conventional public transport services to reach

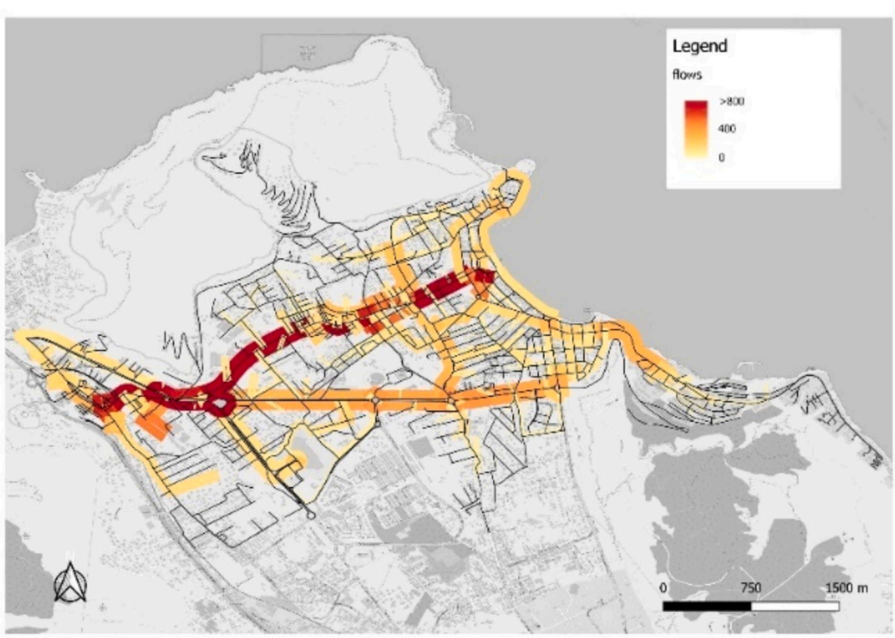

Fig. 8. Identification of passenger desire lines. The map shows the daily passenger flows on the road segments after traffic assignment performed by AEquilibraE.

```
PROCEDURE ComputeFixedRoutes(G=(N,L), c, f, A, B, δ, α, RankPUDOs)
    # INPUT
    #   G=(N,L)     : directed graph with nodes N and links L
    #   c[i,j] > 0  : travel cost on link (i,j) ∈ L
    #   f[i,j] ≥ 0  : flow assigned to link (i,j)
    #   A, B ∈ N    : fixed PUDOs (e.g. transport hubs) with the highest attracted
                      and generated demand
    #   δ ≥ 0       : tolerance on path cost over the cost of the shortest path
    #   α ∈ (0,1)   : desired threshold of covered flow
    #   RankPUDOs   : optional list of candidate PUDOs ordered by (attracted+generated) demand
    #
    # OUTPUT
    #   FixedLine = [P1, P2, ..., Pk]  (ordered list of selected paths)

    F ← SUM_{(i,j)∈L} f[i,j]                      # total flow on the graph
    FixedLine ← []
    CoveredLinks ← ∅                               # set of covered links
    UsedPUDOs ← {A, B}

    WHILE TRUE:
        # ---- (1) Shortest paths and cost thresholds ----
        (Pshort_AB, cshort_AB) ← SHORTEST_PATH(G, c, A, B)
        (Pshort_BA, cshort_BA) ← SHORTEST_PATH(G, c, B, A)
        θ_AB ← cshort_AB * (1 + δ)
        θ_BA ← cshort_BA * (1 + δ)

        # ---- (2) Set of admissible paths (both directions) ----
        Pθ_AB ← ENUM_ADMISSIBLE_PATHS(G, c, A, B, θ_AB)
        Pθ_BA ← ENUM_ADMISSIBLE_PATHS(G, c, B, A, θ_BA)
        Pθ ← (Pθ_AB ∪ Pθ_BA)

        IF Pθ = ∅ THEN
            # No A↔B path within the cost threshold: try a new PUDO.
            I ← NEXT_PUDO_WITH_MAX_RESIDUAL_DEMAND(RankPUDOs, UsedPUDOs, CoveredLinks, f)
            IF I = NIL THEN BREAK
            B ← I
            UsedPUDOs ← UsedPUDOs ∪ {I}
            CONTINUE
        END IF

        # ------- (3) Flow on an admissible path -------
        # Φ(P) = SUM_{(i,j)∈LINKS(P)} f[i,j]

        # ------- (4) First selected path -------
        IF FixedLine is EMPTY THEN
            P1 ← ARGMAX_{P∈Pθ} Φ(P)
            APPEND(FixedLine, P1)
            CoveredLinks ← CoveredLinks ∪ LINKS(P1)
            Φ_cum ← SUM_{(i,j)∈CoveredLinks} f[i,j]
            IF Φ_cum ≥ α * F THEN BREAK
        END IF

        # ------- (5) Iterative augmentation -------
        REPEAT
            Candidates ← Pθ \ FixedLine         # set difference (paths not yet selected)
            IF Candidates = ∅ THEN EXIT REPEAT

            # Additional (marginal) flow of a path:
            # Φ_add(P) = SUM_{(i,j)∈(LINKS(P) \ CoveredLinks)} f[i,j]
            Pnext ← ARGMAX_{P ∈ Candidates} Φ_add(P)

            IF Φ_add(Pnext) = 0 THEN EXIT REPEAT

            APPEND(FixedLine, Pnext)
            CoveredLinks ← CoveredLinks ∪ LINKS(Pnext)
            Φ_cum ← SUM_{(i,j)∈CoveredLinks} f[i,j]
        UNTIL Φ_cum ≥ α * F

        # ------- (6) Stopping condition -------
        IF Φ_cum ≥ α * F THEN BREAK

        # No further gain with current (A,B): pivot to another PUDO
        I ← NEXT_PUDO_WITH_MAX_RESIDUAL_DEMAND(RankPUDOs, UsedPUDOs, CoveredLinks, f)
        IF I = NIL THEN BREAK
        B ← I
        UsedPUDOs ← UsedPUDOs ∪ {I}
    END WHILE

    # ---- (7) Final output ----
    RETURN FixedLine
END PROCEDURE
FUNCTIONS:
# Φ(P): returns path flow
Φ(P) = SUM_{(i,j)∈LINKS(P)} f[i,j]

# Φ_add(P): returns additional (marginal) flow relative to CoveredLinks
Φ_add(P) = SUM_{(i,j)∈(LINKS(P) \ CoveredLinks)} f[i,j]

# LINKS(P): set of links composing path P

# Enumerate simple paths s→t with cost ≤ θ
ENUM_ADMISSIBLE_PATHS(G, c, s, t, θ)

# Pick next PUDO with maximum residual demand; if none exists return NIL
NEXT_PUDO_WITH_MAX_RESIDUAL_DEMAND(RankPUDOs, UsedPUDOs, CoveredLinks, f):
    # RD(v) = SUM_{(i,j)∈L : (i=v OR j=v) AND (i,j) ∉ CoveredLinks} f[i,j]
    FOR v IN RankPUDOs IN ORDER:
        IF v ∉ UsedPUDOs AND RD(v) > 0:
            RETURN v
    RETURN NIL
```

