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Assessing potential sustainability benefits of micromobility: a new data driven approach

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Abstract

Promoting the shift from private cars to micromobility (e.g., bike, e-bike, scooter) can represent a valuable action to improve city sustainability and liveability. Micromobility can help to replace trips by individual private cars (e.g., daily short round trips) as well as to improve coverage and accessibility of transit services, and, subsequently, to reduce the traffic impacts (e.g., pollutant emissions). It can be seen as a potential solution to move people more efficiently in urban areas, as well as to push people towards a more active mobility behaviour, contributing to the well-being goals. In this context, the paper, rather than inferring the users' propensity to change their travel mode, proposes a methodology to identify car trips that can be considered the most compatible with micromobility. Estimation of the potential demand (e.g., the upper level of car trips that could be replaced by micromobility) is carried out by exploiting the opportunity offered by floating car data (FCD) for characterising car trips. Its goodness is therefore evaluated through an application to a real case study (i.e., the city of Trani, Apulia Region, Southern Italy), divided into seventy traffic zones, and where a FCD dataset of about 5,200 trips was available. The FCD allowed the car trips to be characterised (e.g., origin and destination, path features) instead of using the traditional surveys. The results indicate that a significant share of daily car trips can be substituted (i.e., the most compatible) by micromobility (31% of car round trips in the case study), with considerable potential environmental gains (traffic emission reduction; less than 21% of total emissions from private cars). Results can be of interest to local authorities in integrating micromobility in urban mobility planning and promoting new sustainable transport alternatives, as well as to transport companies for designing new appeal services. The developed methodology is parametric and uses easy-to-obtain data available worldwide; thus, it can be easily transferred to other city contexts.

Keywords Micro-mobility, Micromobility, Active mobility, Physical mobility, Floating car data, Demand analysis

1 Introduction

The transportation system assures users to satisfy their needs of travelling, however, many trips are undertaken by private cars, which are not environmental, social and economic sustainable. In Europe and Italy, for example, private cars are responsible for approximately 61% and of about the 69% of all pollutant emissions produced by transportation [39]. Such a figure, within the urban area, is stronger. For example, the transportation sector in Asian cities is responsible for 80% of air pollution, and the problem will become more serious in the future with the growth of emerging Asian economies and the popularity of private vehicles. Urban areas also face with issues related to road accidents (*social* sustainability), as well as congestion with the subsequent increase in travel costs (e.g., the cost of peak traffic congestion in the United States is approximately 13 cents/mile; [45]). Therefore, a car-dependent city becomes dysfunctional, inefficient and unliveable [100]. The transportation system, on one hand, ensures the satisfaction of the mobility needs of people and business; on the other hand, it can create

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an unsafe and unhealthy environment where to live. In addition, dependence on travelling with motorised and private vehicles can cause reduction in physical activity with subsequent health problems. The last data from the World Health Organization (WHO, [105]) reveal that, at the global level, nine out of ten people breathe air containing pollutants exceeding WHO air quality guidelines. Air pollution is also fourth in the list of global health risk factors [83]. Research results [48] indicate that in relation to the costs associated with the treatment of diseases caused by pollution, the assessment of accident risk assessment every kilometre travelled by car, in EU countries, costs society on average 0.15 € whereas every km travelled by bicycle benefits society in the form of 0.16 €, due to the improvement of public health and the absence of negative effects associated with car use.

Then, the city planners are facing with the emergency to develop, promote and implement actions that allows the mobility needs of people and businesses in cities (and their surroundings) to be satisfied in order to assure a better quality of life. Among the actions that can be implemented in urban areas to reduce the car dependence and promote more environment-friendly modes, there is the promotion of the public transport, which should become the cornerstone of sustainable urban mobility, and whose promotion cannot come than from the integration of the services in a multimodal network with the subsequent promotion of the interchange among transport modes [5, 71, 85, 103]. In this context, the development of the mobility as a service (MaaS, e.g. [6, 51, 52, 86, 89]) solutions is significant, which is a novel brand of transport that could replace private cars with multimodal personalised mobility packages enabled by a digital platform capable of integrating travel planning, booking and ticketing, and real-time information services. From its first applications, this innovation was rapidly considered a potential solution for more sustainable urban mobility practices by simplifying and facilitating access to different mobility services and enabling a modal shift from private cars towards shared and less pollutant mobility [86]. However, many challenges are still ahead for MaaS solutions to become drivers of sustainable mobility, such as the potential of active modes in MaaS. Sustainable mobility is thus approached below through the lens of micromobility, and it is proposed to advance knowledge on micromobility as a key enabler of sustainability and sustainable value creation. Different cities experimented how the presence of micromobility can push users in changing their mode-choice behaviour. But these results are quite city-specific, probably because this depends on the urban context and the users' habits. For example, from a survey carried out in Paris [21], it emerged that the micromobility is used for travels of less than 15 min and 2.5 miles. In particular, 21% of travels by micromobility come from motorised ones, while 35% from walking. In Oslo [43], micromobility took 60% of users from walking, 23% from the transit system, 3% from private cars, and the remaining from other modes. This modal shift cannot only be encouraged by supporting users with new telematics tools, but it also depends on the characteristics of travel [34, 45, 54, 57, 96]. For example, there are some types of private car travels, such as systematic travels over short distances [42], that could be replaced by means of transport which are more environment-friendly (e.g., electric scooters). As said, micromobility can be also seen as a segment of MaaS [53]; therefore, in this context, the micromobility represents a valuable lever for supporting the shift from motorised modes. Naturally, to favour this modal shift, interventions in transport supply must be planned [91] and simulated to assess their contribution to sustainability [87, 104]. Therefore, assessment methodologies that include the simulation of micromobility need, as shown, for example, by Jacyna et al. [59], who proposed an approach to simulate the flow of bikes in a city, also considering the travel purpose, or by Reck et al. [84] that developed a mode choice model including shared and private micromobility.

To date, there is no unambiguous definition of micromobility. In a first definition, provided by the Society of Automotive Engineers [94], the micromobility is a mobility performed by using *vehicles that are primarily designed for human transport and to be used on paved roadways and paths*, the human-powered vehicles are excluded. The vehicles have to be fully or partially powered, with a curb weight less than 227 kg and a top speed less than 48 km/h. A second definition, provided by International Transport Forum [57], is still based on the *vehicles with a mass of no more than 350 kg and a design speed no higher than 45 km/h*. This definition includes *human-powered and electrically-assisted vehicles, such as bicycles, e-bikes, skates and kick scooters.* A further definition [54] refers to a micromobility vehicle *as defined through CEN standard EN 17128:20209* (this standard refers *to personal light vehicles totally or partially electrically powered from self-contained power sources with or without self-balancing system having battery voltages up to 100 VDC, with or without an integrated battery charger with up to a 240 VAC input* [19]). *Bicycles (as defined through ISO 4210) are not new micromobility devices, and electric power assisted cycles (EPACs), as defined through EN15194, though newer than bicycles, are very similar to bicycles so that they can be treated in almost the same way.* In the paper, this last definition, which also includes both traditional and electric bikes, is adopted.

Micromobility can help to push users towards sustainable modes of transport with low (or zero) environmental emissions [1]. Some studies pointed out the cultural, legal, political, organisational, financial and knowledge-related elements that could hamper the transition towards an environmental-friendly mobility [10], while others evaluated the environmental performance of micromobility in the framework of life cycle assessment (e.g., [30, 97]). De Bortoli [30] compared the impacts of shared micromobility and private micromobility considering different scenarios. Sun and Ertz [97] focused on shared micromobility concluding that, currently, such services (excluding docked bike sharing) do not produce an improvement in terms of emissions mainly due to its low rate. Thus, city authorities must promote policies for demand management able to encourage the use of less intrusive transport modes. In this context, recently the European Commission (EC) promoted the development of guidelines for the implementation of sustainable urban mobility plans (SUMPs, [98]) which foster towards an integrated and balanced development of all transport modes. In addition, given that micromobility is changing how some people move around the city, bringing along new and urgent challenges such as operational issues relating to safety, use of public space, traffic management and others, for local and regional authorities, urban planners and national decision-makers, the EC promoted the guidelines for better integrating micromobility within urban mobility planning [22, 90, 98]. Thus, the integration between micromobility and public transport can help to unfasten urban spaces from motorized transport. The safety aspects of micromobility (e.g., the perception of road safety by micromobility users) are addressed in the literature considering both aspects related to infrastructures and elements concerning the protection devices. In the first case, it tries to achieve safety by adopting policies on the road network (e.g., avoiding to have bikes and cars sharing the lanes). In the latter, safety is provided by personal devices (e.g., helmets).

Therefore, the main objective of the paper derives, i.e., to propose an approach to identify the car travels that are the most compatible with the micromobility and then to provide a first estimation of the potential demand by private car that may be replaced by micromobility (i.e., shift from private car to micromobility without asking users to change substantially their travel behaviours). Besides, given that the telematics and GPS (Global Position System)-based applications allow users to be traced continuously in time and space, the proposed approach exploits the opportunity given by floating car data (FCD) to identify the private car trips that could be replaced by micromobility. Therefore, recalling Agenda 2030 by the United Nations (UN) and its seventeen goals, the paper wants to contribute to the Sustainable Development Goal 11 (SDG 11), and in particular to target 11.2 (that relies with the sustainable transport systems [101]), also considering that the micromobility can be an effective means to improve transit coverage.

