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Combining walkability assessments at different scales in measuring spatial inequalities in access to railway stations

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ABSTRACT

Introduction: One of the goals of Agenda 2030 is to make cities inclusive, safe, and sustainable, promoting transport and social equity. One of the ways to promote social inclusion is encouraging people to use efficient and affordable mass rapid transit services. Therefore, ensuring good pedestrian accessibility to railway stations is a priority for policymakers. In this perspective, it is not surprising that 15-min cities and transit-oriented development are widely debated concepts and applied with policies encouraging sustainable transportation modes and building inclusive communities. However, disparities in policy practice seem to exist between suburban areas and cores in many European cities. Indeed, the quality of pedestrian infrastructure is not at the same level in different areas, creating disadvantaged communities with lower access to public transport services and forced to be car-dependent.

Method: Presenting a case study, the paper aims to investigate the impacts of road connectivity and pedestrian network quality on spatial and social equity in access railway stations. Fourteen railway stations in Palermo (Italy) were analyzed. The paper proposes a GIS-based approach combining walkability assessments at different scales. Firstly, walkability around railway stations was analyzed considering meso-scale indicators related to road connectivity (road density, intersection density, Ped-shed ratio). Secondarily, since quality-related factors are crucial in evaluating pedestrian accessibility, three criteria (practicability, safety, and pleasantness) to evaluate street-level walkability around railway stations are defined based on the literature.

Results: Combining both the assessments, big disparities in accessibility between railway stations located in suburban areas and city centre were found. Poor accessibility in suburbs represents a social equity problem, undermining the effectiveness of rail services as equitable modes of transportation.

Conclusions: This approach can be a decision-support tool, identifying what priority measures are needed and where to improve the quality of the pedestrian network to support public transport use in suburban areas.

1. Introduction

Today, cities are facing numerous challenges in the form of congestion, pollution, and urban sprawl. According to the New Urban

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Agenda (United Nations General Assembly, 2016), 75 % of the world's population will prefer to live in cities based on the current urbanization and population growth scenario. The increase in population in metropolitan areas will not only create a demand for amenities and activities but will also lead to an increase in the usage of private vehicles, ultimately causing more traffic congestion, pollution, and posing a challenge to urbanization. The situation will be worse for cities with already aging infrastructure that are facing modern urbanization challenges. For these reasons, one of the goals of Agenda 2030 is to make cities inclusive, safe, and sustainable, promoting transport and social equity (United Nations, 2015).

In this context, promoting public transport as an alternative to private vehicles and advocating for walking to access public transit hubs within the urban context will play a pivotal role in addressing these challenges and uplifting urban dynamics, promoting social equity (Collins et al., 2023). One of the main encouraged policies is promoting efficient mass rapid transit. In Europe typically, more than 50 % of trips to and from railway stations are made on foot (La Paix and Geurs, 2014). Therefore, ensuring good pedestrian accessibility to railway stations is a priority to encourage people to use public transport.

In the search of accessible transportation, walkability has become a foundation for urban planning. Walkability can be defined as the extent to which walking is encouraged by the built environment within a neighbourhood.

Promoting walking to access public transport hubs has several benefits. Walking not only has significant impacts on public health by helping individuals meet the recommended physical activity goals within their daily routines (Pae and Akar, 2020) and avoid diseases due to sedentary behaviour (Dutheil et al., 2020; Hamer and Chida, 2008), but it also helps to deal with the challenges of car dependency, traffic congestion, pollution, and urban transformation, reducing the environmental impact of transport (La Rocca, 2009). Walkable urban areas contribute to the development of healthier (Kelly et al., 2014), more sustainable, inclusive, and socially vibrant communities (Avila-Palencia et al., 2018), supporting the achievement of Goal 11 of the United Nations' Sustainable Development Goals.