Fig. 9. The algorithm to compute fixed routes.

more distant destinations; 3) the algorithm calculates all possible routes between A and B within a cost threshold (in our case the travel time); 4) the algorithm selects the route between A and B that has the highest total flow; 5) this flow is compared with a flow threshold (in our case, we chose 70 % of the total flow on the graph); if the flow of the selected path does not reach the chosen flow threshold, then the algorithm, assuming the first selected path is valid, searches for another path, always within the cost threshold, that leads to having the additional flow higher than that of the already selected path (in fact, some links could already be part of the first selected path); 6) the flow threshold is checked again and the iterative process continues until the flow threshold is reached. If the threshold is not reached by the routes between A and B within a cost threshold, a new PUDO I – having the residual highest trip attraction and generation - must be defined.

Then, we decided to set a threshold for the traffic flows (under 500 but over 150 daily passengers) to opt to introduce a detour.

As result of the algorithm, two fixed routes, named A and B, have been planned along Viale dell'Olimpo, Via Partanna Mondello, and Via Mattei. These two routes cross the study area clockwise (route A) and anticlockwise (route B). This choice has been made to allow users to reach the desired destination without having to make a complete round, reducing waiting times at stops and in-vehicle time. Both fixed routes are about 11 km long and the travel time is 33 min for route A and 34 min for route B, considering a commercial speed of 20 km/h. Some detours have been added in all those areas that had significant flows – albeit lower than those related to routes A and B - and that fixed routes could not cover. As shown in Figs. 10 and 11, 8 detours are associated with each fixed route.

The detours were defined considering the extra time that passengers already on board must eventually spend due to a detour request, limiting it and guaranteeing the reliability of the service. For each detour, inversion nodes can be inserted to avoid vehicles driving the whole detour and reduce the detour time.

Moreover, to limit waiting times at stops, it is important to guarantee an adequate number of vehicles running along the routes. Once the passenger flows on each link were obtained, the next step was to quantify the number of vehicles needed to satisfy the demand. For the fleet sizing, the road section characterized by the highest number of passengers, located in Via Partanna Mondello, was taken into consideration. On this road, we predicted 796 passengers per day in one direction and 802 passengers per day in the other. Considering the probability of receiving requests from stops located on detours, an average turnaround time of 50 min was hypothesized, resulting in a fleet of ten 22-seater minibuses.

3.7. *Identification of pick-up/drop-off points*

To identify PUDOs, we considered some conditions that a location must satisfy:

- the location must guarantee the vehicle to stop safely and without hindering vehicular traffic;
- it must ensure that the user can wait safely;
- it must be easily identifiable by the users;
- it must be at a walkable distance from most of the residences and points of interest.