The paper is organised as follows. Section 2 outlines the literature review. Section 3 presents the proposed methodology, while Sect. 4 presents the results obtained in a real case study. Finally, the discussion, the conclusions, and the possible developments are drawn in Sect. 5 and in Sect. 6.

2 Literature review

In literature, although micromobility is a recent means of transport, several works analysed its role to be an effective means to switch from traditional modes (e.g., car) to more sustainable modes (e.g., e-bike) for short distance travels or for access/egress to/from public transport [75]. Walking, cycling, and other forms of mobility involving the use of wheels increase quality of life and the health conditions by supporting an active lifestyle [13] and, at the same time, produce social, economic, and environmental benefits [106]. Different aspects have been dealt, covering the *demand analysis* (e.g., why the user chooses the micromobility, for which type of travels, mobility patterns), the *mode choice* (e.g., the demand shift from traditional modes to micromobility), the *integration with the transit services*, the *user safety*, just to name some ones.

2.1 Demand analysis

In terms of *demand analysis*, Fan and Harper [42] proposed a methodology for estimating a threshold value for private car trips that could be replaced by micromobility (they focused on trips less than 3 miles and considered user characteristics and weather conditions). Torrisi et al. [99] investigated the influence of the travelled distance on the trips by university students. It emerged that about the 64% of trips are less than 10 kms, and the 55% are less than 5 kms. Abouelela et al. [2] analysed a demand segment (users 18 to 34 years old) to individuate the potential demand to move from car sharing to e-scooter sharing. The determinants considered in the choice are travel time and cost, the safety, and the weather conditions. Arsenio et al. [7] evaluated the willingness of young people (less than 21 years old) in using e-bikes for home-school/university travels highlighting the barriers (e.g., lack of protected lanes) encountered. Sohrabi and Ermagun [95] proposed a methodology to predict bike share by analysing spatial and temporal patterns of traffic flow. A regression model able to relate the micromobility trips and the urban characteristics (i.e., land use, type of area, transit facilities) was proposed by Jiao and Bai [60]. Similarly, Hosseinzadeh et al. [55] applied a geographically weighted regression to correlate e-scooter travels with demographic characteristics (e.g., gender, age) and urban elements (e.g., network characteristics, transit availability). Lee et al. [66] proposed a regression model to foresee the e-scooter travels in relation to social, economic, and demographic attributes. Poliziani et al. [81] estimated a model to foresee the number of daily micromobility trips by considering as attributes the day of the week (i.e., holiday or weekday), the weather, the temperature. Entropy theory is a further approach proposed in Poliziani et al. [80] to individuate the distribution of the cyclists in the study area on a typical day. Besides, the entropy can be used as an attraction parameter and, then, put in a demand distribution model. Park and Hwang [78] proposed a hybrid model (genetic algorithm and deep learning) for micromobility demand forecasting to manage the service provided to users. Zhang and Song [109] developed a framework to investigate the demand pattern in using micromobility and applied it to the dockless bike sharing. Bordagaray et al. [12] developed a procedure to identify the different uses of shared bikes in relation to the transportation needs.

2.2 Mode choice

In terms of *mode choice*, Eccarius and Lu [37] analysed the factors influencing the choice of an e-scooter sharing service by considering the intentions, motives, and beliefs of the users. Baek et al. [9] proposed a multinomial logit to simulate user choice of e-scooter in a set of hypothetical scenarios. Similarly, Glavić et al. [47] analysed how the micromobility could change the urban travels by testing the user's willingness to use electric scooters. Christoforou et al. [21] developed models to simulate the ownership of a vehicle, the travel frequency, and the travel time. In De Ceunynck et al. [31], the factors influencing the behavioural changes are analysed, highlighting the motivations and the barriers to the choice of micromobility. An investigation of the user intentions to use e-scooters is reported by Lee et al. [64], where the factors affecting the choice are investigated for different demand segments. Günther et al. [50] explored the users' behaviour when using micromobility as a component of a multimodal system, showing that such a system allows a significant reduction in mobility costs.

To evaluate the factors that promote the use of e-scooters, Nikiforiadis et al. [73] tried to identify the profile of users that were attracted to e-scooters by analysing the behaviour of users and non-users. An analysis of mode choice with the logit model among four different micromobility modes (i.e., dockless e-scooters, dockless e-bikes, docked e-bikes, and docked bikes) is proposed by Reck et al. [84]. The main attributes considered in the systemic utility are price, travel distance, and time of day. About 2,800 trips per day are performed by shared micromobility means. Di Gangi et al. [33] analysed the demand of commuters on systematic travels with the objective of assessing the use of e-bike for such travels and evaluating the corresponding (positive) impact on the environment. Parkin et al. [79] proposed an aggregate logistic regression model to simulate the bike choice in the home-work daily trips. The attributes considered in the model specification are: socio-economic data (e.g., number of owned cars, user age) and physical data (e.g., weather). Rowangould and Tayarani [88] analysed how the bike facilities (e.g., lanes for bikes) affect the mode choice, thus reducing the trips by car. In particular, it emerged that the presence of bike reserved routes would push even inexperienced cyclists to use this mode of transport.

Furthermore, delivery services have been successfully shifted to micromobility (mainly bikes) from traditional transport options in many cities. For example, in Copenhagen, Dupljanin et al. [36] investigated the opportunity to shift car-based trips to bicycles showing that bicycle-based fleets provide a faster, more environmentally sustainable, and potentially cheaper alternative to traditional car-based fleets. A study on cargo-bike ownership estimated that by the 41% of car trips can be replaced by micromobility [40]; similar results have been obtained in the Cyclelogistics Project, where 51% of motorized trips were identified potentially suitable with e-bikes. Paloheimo et al. [76] simulated the distribution of book rentals in Finland to and from the city library through citizens, while proposed probabilistic-behavioural models to simulating the use of electric micromobility for crowdshipping.

2.3 Integration with transit

In terms of *integration* with transit services, Azimi et al. [8] investigated the integration between some micromobility modes (such as scooters, bikes) and how this influences the transit market. Focusing on access/egress trips, it emerged that a low rate of users (from 2.2% and 2.6%) used the micromobility for both access and egress to transit. Kager et al. [62] analysed the combined use of bicycles and trains by considering the performance and the flexibility of such an integrated system, also considering that the catchment area for micromobility users is less than 7.5 kms. Similarly, Jonkeren and Kager [61] examined this integrated system from the point of view of the bicycle parking spaces near a train station; the aim is to assess the possible policies to encourage combined bicycle-train travels. To simulate the bike sharing as a means for last-mile travel, Adnan et al. [4] proposed a hybrid model by considering the users habits, attitudes and their perception of some attributes (e.g., weather condition) that influence the choice. Miramontes et al. [70] provided a descriptive analysis related to the user's acceptance in the use of an intermodal hub (bus, metro, tram) offering a set of shared services (e.g., bike sharing). Griffin and Sener [49] developed a planning framework in order to analyse the relationship between a bike sharing system and a transit system by considering the attributes of the bike sharing affecting the integration with the transit system (e.g., distance from the transit stop, bike sharing station location). Van Mil et al. [102] explored the predictors affecting the combination bike-railway. For this purpose, they designed a stated preferences survey where some factors (such as travel time, time and parking cost for bike, time on train, and number, if any, of transfers during the travel on train) are considered. Cheng and Liu [20] proposed an approach to evaluate the user disutility during a combined bike-transit travel. The finding is that the perceived disutility depends on the sex, the trip frequency, and the purpose. Lee et al. [65] developed the concept of bike-based transit development, considering the influence of the catchment area dimensions in users' decision in combining the two transport modes.

In the field of optimization, Li et al. [67] proposed an approach to design jointly a transit network and the access/egress system by bicycles (and walking). Zuo and Wei [110] developed an approach for bike network design with the aim of improving the number of connections by bike, also integrating the bike network with the transit system. Since the decision elements involved in the process are multiple and often in contrast, they proposed to compare different design alternatives with a multi-criteria analysis approach. Wu et al. [107] analysed the shared bike as an access/egress mode to/from a transit system, comparing the role of bike feeder system in the case of existing network or in the case of jointly optimization of the bike and the transit systems.

2.4 User safety

In terms of user *safety*, Yang et al. [108] examined the safety issues correlated with the use of e-scooters, highlighting that accidents suffered by micromobility users depend on the interaction between vehicles and the urban environment. By analysing the riding process in different situations, Ma et al. [68] studied the interactions between e-scooters and environment, with the aim to define a method for accident data collection to better understand the risk connected with the e-scooter use. A descriptive analysis on the accidents involving e-scooters is reported in Bekhit et al. [11] that provided a classification in relation to the severity of the injuries. Prati et al. [82] proposed a data mining approach to individuate the determinants (e.g., type of road, user age, gender) of the accident severity. Siebert et al. [93] provided an analysis on the ergonomics of the brake system to correlate them with user safety. Kamel and Sayed [63] provided an analysis on bike network indicators with the aim to understand their relationship with the user safety. The findings are that a high accessibly (that favours the trips by car), the hight junction number and the length of the route have a negative impact on bike user safety. Carvajal et al. [16] defined a method to individuate the relationship among crashes involving bike users and external factors. The aim is to individuate the spatio-temporal trend of the accidents and their correlation with the characteristics of the users, the type of vehicles involved in the accident, the land-use and the characteristics of the road. Ding and Sze [35] provided a regression method to correlate the bike accidents with a set of predictors (such as road network characteristics, land use, socio-economic data) considering explicitly the interactions between bicycle-vehicle and bicycle-bicycle accidents. Saad et al. [92] focused their analyses on crashes at intersections, the conclusion is that bike lanes, sidewalk width and median width are attributes that contribute to the reduction of accidents. On the other hand, traffic flow, intersection size, and number of intersection legs increase the number of accidents. Similarly, Cai et al. [14] analysed some factors affecting the bike crashes at junctions. One of the findings is that a bike lane, when the turning manoeuvres interfere with the flow of cars, could reduce the safety. Deliali et al. [32] assessed how different types of junctions affect the bike user's safety. In particular, the attention is paid to the presence of reserved bike lanes and, in this case, what happens at junctions by varying their configuration with the aim of alerting the drivers to the presence of bikes.