Moreover, walkability has an impact on the mode choice of individuals and plays a key role in multimodal travel chains, especially in considering walking as first- and last-mile solution to access transit nodes (Bivina et al., 2020; Gupta et al., 2022). In this perspective, low-walkable neighbourhoods, such as ones with large avenues, lack of sidewalks, a high density of traffic lights and poor lighting, influence the decision to walk, also for short distances (Ferrer and Ruiz, 2018). Since pedestrians are vulnerable road users and are at more risk of injury in traffic collisions, poor safety mainly discourages individuals from walking to the nearest railway station for their first- and last-mile journey.

Indeed, the quality of pedestrian infrastructure is not always at the same level in different areas of the city, creating disadvantaged communities having lower access to public transport services and being forced to be car-dependent. Moreover, poor walkability has different impacts depending on social groups. Indeed, in a metropolitan area, different residents live with diverse backgrounds. Residents with reasonable incomes can afford a private car for their daily trips, whereas low-income people are mostly dependent on public transport. Therefore, there is a need to consider the social and transport equity perspective when examining pedestrian accessibility to railway stations in urban and suburban areas (Behbahani et al., 2019). Transport equity means assuring fair and accessible transport options for all individuals disregarding of their income level, age, gender and any other impairment of different nature (Martens, 2017). This comprised assuring that public transport services are accessible for everyone, regardless also of their geographic location, either central or peripheral.

Regardless of socio-economic status, a walkable neighbourhood should provide equal and equitable access to public transportation, primary services, employment, education, etc. On the other hand, poor pedestrian accessibility to public transport services can not only be a barrier to the use of public transport but also generate social exclusion and disadvantaged communities. In this perspective, walkability plays an important role in evaluating inclusivity and community well-being.

Based on these premises, the study aims to propose a set of indicators and combine different GIS-based approaches in measuring spatial inequalities in access to railway stations, evaluating pedestrian accessibility in terms of network connectivity and quality of the pedestrian infrastructure to access the railway stations and the job opportunities, the points of interests (POIs) and residences located at a walkable distance from them. A case study is presented, analysing fourteen railway station areas in Palermo, Italy. The proposed methodology can be considered a useful decision-support tool that policymakers, local authorities, and transport operators can use to prioritize actions by identifying where it is most urgent to allocate resources to improve pedestrian accessibility.

The paper is organized as follows. Section 2 provides background on recent topics like 15-min city and transit-oriented development. Section 3 outlines the different approaches to measuring spatial inequalities and the steps to follow to perform the analyses using GIS software; Section 4 describes the study area, classifying the railway stations according to their characteristics. The results related to the case study are shown in Section 5 and discussed in Section 6, while some conclusions are drawn in Section 7.

2. Background

The accessibility literature has proliferated in the past decades with diverse studies in terms of research questions, adopted approaches, and implemented accessibility measures. This is not surprising, in part because accessibility has strong impacts on economic development, real estate values, transport mode choice, social cohesion, and so on, and in part because of the multiple ways in which accessibility can be measured.

The literature on the nexus between accessibility and equity also reflects this diversity (Martens et al., 2022).

Evaluating the spatial inequalities in access to railway services (horizontal equity) and identifying accessibility issues having social impacts (vertical equity) is critical, especially considering that low-density areas have limited public transport services that can fulfil people's fundamental needs, connecting them to essential services and job opportunities (Guo and Brakewood, 2024). Access to job opportunities is one of the main parameters used to investigate the impact of rail infrastructures on spatial equity (Li and Zhang, 2024).

The variation in travel time due to new infrastructure or change in timetables (Cavallaro et al., 2020) can be evaluated using spatial analysis, often based on GIS. Regarding social equity, several authors used Gini index and Laurentz curve to measure the distribution of transit accessibility within each city and to compare the distribution between different social groups (Raza et al., 2023; Baghestani et al., 2024). Also the node-place model incorporating equity metrics like the number of foreigners, older people and low-income people within the railway station service area was used to address potential inequity issues (Zhao et al., 2024).