For the second criterium, the stop must therefore be located on sidewalks, providing a safe space for waiting for the vehicle and limiting the conflicts between vehicles and users. Thus, we avoided locating PUDOs in unpaved shoulders, grassy medians, or roads lacking pedestrian infrastructure that could force users to walk dangerously close to moving vehicles, increase the risk of falls for elderly or mobility-impaired individuals, and do not support individuals with disabilities. Moreover, the PUDO locations must provide adequate pedestrian-oriented lighting, which is seen as one of the key factors in evaluating safety in isolated or suburban areas, from both perceived and actual safety standpoints. Well-lit areas allow pedestrians to see their surroundings clearly, identifying potential hazards, and deter crime, encouraging the use of the service also after dark. Otherwise, poor lighting contributes to feelings of vulnerability.

To find locations meeting all the conditions defined above, we firstly included the existing bus stops along the fixed routes and detours in the set of possible PUDOs, since these bus stops are located in safe places, they are very well known by the residents of the study area and the bus stop poles can be used to give information about the service. Moreover,

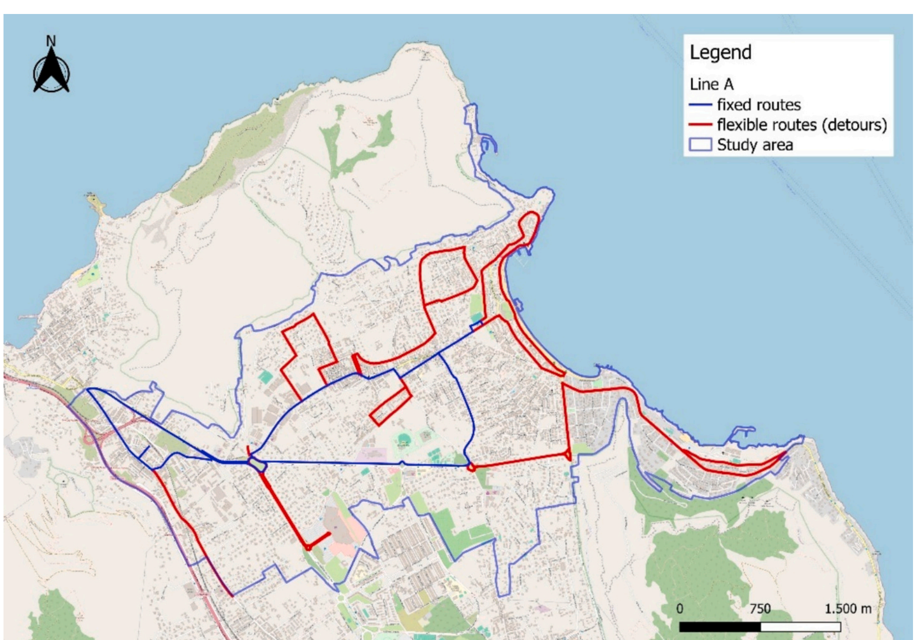

Fig. 10. Line A: fixed route (blue) and detours (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

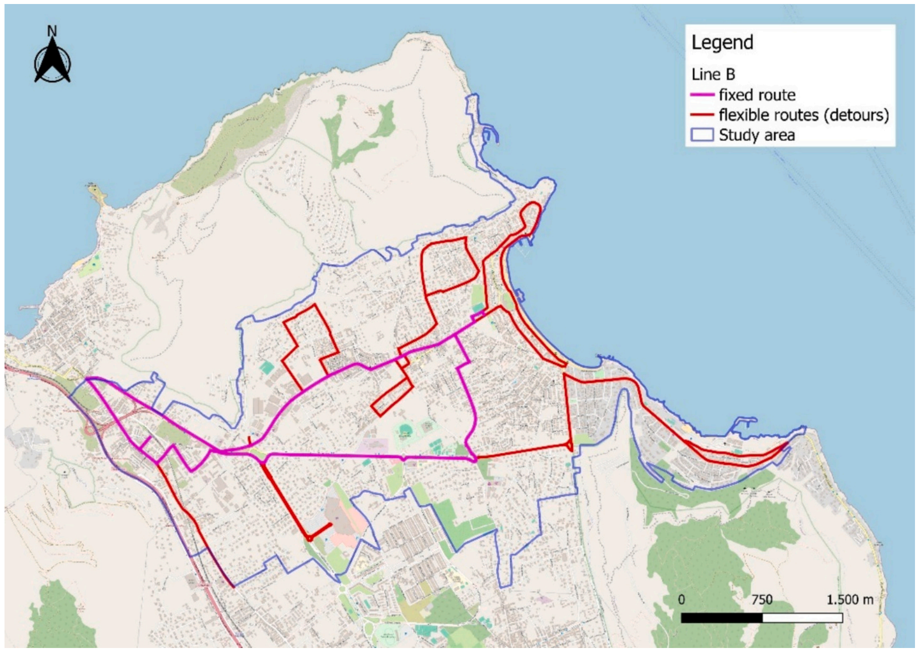

Fig. 11. Line B: fixed route (purple) and detours (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the public transport company identified the location of these bus stops considering the proximity to points of interest.