2.5 Gap

The above literature review shows that some mobility and transport aspects of micromobility have attracted researchers, and some significant indications to foster users of the private cars towards micromobility have been proposed. However, few studies pointed out the potential demand that could be replaced (or easily transferred) from car to micromobility (e.g., given that it could be more comfortable to travel in urban areas avoiding the traffic delays as well as the parking issues) and the potential benefits in terms of well-being and environmental aspects. The paper points out the latter. Besides, the above review highlights the need for predictive tools that can be used during the planning phase (e.g., SUMPs preparation). Then, this study wants to contribute by proposing a method that takes advantage of the opportunity offered by FCD combined with vehicle registration data (which allows one to limit the use of resources for delivering traditional surveys, [29]), to individuate the potential demand to be shifted (i.e., replaced by) towards micromobility. The joint use of FCD and vehicle registration data allows to obtain a significant overview of private car travels, with important practical implications. For example, the use of standard, well-established data and procedures, as discussed below, allows transferability and a large use worldwide. Indeed, the framework can be applied to different cities in the world, and the use of standard and easy-to-implement procedures, allows not only a broader application but also a unique reference that promotes the comparison of cities in terms of sustainability and liveability.

In fact, FCD are usually used in the transport field to address a variety of problems, from freight distribution [24, 26] to path choice models [23, 28]. They were showed to be reliable in calculating origin–destination matrices [27], providing, at the same time, an effective alternative to traditional surveys. In the traditional way, to investigate the rate of demand that could choose a transport mode, a survey (with related times and costs) must be designed and, often, the number of interviews is low, and some answers are incomplete and/or unreliable. FCD overcome these problems by providing, in the specific case treated in this paper, a dataset of trips to be classified in order to individuate a class of trips that could be replaced by micromobility (see next section for details).

3 Methodology

The purpose of the proposed methodology is to obtain the potential demand by private cars that can be replaced by micromobility evaluating the potential gain/benefits in terms of environmental impacts. In particular, in order to shift users from private cars to micromobility, only particular trips made by the residents in the study area will be considered. In particular, attention is paid to specific systematic trips performed by residents (e.g., round home-to-work trips). We refer to mobility segments that can be easily and shortly interested by such a shift and cities can implement operational or tactical actions for supporting it. In fact, the focus is on trips that do not require changes in users' travel behaviours (e.g., round trips and home-based trips within well-defined length/duration thresholds).

Figure 1 shows the proposed procedure, articulated in two interacting stages:

- *data and trips analysis*; it aims to identify the *potential demand* for micromobility inferring current private car trips;
- *system simulation*; it aims us to evaluate the environmental benefits of such a mode shift through quantitative and easy-to-calculate *indicators*.

3.1 Data and trips analysis

At this stage, receiving as main input the *floating car data* and, by means of a *data analysis* procedure (that takes as input the *study area zoning* to link the geographical data with the zones in the study area), it gives as output the characteristics (e.g., length, travel time, number of stops) of the *trips* performed by private car users. Note that this data analysis refers to a sample of trips without any information on the users: the dataset contains the route followed point by point but, as an example, it is not possible to know if the car belongs to a resident (or in general to a systematic city user) in the study area or not, as well as who is the driver. Therefore, some assumptions are made based on knowledge acquired from the study area. For example, comparing the *registration data* of the vehicles with the systematicity of the trips (e.g., origin and destination, departure and arrival time, day of the weeks – *trips analysis*) it is possible to infer it. In particular, to obtain this information, a dataset of *vehicle registration data* is used as an additional input for the *trip analysis* procedure. At this stage, the procedure starts with the identification of the type of trips performed by residents, also considering the vehicle type (distinguishing small, medium and large vehicles). By crossing the collected trips with the vehicle registration data, it is possible to compare the origin of the first trip in the morning with the municipality where the vehicle is registered. If this comparison is positive, it is assumed that the user is a resident.

The trips of the residents (i.e., systematic city users) are analysed individuating two (disjoint) sets:

(1) *trip chains* (sequence of trips, following each other so that the destination of one trip is the origin of the next),
(2) home-based *round trips* (a particular case of trip chain composed by only two trips).

The procedure for identifying round trips and trip chains from FCD is schematised in Fig. 3. The extraction of these types of trip is performed considering some constraints (e.g., travel time, travel distance, stop time at destination). As previously assumed, the daily-surveyed trips start from home and end at home. Therefore, identification of home is required given that FCD do not provide such an info. A reasonable assumption is that the home is the initial point (point A in Fig. 2) of the first trip and the final point (point B in Fig. 2) of the last daily trip. To avoid problems related to the fact that the vehicle may have been parked in different places, a circle (radius r) centred in the point A is considered: if point B falls in the influence (circle) area, then home is assumed to be in this