Ensuring high-quality accessibility for pedestrians to railway stations is seldom evaluated beyond measurable factors such as walking distance and time (Jehle et al., 2022). However, the accessibility of railway stations is deeply affected by walkability, defined both in terms of road connectivity and pedestrian network quality.

Road connectivity is a key component for good neighbourhood design; increased road connectivity due to grid-like networks, small blocks, and limited cul-de-sacs, encourages walking, reducing travel distances and providing a wide range of routes from which to choose. As highlighted by Dill (2004), there is a wide range of measures of connectivity that can be used to assess how much the neighbourhood design is able to promote walking. The main network connectivity indicators used by transportation and urban planners are reported in Table 1.

Each of these connectivity indicators not only represents a different way to measure pedestrian accessibility but captures different aspects as well. However, some of them are likely to be highly and positively correlated. For example, CNR and LNR are usually correlated with intersection density and road density, being dependent on them. Other indicators have limitations in their use due to the complex nature or time-consuming estimation. For example, block length is not easy to obtain since you need to perform several spatial operations in a GIS software to identify the blocks within a defined area; moreover, block length differs considering different directions: blocks can be short in a direction and long in the opposite one. Also, PRD is difficult to use in research requiring selected points as origins and destinations.

Emphasizing the role of network connectivity around railway stations is one of the principles of the Transit-Oriented Development approach, which integrates transport and urban planning for creating sustainable, transit-friendly urban communities and vibrant neighbourhoods. The term "transit-oriented development" or "TOD" became popular in the early 1990s, when Peter Calthorpe

Table 1
Network connectivity indicators.

Indicator	Definition	Impact
Road density	Total street length per 1 km^2 area.	Higher road density means more roads are present in a given area, which can lead to better accessibility.
Intersection density	Number of road intersections per 1 km^2 area, where intersections are the junctions at which three or more road segments intersect.	A high intersection density indicates a walking-friendly environment, allowing pedestrian to change direction frequently and reach destinations following a more direct route.
Connected node ratio (CNR)	Number of road intersections divided by the number of nodes (intersections plus cul-de-sacs).	The maximum value is 1.0. Higher numbers indicate that there are relatively few cul-de-sacs and dead ends, and presumably a higher level of connectivity. Values of 0.7 or higher are favored.
Link-node ratio (LNR)	Number of links divided by the number of nodes (intersections plus cul-de-sacs).	The link count represents the number of street segments between two nodes, and the node count is the sum of the number of intersections and the number of dead ends (cul-de-sacs). A perfect grid has a LNR of 2.5. A LNR of 1.4 or more is a desirable target.
Block length	Average block length for blocks within a defined area.	Shorter blocks mean more intersections and therefore a greater number of routes available.
Block size	It captures two dimensions of the block, rather than the individual length of each side. This can be measured by the area or the perimeter.	Small blocks mean more intersections and therefore a greater number of routes available. Block size could be used as a research tool or performance measure by calculating the share of blocks meeting a standard or the average value.
Block density	Number of blocks per km^2.	Increased block density is thought to represent increased connectivity: more blocks mean smaller blocks and more intersections.
Pedestrian Route Directness (PRD)	Ratio of route distance to straight-line distance for two selected points.	The lowest possible value is 1.00, where the route is the same distance as the "crow flies" distance. Values closer to 1.00 indicate a more direct route, theoretically representing a more connected network.
Alpha index	Ratio of the number of actual circuits to the maximum number of circuits and is equal to (# links - # nodes + 1)/(2(# nodes) – 5).	Values for the alpha index range from 0 to 1, with higher values representing a more connected network. Trees and simple networks will have a value of 0. A value of 1 indicates a completely connected network.
Gamma index	Ratio of the number of links in the network to the maximum possible number of links between nodes. The maximum possible number of links is expressed as 3*(# nodes −2) because the network is abstracted as a planar graph.	Gamma index ranges from 0 to 1 and is often expressed as a percentage of connectivity, e.g.a gamma index of 0.54 means that the network if 54 percent connected.
Pedestrian Catchment Area ratio (PCA)	Ratio between the network-defined service area considering a walkable network distance (for example, 500 m) from a fixed point and the theoretical service area considering Euclidean distances (buffer with a radius of 500 m).	PCA ratio measures how well the road network covers the area around a specific key destination. Values of the ratio close to 1 indicate extremely walkable areas, while a score less than 0.30 would reflect an inaccessible walking environment. Although there has not been enough research to determine an optimal PCA score, it is suggested that a minimum score of 0.5–0.6 is a useful threshold (Schlossberg, 2006).