To meet the fourth criterium, an accessibility analysis was carried out, assessing the pedestrian catchment areas to each bus stop within 5 min (300 m) and 10 min (600 m) (Fig. 12). The uncovered areas were then identified, and some additional PUDOs were added to effectively cover the entire area and serve some points of interest. We added some PUDOs in the northern part of the study area to improve accessibility, a PUDO in front of Tommaso Natale railway station to promote the integration with the railway service and another one in front of some supermarkets. The PUDOs added after the accessibility analysis were also placed in locations meeting all the criteria defined above. To satisfy the criterium according to which the PUDOs must be easily identifiable by users, we chose to put the new PUDOs next to some road intersections or some well-known services (like the supermarkets) and then, in the pilot study, we named them with the name of the roads intersecting near the location or the name of the service the PUDO will serve.

A technical constraint was added to meet a condition required by smartphone applications: stops belonging to the same line should be at least 200 m apart to allow GPS-based mobile applications to distinguish each stop from the other during navigation. Thus, some bus stops included in the set of possible PUDOs were removed. The PUDOs must satisfy a demand that justifies their inclusion. Thus, the number of inhabitants that can access the microtransit service within a walkable

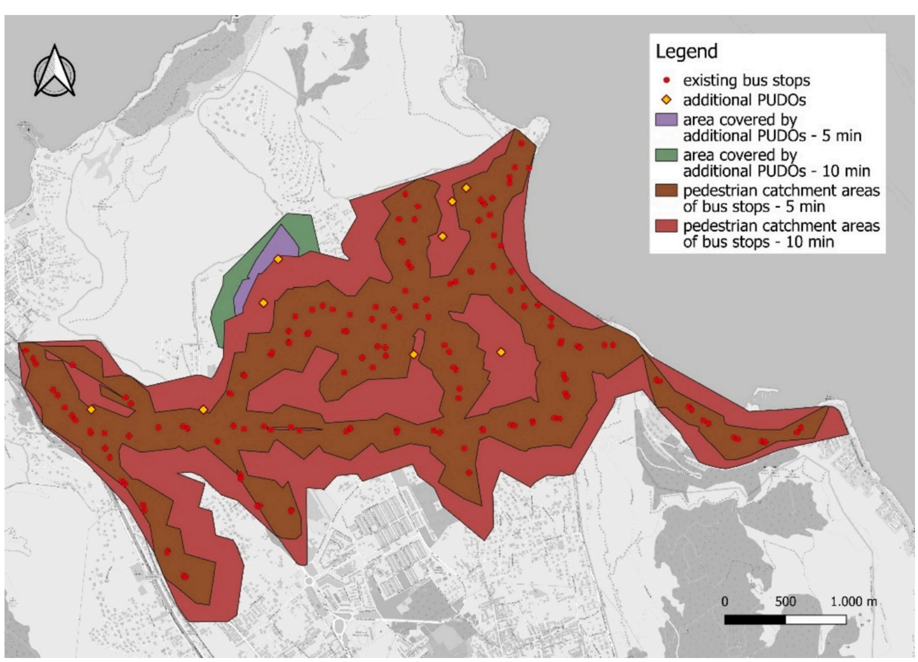

Fig. 12. Identification of uncovered areas and definition of additional PUDOs to increase coverage.

distance was calculated. Considering the fixed routes and the detours of Line A, 54 % of the inhabitants live within a 5-min walk of a PUDO, and almost 90 % within a 10-min walk (Fig. 13). Considering Line B, the number of inhabitants living within a 5- and 10-min walk are 60 % and 92 %, respectively (Fig. 14).

Thus, the list of PUDOs verified the requirement of having access time within 10 min from the residences that was set in the design of the SP survey and that affected the estimation of the O—D matrix.

Finally, each stop was given a name and the vehicle's heading angle at the stop was calculated as requested by navigation applications.

4. Pilot study

The microtransit routes were tested through a small-scale pilot study involving students and staff of the University of Palermo. The pilot was carried out during two weeks between November and December 2022 using the MVMANT app developed by the startup Edisonweb s.r.l. Considering the narrow user base, users' requests have been satisfied by a fleet consisting of 4 vehicles running along the two circular routes A and B. Two vehicles were assigned to Line A and its detours and two to Line B and its detours. The service has been operating from 3 to 7 p.m. every day except Sunday. The service was free of charge. Two depots were identified in front of Tommaso Natale railway station and in the parking area Galatea.

Two mobile applications were tested: one for drivers and one for the users.