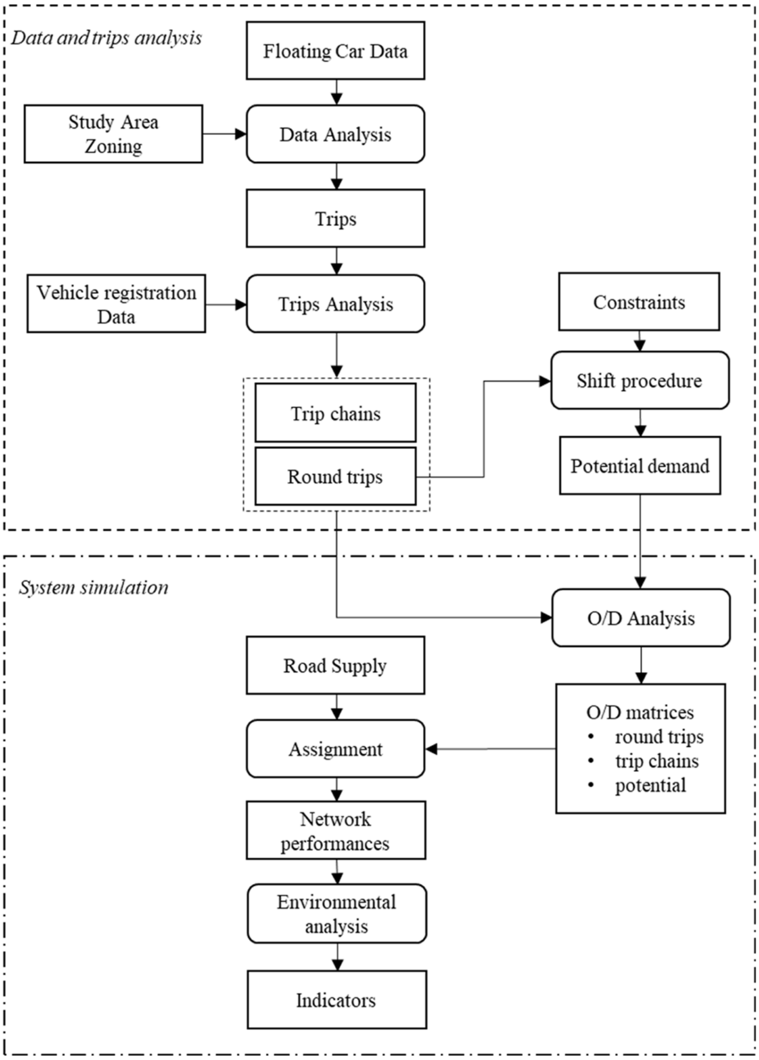


Fig. 1 Proposed methodology

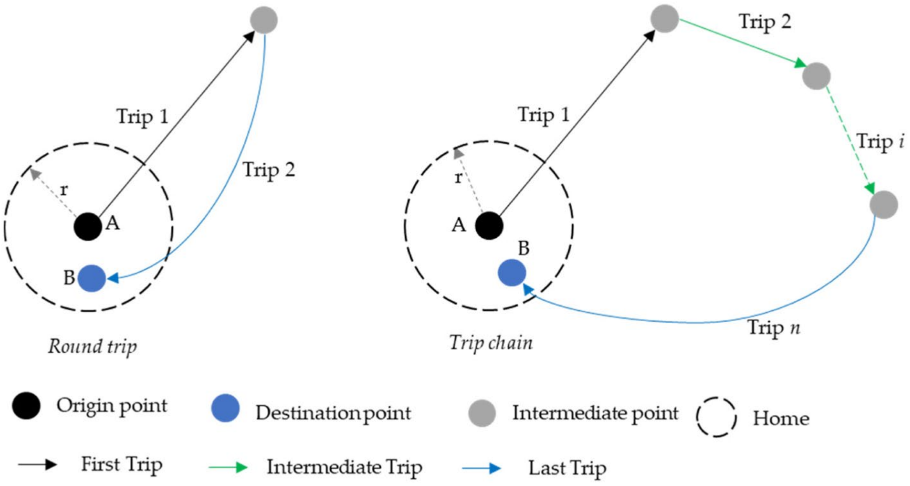


Fig. 2 Round trip and trip chain example

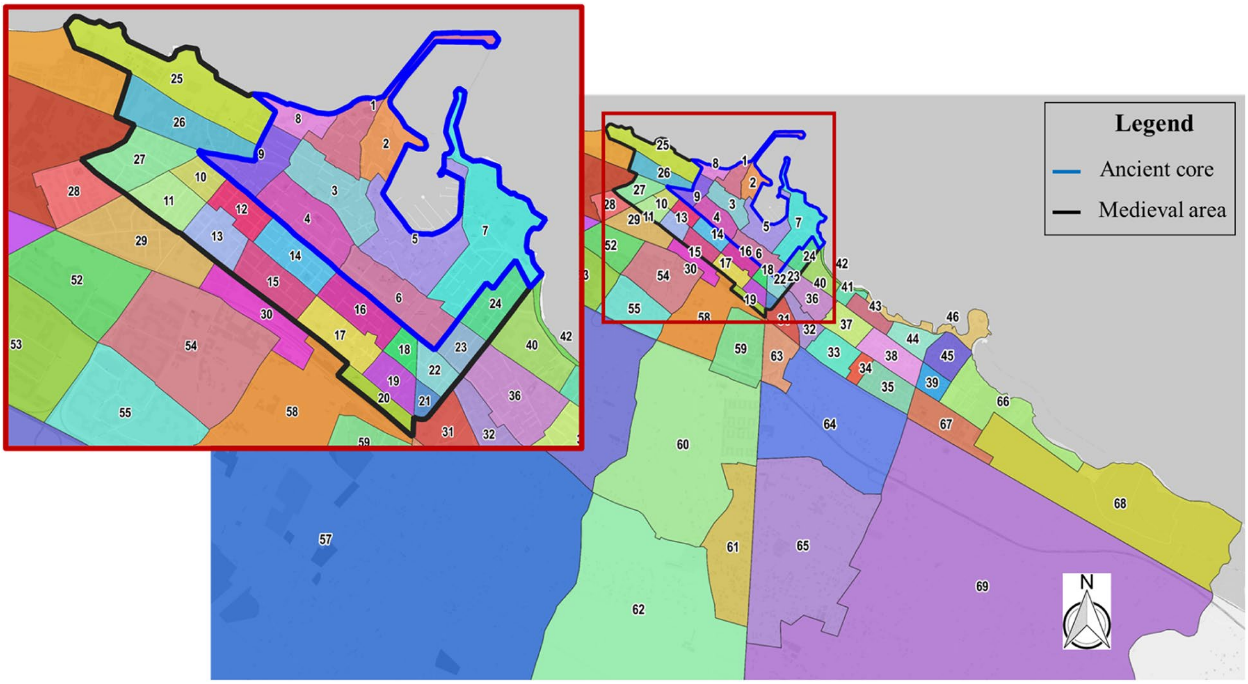


Fig. 3 Study area and zoning (with a zoom on the ancient district)

area (obviously, other methods could be implemented also taking into consideration the plot of urban network). The collected trips are then analysed as follows: the first trip starts from home; the second trip starts from another point with two possibilities:

(1) the destination is home and then a *round trip* is undertaken;
(2) the destination is different than home and then a *trip chain* is performed (in this case, the procedure continues until all the trips in the trip chain are identified).

Subsequently, assuming that the private car trips that could be replaced by micromobility are the round trips (for the already discussed reasons), a *shift procedure* is applied to round trips in order to obtain the *potential demand* to replace through micromobility. This procedure adopts some *constraints* (in particular, travel length, travel time, stop time at destination) to characterise the trips which could be easily transferred to micromobility (i.e., to individuate the potential demand). Note that the output of this approach is a rigid demand: in fact, the use of FCD does not allow us to evaluate how a variation in the costs affect user behaviour in deciding if undertaking the travel or not.

3.2 System simulation

Once the potential demand is estimated, the further stage allows the environmental benefits to be estimated. The *O/D analysis* procedure allows to build the *O/D matrices* (one related to round trips, one related to trip chains and one related to potential demand) for being used for the traffic simulation. Since the FCD are a sample of all travelling cars, an expansion procedure is required. In fact, from vehicle registration data, according to Comi et al. [25], it is possible to define an expansion index for each surveyed vehicle.

The following step is the assignment of the O/D matrices to the road network. The *assignment* procedure allows one to simulate the interaction between the demand and the *road supply* to obtain the *network performances* (e.g., flows and costs). The network performances are the input for a procedure for *environmental analysis* that considering the vehicular flows evaluates a set of environmental *indicators* (e.g., emissions by pollutant type).

4 Application to a real test case

The procedure proposed in the earlier section was applied in the city of Trani to assess the environmental traffic impact. Trani is a city of about 55,000 inhabitants located on the Adriatic coast of the Apulia region (Southern Italy). The city is made up of three main areas (Fig. 3): the ancient core, the medieval area, and the modern area [77]. The study area was divided into 70 traffic zones (Fig. 3, the colours are used to identify the zones but without any reference to zone attributes). The first 27 constitute the ancient core (9 zones) and the medieval area (18 zones).

The structure of the city implies that the car circulation, both in the ancient core and in the medieval area, is not very easy because of the narrow roads and the area regulation (the ancient core and a part of the medieval area belong to the Limited Traffic Zone – LTZ).

The population (Fig. 4) is mainly distributed (about 71%) in the modern area, while the ancient core and the medieval area account for the 9% and the 20%, respectively. The employee distribution follows a similar pattern: about 13% in the ancient core, about 26% in the medieval area, and the remaining in the modern area. About the modal share observed in the study area, statistical data from census [58] demonstrate that about the 38% of systematic trips are performed by car, about the 9% by bus, about the 52% by walking (Fig. 5). The high share of people traveling on foot is not surprising given the size of the city (i.e., the longest travel in the study area is of about 14 kms). The average distance to cover within the study area is of about 2.50 kms.

4.1 Data and trips analysis

The collected data provides information on car trips in the study area from the first to the last trip of the entire day (i.e., at least one point inside the study area on the survey days). The available data relies with the trips of private cars (e.g., without considering taxi and other service vehicles) and they were analysed in order to identify the trip patterns. Four working-day FCD (collected in November 2018) for a total of 5,255 sampled trips were available. Each entry in the database contains the vehicle identifier (an ID), the date (the date when the record has been gathered), the timestamp (the time when the record has been gathered), the geographical location (latitude and longitude), the speed, the type of road (e.g., urban, extra-urban, highway), and the direction angle (the angle with respect to the north). Besides, the registration data related to each sampled vehicle were extracted by national vehicle registration dataset [3]: vehicle class (e.g., small car, SUV), brand, vehicle registration year, fuel type (e.g., petrol or diesel).

Figure 6 details the procedure showed in Fig. 2 for the potential demand identification. It reports the implementation of the shift/replacement procedure performed to analyse the data with the aim to extract the trips that can be considered the most compatible with the micromobility, i.e., potentially those can be transferred from car to micromobility. The assumption is that the potential (compatible) demand comes from the residents that