identifies the station area as a fundamental building block for transportation and land use integration. TOD is defined as "mix residential, retail, office, open space, and public uses in a walkable environment, making it convenient for residents and employees to travel by transit, bicycle, foot or car" (Calthorpe, 1995). Calthorpe adds that a TOD is "a mixed-use community within an average 2000-foot walking distance of a transit stop and a core commercial area".

Jeffrey et al. (2019) highlighted that walkability improves train station access and can be used for measuring TOD potential; with this perspective, the authors evaluated the potential of 230 train station areas in metropolitan Melbourne, Australia, to function as a TOD using 14 different walkability measures, including PCA ratio and CNR as indicators related to the network design.

Also, previous studies already include walkability measures in assessing the potential of railway station areas to become TOD. For example, Schlossberg and Brown (2004) classified 11 TODs in Portland in terms of their walkability using 6 built environment indicators (quantity of accessible paths, i.e. minor roads; quantity of impedance paths, i.e. arterial roads; PCA ratio; impedance PCA calculated excluding the high-volume, high-speed corridor; intersection density, and density of dead ends). Finally, Kamruzzaman et al. (2014) included some indicators related to network connectivity in their six TOD indicators (employment density, residential density, land use diversity, intersection density, cul-de-sac density, and public transit accessibility) to classify 1734 census districts in Brisbane.

However, these studies only consider network connectivity indicators to assess the TOD potential of the railway station areas, neglecting the impact that the quality of the pedestrian realm has on the choice of walking as primary mode of transport and on the use of public transport (Ha et al., 2023).

In recent years, in response to new urban challenges, the TOD concept evolved into the concept of "equitable TOD", considering not only the benefits of TOD, such as improved mobility, environmental benefits, economic advantages, reduced congestion, and improved public health and well-being, but also actions to mitigate same potential adverse effects related to social equity. Indeed, TOD-induced gentrification and the displacement of low-income residents and small neighbourhood businesses could amplify the existing economic disparity and social inequity (Zhao et al., 2024). Thus, some recent studies include walkability measures for evaluating the equity performance of railway station areas within the TOD framework (Appleyard et al., 2019; Wan et al., 2023).

A further evolution of the TOD concept can be found in the most recent 15-min city concept, which has gained a great momentum among urban policymakers and politicians. Its popularity increased significantly during the Covid-19 pandemic and the resulting lockdown restrictions imposed to restrict mobility. This increased public attention to the substantial need for easy access by foot or bicycle to everyday facilities and essential services, not only around railway stations, but also around places of residence. The idea is a radical re-thinking of the city as composed of urban areas whereby residents can access their daily needs within a 15-min walk, bicycle or transit ride from their home (Moreno et al., 2021). Railway stations represent the "gateway" where users start their last mile after getting off the train and, starting from this perspective, Borghetti et al. (2021) applied the idea of the 15-min city to railway stations. They developed walking isochrones to identify the different services and POIs reachable by pedestrians within a 15-min walking radius (850 m) from the railway stations. A similar approach was implemented by Fazio et al. (2023), proposing a GIS-based methodology to analyze railway stations in terms of ease of access and number of opportunities that can be easily reached in their surroundings, developing 15-min isochrones. The authors highlighted the need to consider the current conditions of the pedestrian infrastructure in assessing the accessibility of the railway stations; in this perspective, they assigned a pedestrian speed on each arc of the pedestrian network, based on technical characteristics of sidewalks (slope and width). Therefore, in the applications of the 15-min city concept, the focus has recently been expanded from the network connectivity to the quality of the pedestrian realm. From this perspective, different micro-scale walkability assessments were developed (Bartzokas-Tsiompras et al., 2023).