The driver application enables dynamic routing, showing on a map the route the vehicle must take to reach a user's requested pick-up or drop-off point and the stops to pass through before reaching it. Thus, the driver application is a navigation app. The app works in real time so when a request involving a detour arrives, the route that the driver must follow is updated. The app works differently with fixed line stops and detour stops because the fixed line stops must be passed following a precise sequence while the stops along a detour may not even be all travelled once a trip request involving this detour occurs; this means that the vehicle can travel to the stop where there is the request and then make a U-turn to reach the fixed line again.

Once trip requests were met, the vehicles would return to the nearest depot to await further trip requests.

The user application allows users to book a ride in real time. During the trip request, the user selects the desired pick-up and drop-off points among the available stops. The application shows users several options, assigned to each certain waiting time and in-vehicle time (Fig. 15). In fact, the application estimates waiting time and in-vehicle time, predicting the speed on each link using a Kalman filter, which updates the value considering the time series data.

Once the desired ride is selected, a virtual ticket with a QR code appears, and a vehicle is assigned to satisfy the trip request. The virtual ticket allows the driver to identify and check in the passenger, framing the QR code with the driver app. The driver app also allows drivers to check out passengers once their trip requests were fulfilled.

The pilot study mainly aimed to assess the waiting time and the in-vehicle time that users can experience and compare them to the ones estimated by the application and shown to the user during the trip request, verifying the reliability of the online platform.

A total of 94 trip requests were satisfied, while 41 rides were carried out by the fleet grouping the travel requests. All the trip requests were made by single users. 17 out 41 rides were made only satisfying a single trip request. The maximum number of trip requests grouped into a single ride was 6. Mostly, users sharing the ride inside the vehicle at the same time were two; however, the maximum number of users inside the vehicle at the same time was 4.

Caduti sul Lavoro and Partanna Mondello Dionisio, located along fixed lines, and Tommaso Natale Socrate, located along a detour, were the most requested pick-up points (7 trip requests); Parcheggio Galatea and Stazione Tommaso Natale, both located along fixed lines and allowing the former to connect with a high-frequency bus line and the latter with the railway line, were the most requested drop-off points (30 trip requests).

Vehicles along Line A served 39 trip requests, while those traveling along Line B satisfied 55 trip requests. Vehicles 1 and 2 along Line A met 17 and 22 trip requests, respectively; vehicle 3 traveling along Line B satisfied 17 trip requests, while vehicle 4 was the most used (38 users).

For each trip request, we recorded the booking time, the vehicle departure time from the pick-up stop and the arrival time at the drop-off stop, considering the time spent picking up and dropping off passengers.

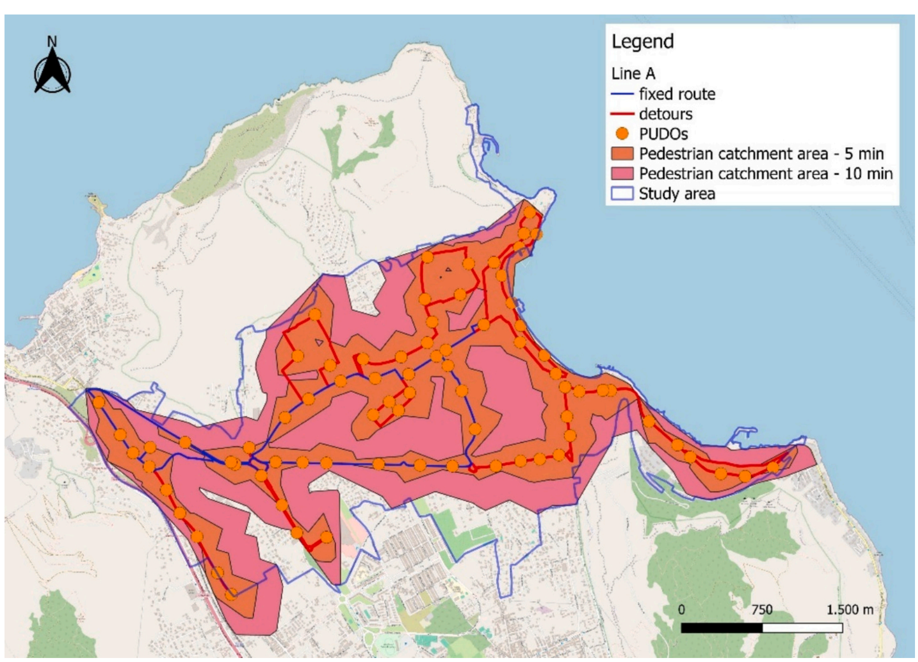

Fig. 13. The pedestrian catchment area of the PUDOs for Line A within 5 (orange) and 10 min (pink). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