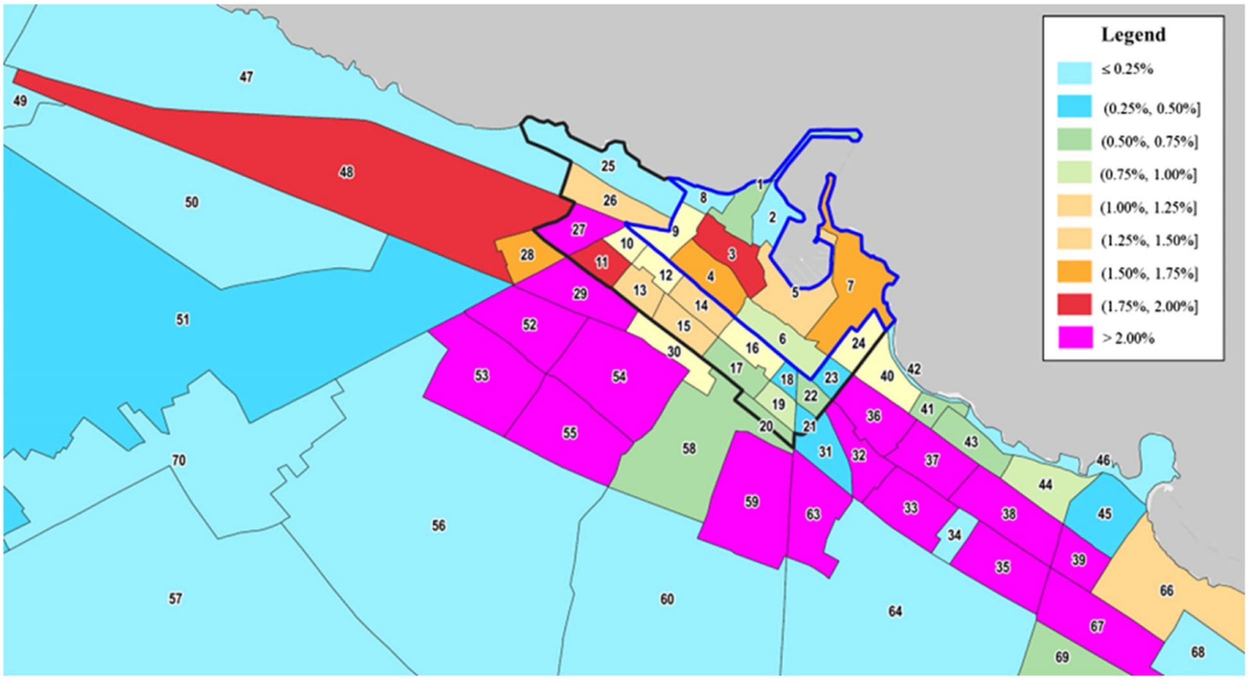


Fig. 4 Distribution of the population in the study area

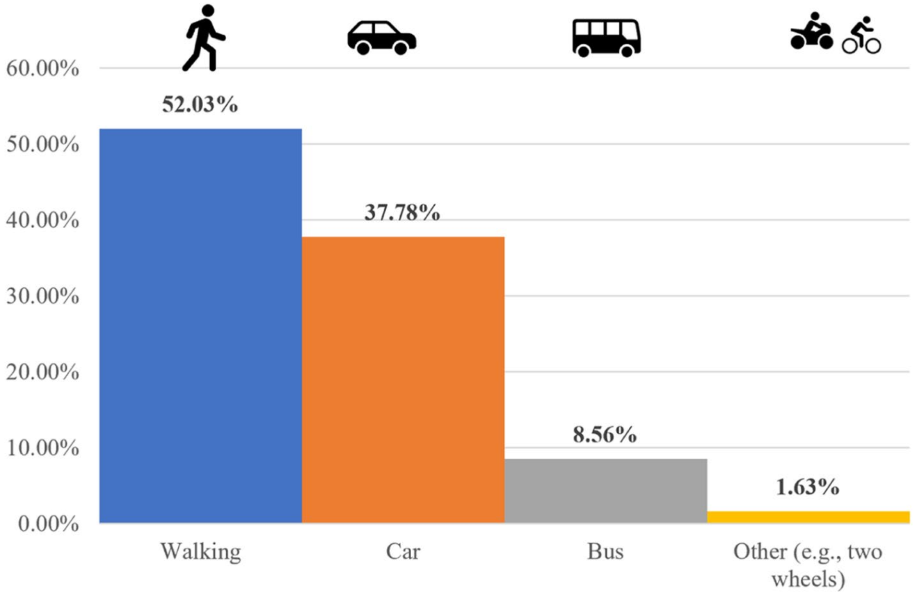


Fig. 5 Modal share in the study area

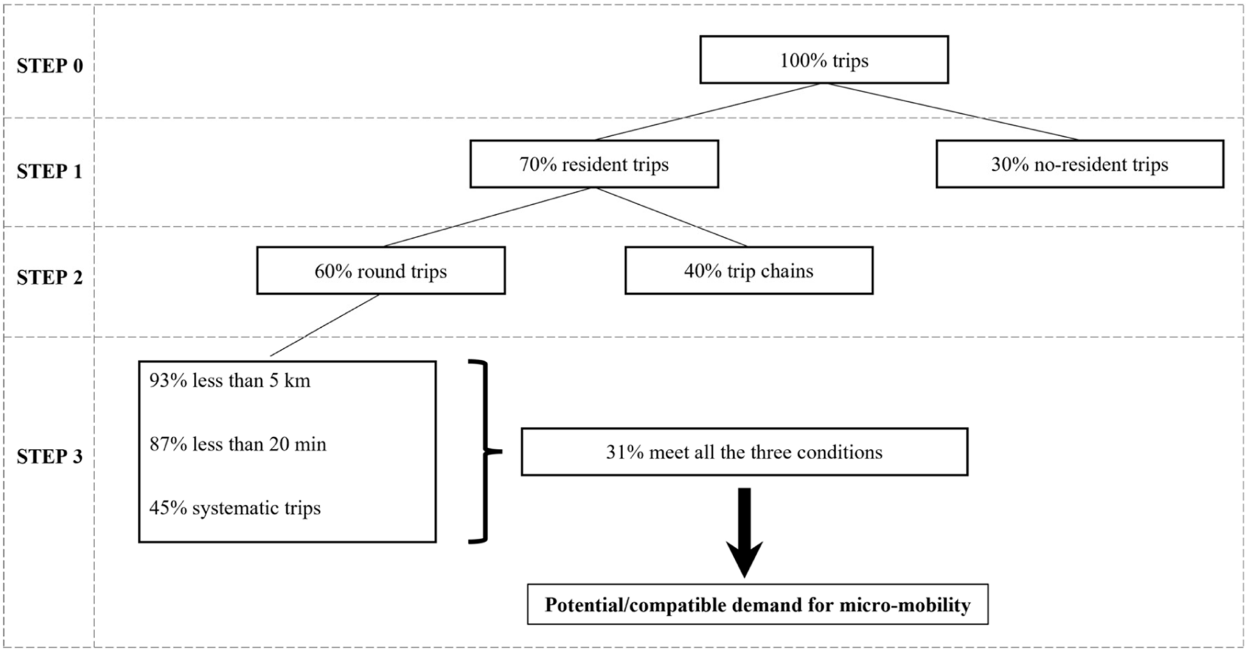


Fig. 6 Sampled trip analysis: trip analysis and shift procedure

perform home-based round trips with respect to some characteristics (related to distance and time). As reported in Fig. 6 the following steps are followed:

Step 0. From the available FCD dataset, all sampled trips inside the study area are extracted (*100% trips*).

Step 1. The analysis performed at this stage allows the trips made by residents and the trips made by non-residents to be identified (i.e., *70% resident trips vs 30% no-resident trips*).

Step 2. Then, referring to the trips performed by residents, only the round trips are considered using the procedure described in Sect. 3. In this case study, *60%* of travels are *round trips*.

Step 3. A set of constraints is introduced to filter the round trips and individuate those that, potentially, are compatible and then could be shifted to micromobility. According to the analysis performed on the mobility of the city and taking into account the literature values [56, 69, 72], the following threshold values were identified:

- *length*, only the round trips with length less than 5 kms are considered;
- *time*, only the round trips with a travel time less than 20 min are considered.

In addition to the previous constraints, another constraint on users' habits has been added to capture the systematic nature of the trip (e.g., a trip to work). Since the FCD does not allow us to directly obtain this information, an indirect approach is adopted to understand if a trip is systematic or not. The systematic trips are characterised in relation to origin, destination, departure and arrival times as well as if the stop time at destination is longer than 2 h. About 93% of the trips are less than 5 km, about 87% are shorter than 20 min, about 45% have a stop time at destination longer than 2 h. Finally, about *31% of trips* represent the potential (compatible) demand. Figures 7 and 8 report the distribution of the such a demand across the zones in the study area. In particular, Fig. 7 plots the produced (*potential/compatible-demand*) trips, while Fig. 8 the attracted (*potential-demand*) ones. It emerges that the ancient district of the study area (zones from 1 to 27) generated about the 27% of the trips and attracted almost the 29% of the trips.

4.2 System simulation

Once the potential/compatible demand by private cars that can be replaced by micromobility is identified, the following stage foresees the calculation of the link flows and then the pollutant emission produced by traffic. Link flow is the result of the interaction between demand and supply. Among the different assignment procedures present in the literature (Cascetta, [17]), the deterministic user equilibrium is used. For simulating the road supply system, network flow theory models, based on congested network flow models, are used. The network structure is represented by a graph *G(N, L)*, constituted by a set of nodes *N* and a set of links *L* (each link consists of an ordered pair of nodes). At each link, a generalised travel cost (i.e., linear combination of the link travel time and the time spent at the end node of the link) is associated. The demand matrix is built by using the FCD dataset [27]. In particular, according to the procedure discussed in earlier Sect. 4.1, three O/D matrices are considered: the matrix corresponding to the round trips, that to the

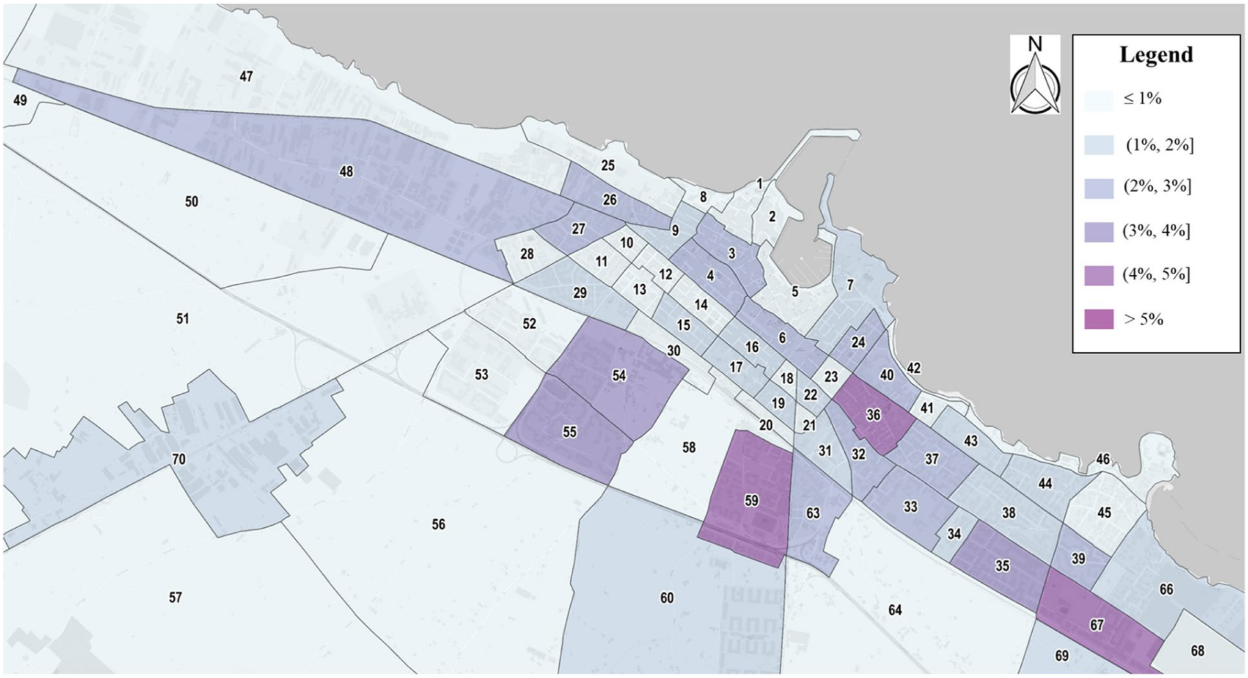


Fig. 7 Potential/compatible demand: generated trips (shares with respect to total trips by cars)

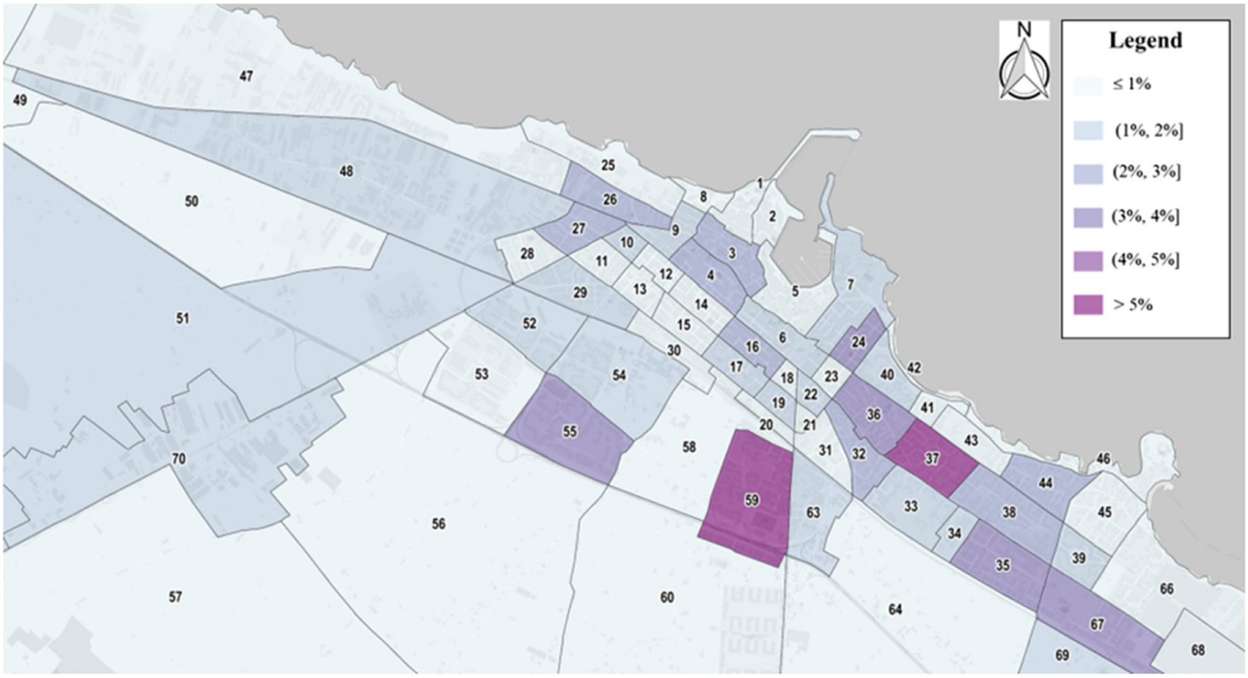


Fig. 8 Potential/compatible demand: attracted trips (shares with respect to total trips by cars)

trip chains, and the further one for the potential/compatible demand.

Calculated the performance measures and user flows for each supply element (network link), the next step is the estimation of the pollutant emissions. Air pollution has received much attention recently, and there is a large literature (e.g., [15, 41]). There are several emission models that could be applied to obtain environmental impacts [74], such models require the simulation of the transport system whose results (e.g., flows, acceleration, speed) are used as input for the calculation of emissions. One of the most extensive traffic emission modelling methods used within the European context is COPERT (COmputer Programme to calculate Emissions from Road Transport [38]), promoted by the European Environmental Agency within the CORINAIR programme. Even if the model was specified for estimation of national emissions of traffic-related pollutants, in this study the methodology was adapted for the urban and metropolitan contexts. The procedure receives as input the data on vehicle dimension, type of fuel, travelled distance, vehicle speed, Euro emission standard. For the purpose of this paper, the cars are divided into three classes (small, medium and large), considering the type of fuel (petrol, diesel, other) and the Euro standard (pre-ECE and from Euro 1 to Euro 6). The classification of fuel type can be justified by considering the fleet of cars moving in Italy. In fact (see Fig. 9) at national level diesel and petrol fuelled cars are predominant (44% and 46% respectively). The same for the Apulia (the region where the study area is located) and the study area (where the rate of diesel cars increases to about 54%, bringing the petrol and diesel fuelled to 93%). In Italy and in Apulia, the bi-fuelled cars (e.g., gasoline and methane) are less than 9% and this rate drops to about 6% in the study area. The rate of hybrid cars and the full electric cars is negligible (less than 0.5% in the study area); thus, it is assumed irrelevant for the aim of this work.

Although COPERT allows us to calculate the total emissions by different pollutant and greenhouse gas types, like CO_2, CO, NO_x, being the hearth temperature connected with the accumulation of greenhouse gases and allowing CO_2 to be considered a proxy of environmental impacts, the considerations reported in the next sections refer to this latter mentioned gas. Similarly, the estimations of all road pollutant and greenhouse gases can be performed.

4.2.1 Current scenario

In the current scenario, the emissions due to travel in the study area are considered, distinguishing trip chains and round trips. A first consideration is on total CO_2 emissions by fuel type (Fig. 10a) showing similar contribution by round and trip-chain travels by cars. As reported in Fig. 5, the round trips account for about 40% of the total trips undertaken in the study area. In particular,

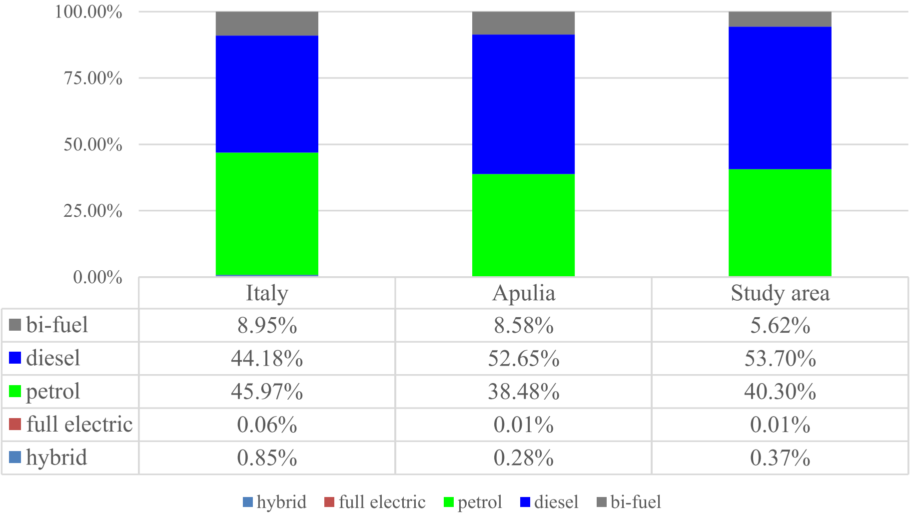
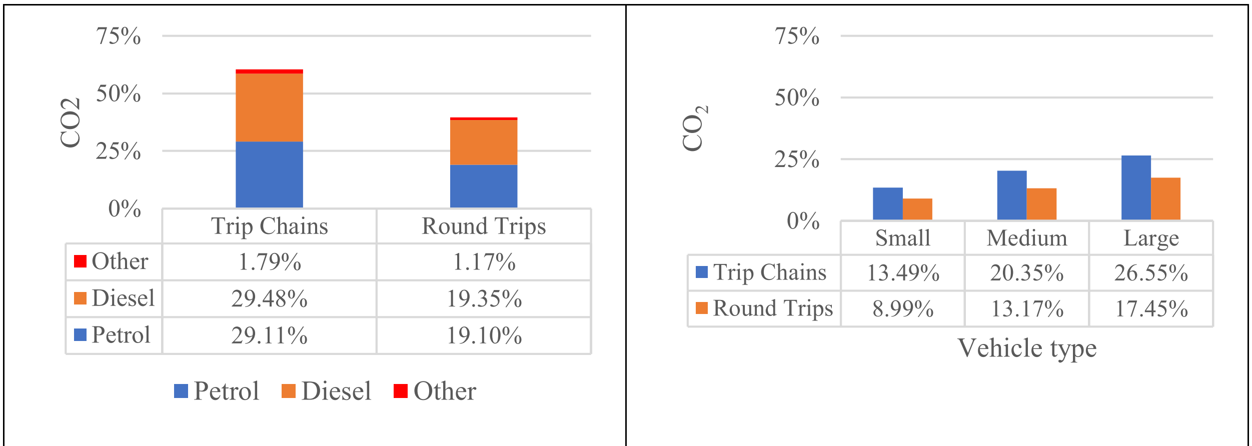
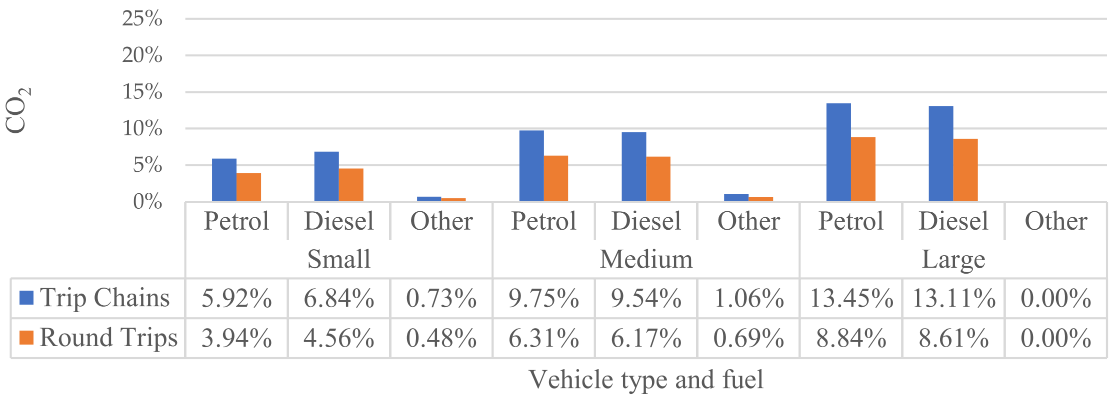