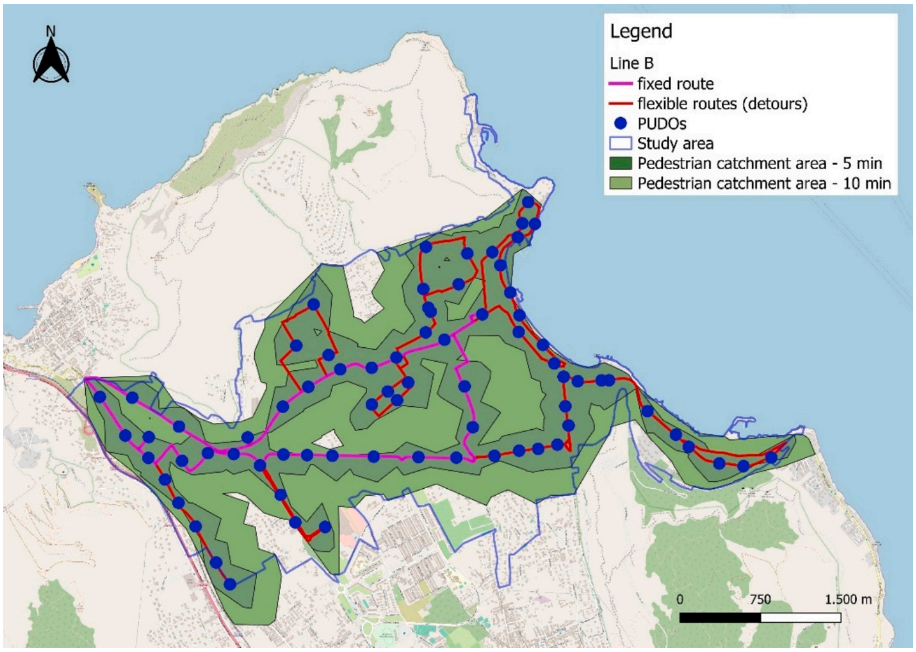

Fig. 14. The pedestrian catchment area of the PUDOs for Line B within 5 (dark green) and 10 min (light green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

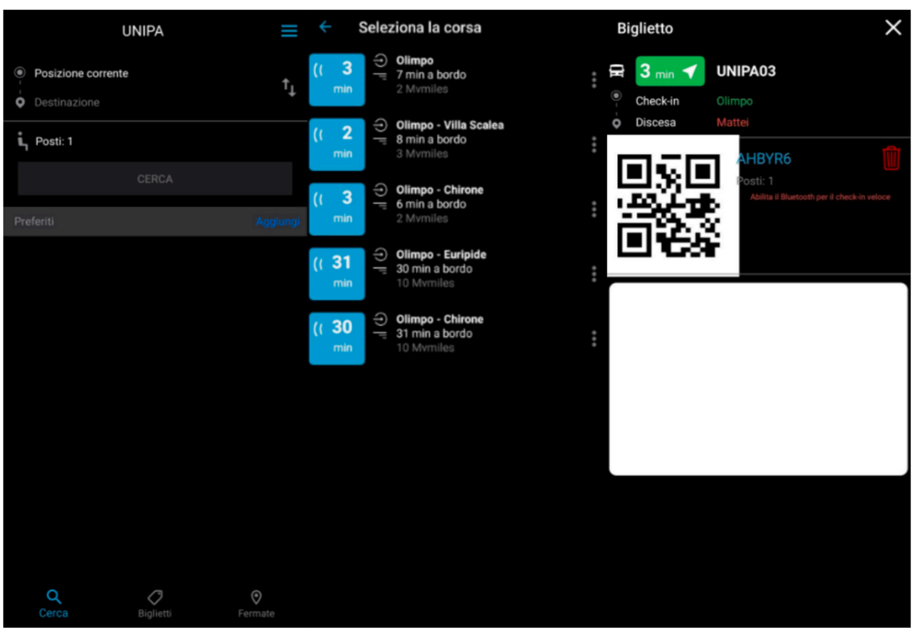

Fig. 15. MVMANT user interface: Home screen (booking interface) featuring search bars for pick-up location and destination (left); Ride Selection screen showcasing various travel options (centre); Driver and Ride Confirmation screen displaying ride details and QR code for check-in (right).

Considering all the trip requests, the waiting time experienced by users varied from a minimum of 1 min to a maximum of 31 min, with an average waiting time of 10 min. The in-vehicle time experienced by users varied from a minimum of 1 min to a maximum of 28 min, with an average in-vehicle time of 11 min. In 34 % (32 out of 90) of the rides, users experienced a waiting time within the range 6–10 min, while in 36 % (34 out of 90) of the rides, they experienced an in-vehicle time within the range 6–10 min (Fig. 16).

It was possible to determine the difference between the actual waiting and in-vehicle times and those displayed by the application. The differences between the observed waiting times and the ones estimated by the mobile application were 5 min (Root-Mean-Square Error, RMSE) considering an average waiting time of 10 min (%RMSE = 50 %, Pearson Correlation Coefficient, PCC = 0.83). The differences between the observed in-vehicle times and the ones estimated by the mobile application were 5 min (RMSE) considering an average in-vehicle time of 11 min (%RMSE = 46 %, PCC = 0.74).

As can be noted from Figs. 17 and 18, the mobile application overestimates the waiting time and the in-vehicle time experienced by users in most cases.