Fig. 9 Italian cars fleet by fuel at different spatial levels



a) Daily emissions by fuel type

b) Daily emissions by vehicle type

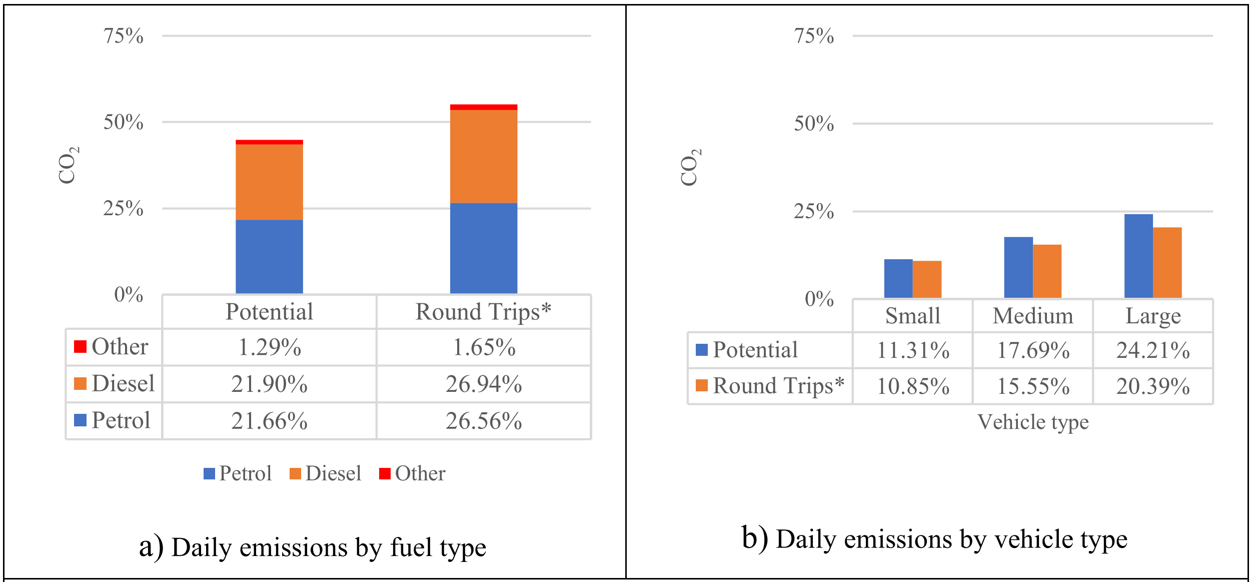


c) Daily emissions by fuel and vehicle type

Fig. 10 Current scenario: daily CO_2 emissions the 19.10% of CO_2 is emitted by petrol cars travelling on round trips, while 29.11% is due to trip chains. 19.35% is emitted by diesel cars on round trips and 29.48% on trip chains. More than 1% of CO_2 emission is emitted by other fuelled cars (e.g., LPG). Considering the vehicle dimensions (Fig. 10b) the small vehicles are responsible for 22.48% of CO_2 emissions (about 9% from round trips), the medium vehicles produce 33.52% of CO_2 emissions (about 13% from round trips). Finally, the large vehicles account 44.00% of CO_2 (about 18% is from round trips). Figure 10c, by crossing this information, shows the CO_2 emissions by fuel and vehicle type.

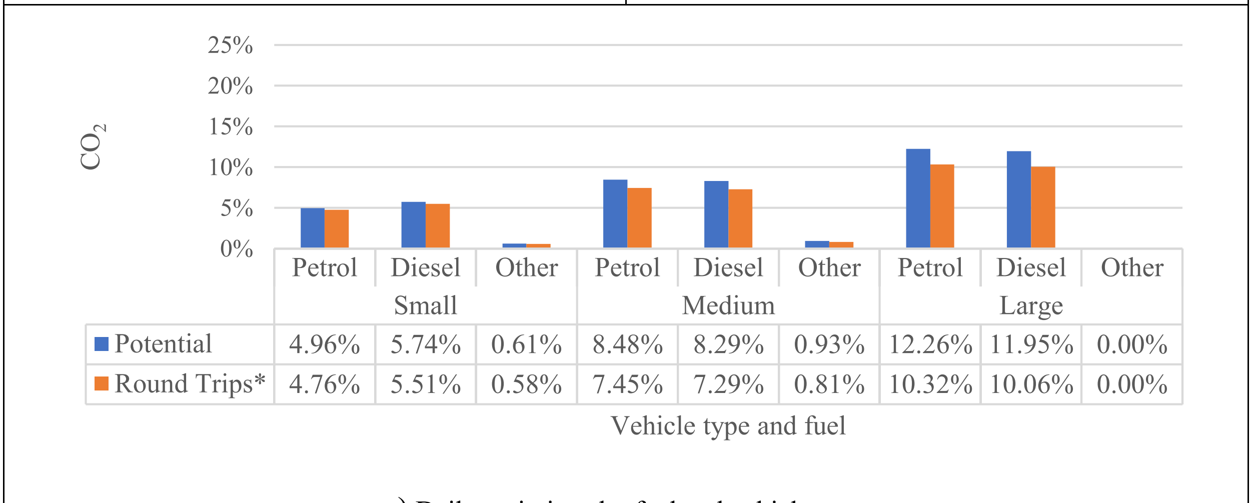
4.2.2 The future scenario

After the expansion to the universe, about 54,200 trips by private car per day were estimated within the study area: those respecting the conditions to be demand potential/compatible for micromobility are about 7,000 trips per day. A comparison between round trips and demand by private cars shifted to micromobility (potential/compatible demand) has been carried out. As earlier discussed, such a demand refers only to round trips and represents its 31%, then below the results of the performed assessment focus on such trips. In addition, such round trips will be indicated in Fig. 11 with an asterisk (to differentiate with respect to



a) Daily emissions by fuel type

b) Daily emissions by vehicle type



c) Daily emissions by fuel and vehicle type

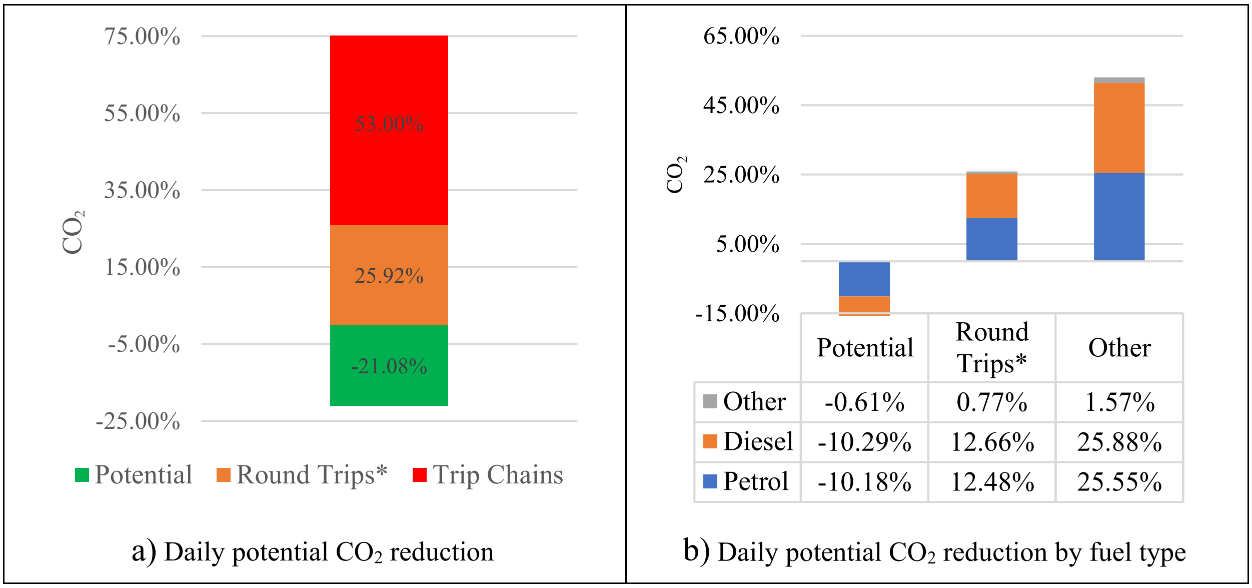
Fig. 11 Potential demand: CO_2 emissions those in Fig. 10), and the share values refer to the all round trips.