At the end of the pilot study, a customer satisfaction survey was addressed to the users. The questionnaire included questions regarding the ease of use of the user mobile application, the user interface, the waiting time and in-vehicle time estimate made by the app, and the

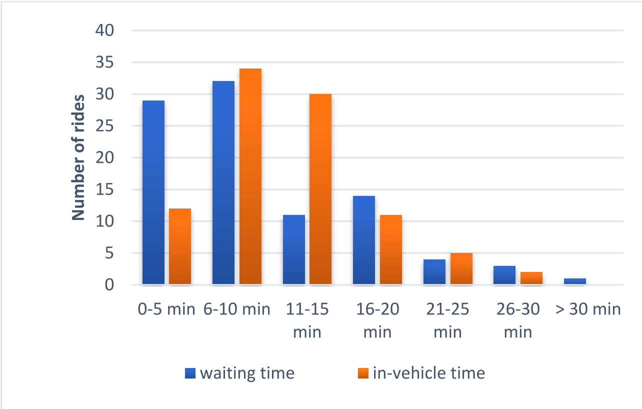

Fig. 16. Distribution of experienced waiting time and in-vehicle time.

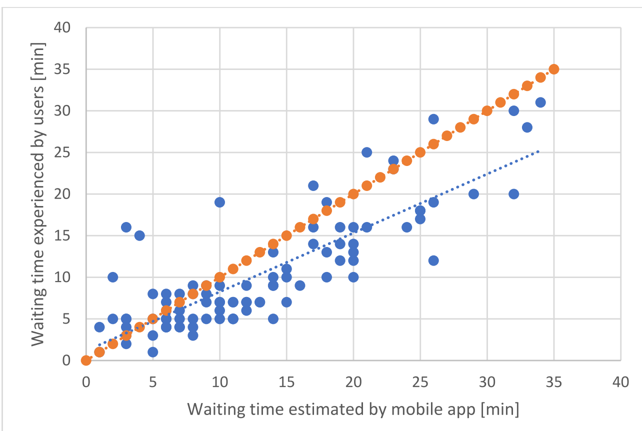

Fig. 17. Differences between the observed waiting times and the ones estimated by the mobile application.

overall evaluation of the service. We asked to evaluate these features using a Likert scale. Also, the price the users could be willing to pay to use the microtransit service was asked to respondents.

The results of the survey showed a general appreciation of the time estimate made by the app, but a lower appreciation regarding the user interface and the ease of use of the mobile application. Regarding the cost of the service, 70 % of users were willing to pay €2.00, 20 % were willing to pay €2.50, and 10 % were willing to pay €1.50. Overall, the interviewed users were satisfied with the service, with 50 % rating it as "good," 20 % rating it as "fair," and 10 % rating it as "excellent."

5. Conclusions

Despite governments' efforts to develop public transportation services aiming to improve transportation equity, the lack of funds for transit operators, the low mix of land use patterns, and car-oriented community designs lead to inadequate and inefficient transit services, especially in low-population or low job density areas.

In this paper, we proposed a semi-flexible microtransit service. The following circumstance influenced this decision: a public transport company currently operates at the city level using fixed schedules and routes, and our proposal advocates for a gradual transition towards greater flexibility in suburban areas. Operating with flexible routes and without a fixed schedule, microtransit could expand access to transit hubs and replace traditional low-quality bus lines in suburban areas. Ensuring the mobility of low-income or elderly people with transit services through microtransit can contribute to minimizing social exclusion. Microtransit PUDOs can be more accessible than bus stops, preventing elderly people from walking long distances; microtransit can reduce waiting times at stops, preventing elderly people from standing for a long time; and if financially supported as public transport, it can cost as much as a bus, meeting the needs of low-income people.

This paper shows that semi-flexible microtransit services can be designed using a multi-step GIS-based approach, considering the microtransit demand, accessibility, safety, spatial and technical constraints. These features were only partially considered in previous studies about the design of microtransit services. Several authors, including Itani et al. (2024), have explored these characteristics from a qualitative perspective. In this study, we extended the analysis by integrating a quantitative approach.

The traffic assignment of the daily microtransit O—D matrix – estimated using RP and SP surveys – could help to identify the potential microtransit routes where to locate PUDO stops. However, other criteria, like the safety of pick-up and drop-off locations, the degradation of the road surface or the road width, must be taken into account. We proposed a method to go beyond the criteria usually adopted by public transport companies and provide them with a framework to preliminarily design the service.