It emerges that the potential/compatible demand produces about 25% of CO_2 (Fig. 11a), basically equally distributed between diesel and petrol vehicles (the other types of vehicle are less than 1%). In relation to vehicle type, the majority of the CO_2 emissions (as expected) are produced by large vehicles (Fig. 11b), while considering the type of fuel (Fig. 11c), there is no appreciable difference between diesel and petrol vehicles.

To highlight the reduction in CO_2 emissions, Fig. 12 shows the aggregate values of emissions related to each type of trip. In Fig. 12a, the emissions of all trips detected in the study area are grouped by type: trip chains, round trips* (without potential/compatible demand) and potential/compatible demand. As shown in Fig. 10a, the shift towards micromobility could cause (respect to all trips) a reduction of about 21% of all emissions produced by cars. Similarly, according to the characteristics of car fleet of the city, petrol and diesel vehicles contribute equally to such a benefit (Fig. 12b). A comparison with other studies can be help to understand the congruence of the results. But this comparison must be taken with due caution. From the work of McQueen et al. [69] emerged that if 15% of travels by car are replaced by e-bikes, the gain in terms of CO_2 reduction is of 12%. In our work, in the face of a replacement of 31% (Fig. 7) of trips replacement, the reduction of CO_2 is 21%. This could demonstrate the validity of the results but, once again, some reservations are plausible.

5 Discussion

The reduction of the use of cars in urban areas is one of the measures that should be adopted to limit the environmental impacts (e.g., greenhouse gas emissions) and to push user towards active mobility. In this context, the use of alternative transport modes, such as eco-friendly transport modes, in some categories of urban travels can positively affect such an issue. In this paper, a method to individuate the potential/compatible demand to shift from car to micromobility has been proposed by using as input floating car data and a set of vehicle registration data. Therefore, rather than inferring on the propensity to change their travel mode, the paper focused on car trips that can be considered the most compatible with the micromobility, i.e., on the demand that can be easily transferred (replaced) to such new transport mode. In particular, current private car travels were analysed and classified according to some criteria using an available dataset of FCD. The data used in the proposed procedure were related to a study area (composed by 70 zones) in the southern Italy and were related to a sample of about 5,200 trips performed in 4 working days. The proposed procedure assumed that the demand to be shifted (replaced) derives from the systematic round trips performed by users residing in the study area and with respect to some constraints in distance and time. The procedure contains two interacting blocks: the first one allows the classification of the trips and then to individuate the potential demand; the second one, which allows the origin/destination matrix (to use in the assignment



a) Daily potential CO_2 reduction

b) Daily potential CO_2 reduction by fuel type

Fig. 12 CO_2 reduction

procedure needed to calculate the network performances) to be assigned to the road network, and the performances and features to be estimated. The methodology was based on the collection of open and proprietary (e.g., FCD) sources of data that describe some of the main features of city road network, allowing to have a complete picture of the private car trips, limiting the use of traditional surveys techniques with a subsequent decrease in resources (e.g., time and money for delivering the surveys/questionnaires).

The analysis of FCD allowed the private car trips in Trani to be characterised and to have a first estimation of the potential/compatible share of car trips that could be replaced (and/or eventually shifted) by micromobility. The results show that for working-day trips, 70% of the full (expanded) private car trips are done by residents, and 40% of them are of round-trip type. Besides, 31% of such round trips are less and 5 km, shorter than 20 min and are therefore compatible with micromobility.

From the environmental assessment analysis, it emerged that the round trips cause about 40% of CO_2 emissions in urban area and that 31% of them could potentially shift (replace) towards micromobility, with a saving in emissions of about 21% with respect to the total private car emissions. Such a consistent and significant CO_2 emission decrease is also driven by the reduction of the number of vehicles driving in the city centres, with a subsequent reduction of congestions as well of travelled kms by cars.

The potential applications of the methodology are plenty. It gives micromobility service operators a clear picture of where the most untapped demand is located and thus where the service is more needed. In addition, to local administrations and urban planners, it provides a map of where substantial infrastructural intervention is needed for the population to be able to fully embrace micromobility modes, and to quantify the benefits that such a shift causes. Furthermore, the proposed approach is very valid, at the first stage of investigation, during the development of SUMPs, when a first estimation of potential benefits from some actions is required. Besides, the results obtained demonstrate that the floating car data, reliable and easy to acquire, could provide a valuable picture of private car travel patterns and, in some aspects, can successfully replace the data from traditional surveys. This research could be framed in the SDG 11 (target 11.2) defined by the United Nations. In fact, the micromobility could be considered a relevant lever for pushing users from motorized transport modes to environment-friendly modes.

But it is necessary to indicate some limitations of the proposed procedure. On one hand, the use of the FCD facilitates access to mobility information (alternatively a complex investigation would be needed) but, on the other hand, it does not allow us the exploitation of some of the attributes used by traditional demand models. As an example, this weakness does not allow to have information on the purpose of the travel or the user preference in term of available modes (i.e., how the user perceives the transport modes available for the trip).

Of course, with respect to the process followed in this study, the propensity of the potential residents to use micromobility, and the existence of natural clusters of users with similar travel behaviours in relation to their daily activities (included to become crowdshippers [18, 44, 46] by micromobility, given that, as shown in the literature review, some cities obtained significant sustainable results) or their personal values, mobility need and lifestyles, should be pointed out and further analysis is in progress to also investigate these aspects. For example, recent studies underline that age, gender, and income, as well as psychological factors (e.g., environmental values) and weather conditions, can have some influence in adopting micromobility [72]. Further adjustment of the proposed methodology refers to the investigation of representativeness of FCD for identifying the relevant characteristics of trips to be transferred to micromobility, as well as in the acceptability of travel distances and the level of perceived road safety by micromobility users. Therefore, the identification of threshold values in relation to the travel distance or time should be explored taking into account the plano-altimetric trend of the land which could push or not to the use of micromobility devices. Besides, through behavioural models based on random utility theory, it would be possible to include personal and psychological factors (e.g., age, gender, income, perceived danger, "green" attitude, hedonic value and other perceived compatibility with personal values, mobility needs and lifestyle), while by classifying FCD trips through activity characteristics and land-use information, we could further determine trip chains and related tour complexity.

All these represent future developments of this research with the aim of giving even more insight into the estimation of potential micromobility demand for the sustainable and liveable development of worldwide cities.

6 Conclusions

A methodology for identifying the car travels that are the most compatible with the micromobility was proposed and its goodness was tested through a real case study application (Trani, Southern Italy). It allowed us to provide a first estimation of the potential demand by private cars that can be replaced by micromobility, i.e., about *31%* of the workday home-based trips. The developed methodology is parametric, and thus, it can be easily transferred in other city contexts where FCD data are available, taking the compatibility of the network (including the O/D compatibility analysis), with respect to micromobility solutions, into consideration.

While the results of this study offer a new understanding of the congestion and environmental impacts of short car trip replacement with micromobility modes, there are thus several opportunities for model improvement and future work, too. The FCD penetration rate estimation is based on a registration data, that as shown in the literature can be a good starting point, however it is subject to different aspects that depend on the specificity of each investigated city. The use of micromobility could be, obviously, impacted by weather conditions, e.g., during the winter there will be days where freezing temperatures and rain (or snow) conditions that pose as a restriction to micromobility travel. Therefore, if we apply our methodology to other cities around the world, the benefits may be different because of climates. In conclusion, the study gives different actors involved in urban planning a tool for assessing the environmental effects of replacing short car trips with micromobility, taking into consideration that such a benefit also derives from a positive effect on congestions and kilometres travelled. The shown results could become more significant for a high-congested road network, due to the stop-and-go phenomenon that significantly increases the pollutant emissions of traditional vehicles.

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Authors' contributions

Conceptualization, A.C. and A.P.; methodology, A.C. and A.P.; software, A.C. and A.P.; validation, A.C. and A.P.; formal analysis, A.C.; data curation, A.C. and A.P.; writing-original draft preparation, A.P.; writing-review and editing, A.C. and A.P.; supervision, A.C.

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Availability of data and materials

The data that support the findings of this study are available from the Department of Enterprise Engineering, University of Rome, on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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