The methodology was applied to a case study, using a suburban area

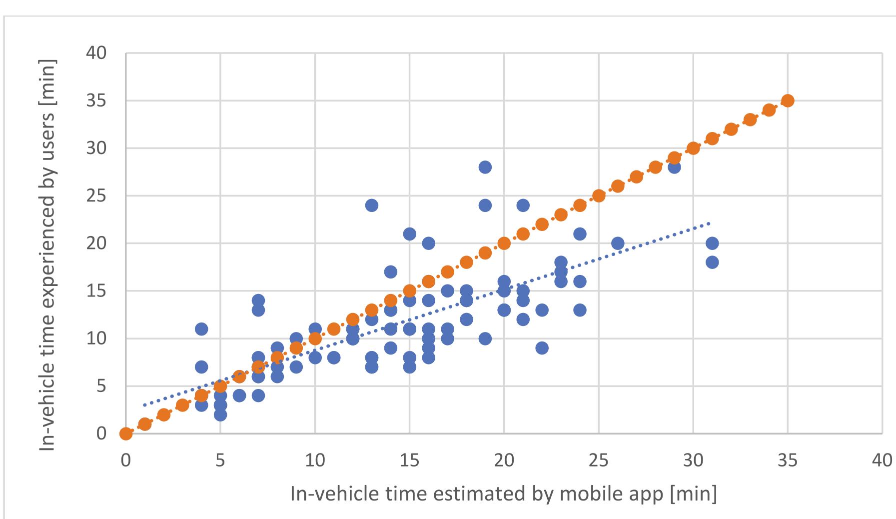

Fig. 18. Differences between the observed in-vehicle times and the ones estimated by the mobile application.

in the northern part of Palermo, Italy, as a study area. However, the method is generalizable and may be applied in other contexts. The identification of fixed routes is undertaken by considering the road segment with the highest traffic flow, as indicated by the traffic assignment, and, starting from there, a sequence of road segments is established by selecting the roads with higher traffic flows over others. Below a certain threshold for the traffic flows, we opted to introduce a detour rather than expanding the fixed routes. This threshold is context-specific, depending on the size of the study area, since expanding the fixed routes means increasing the travel time.

We identified some fixed routes serving most of the users, and some detours to expand the access to the service. The design of the microtransit network resulted in 90 % of inhabitants living within a 10-min walk from a PUDO; in this way, microtransit network can be more accessible than the existing bus network, meeting the needs of elderly people. We conducted a pilot study to test the microtransit routes, assessing the average waiting time at stops and the average in-vehicle time experienced by users and compared them with those estimated by a mobile application for users. In the pilot study, the average waiting time at microtransit PUDO's was equal to 10 min, and 76 % of the rides have a waiting time of less than 15 min. These waiting times are significantly lower than those currently experienced by public transport users (20 min for some bus lines, as shown by Table 1). Moreover, considering the surveys conducted to analyze the performance of the bus service in the study area (Table 1), we found that the bus lines with high waiting times (20 min), i.e. bus lines 603 and 616, served on average 6 passengers/h and 23 passengers/h respectively. Thus, for these bus lines, passenger demand is very far from the buses' capacity, resulting in a non-cost-efficient bus service. According to the results of the pilot study, 86 rides out of 94 (91 %) had a waiting time of less than 20 min. Thus, microtransit may offer improved customer experience with better waiting times, potentially attracting higher demand.

Although the mobile application overestimates the waiting time and the in-vehicle time experienced by users in most cases, the customer satisfaction survey conducted during the pilot shows a general appreciation of the users of the in-vehicle and waiting time estimates made by the mobile application. This is because, in most cases, they had to wait less than the application estimates predicted.

A limitation of the pilot was the involvement of only students and staff of the University of Palermo, which did not allow for an assessment of the actual propensity to use this service by residents of the study area, and especially by vulnerable groups.

Customer satisfaction confirms that microtransit can be a viable solution in suburban areas and that users would be willing to pay 2.00 € (a little more than a bus ticket).

However, users' willingness to pay, although estimated through the customer satisfaction survey, could then be different, considering that the service was free during the pilot and the willingness to pay of low-income families was not investigated.

In conclusion, the microtransit service would be an innovative solution to reduce travel experience disparities between residents of suburban areas and urban centers, where traditional public transportation is more efficient. The challenges of suburban areas, such as low population density, a low transport demand that is spatially and temporally dispersed, and the absence of an effective public transportation infrastructure, require flexible approaches. Providing on-demand transportation services using compact vehicles, such as vans or minibuses, integrating digital platforms to facilitate booking and route adaptability, can bridge the gap in suburban mobility, promoting more equitable neighborhoods and sustainable communities.

A limitation of the study is having neglected the temporal variation of demand, considering an average daily and hourly demand. Nonetheless, we aimed to provide public transport companies and local authorities with a straightforward GIS-based method for conducting a preliminary design of a semi-flexible service. In this context, we estimated the average hourly demand and sized the fleet accordingly, as the demand is unlikely to deviate significantly from the average value.

CRediT authorship contribution statement

Alessandro Emilio Capodici: Writing – original draft, Data curation. **Martina Citrano:** Writing – original draft, Data curation. **Gabriele D'Orso:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Formal analysis, Data curation. **Marco Migliore:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Leonardo Minaudo:** Visualization, Software, Data curation. **Riccardo D'Angelo:** Software, Resources, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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