Despite the growing literature on walkability, 15-min cities, TOD and transport equity, little attention is placed on the shortcomings of the transport planning process in bridging the gap between research and practice. Indeed, although 15-min cities and Transit-Oriented Development (TOD) are widely debated concepts and applied with policies encouraging sustainable transportation modes and building inclusive communities, disparities seem to exist between suburban areas and urban cores in many European cities.

Indeed, as found by Poorthuis and Zook (2023), much of the attention in both policy practice and research has been focused on densely populated urban areas, presenting case studies in which actions were implemented to improve the access in the urban cores. However, despite the common refrain that slightly more than half of the world's population now lives in cities (United Nations, 2019), the other half of the world's population lives in less or non-urban areas. This raises the question of how planning concepts aiming to build equitable and walkable neighborhoods – of which we can consider TOD and 15-min city as examples – might apply to suburbs, exurbs and even rural communities. Other authors pointed out this drawback. For example, Birkenfeld et al. (2023) underline the complexity of achieving the 15-min city ideal in large North American cities, with limited households able to complete all daily travel near their homes, especially those living in suburbs. Staricco (2022) and Vale and Lopes (2023) similarly highlight how the model is not always feasible in European cities, where densities within the same urban areas vary a lot. Moreover, analyzing numerous cities worldwide within the framework of the 15-min city concept, Bruno et al. (2024) found a strong heterogeneity of accessibility within cities, recognizing it as one of the sources of inequalities. The online platform developed by them (https://whatif.sonycsl.it/15mincity/) shows how it is difficult to reach essential services within a 15-min walk in suburban areas in many European cities. From this perspective, one key action to increasing accessibility to everyday facilities and essential services is to improve pedestrian access to railway stations, providing affordable, quick and efficient travel to reach a wider pool of opportunities.

However, transport projects are traditionally selected based on utilitarian approaches, disregarding the distributional effects of proposed actions and policies and sometimes worsening inequalities rather than reducing them (Freiberg et al., 2024). The publicly-funded benefits distributed to residents throughout a region by the allocation of public transport hubs, like railway stations, are not always distributed equally among different population groups (Foth et al., 2013). Indeed, numerous factors, including travel demand, land use, population density, connectivity, transit frequency, traffic, and road safety, influence the allocation of transit stops

(Bhuiya et al., 2023). Areas with high pedestrian activity, such as city centers, commercial districts, and business hubs, are expected to have more railway stations than suburban areas to enhance connectivity and provide better opportunities for boarding and exiting trips. Similarly, the design of these stops can be influenced by land use. In residential areas, railway stations can be located to maximize accessibility for residents, while in commercial areas, stations can be strategically placed near shopping malls, office buildings, or business centers. In this context, population density and transit frequency are also worthy of important consideration: greater demand for transit services may require more frequent train services to meet travel needs. However, it is necessary to consider also the distance between stations affecting the travel time and the frequency. Mohiuddin (2021) included also multimodality and the integration of new mobility services as factors to consider in the allocation of railway stations, in order to offer different mobility options in the "first and last mile" (FLM) journey. Moreover, evaluating the accessibility and connectivity of railway stations at various spatial scales—local, regional, and corridor-wide—within the Rhine-Alpine Corridor, Otsuka et al. (2022) found that, on a local scale, accessibility and wayfinding are crucial for train station users, while on a regional scale, the connection between long-distance and local public transportation, including easy transfer policies and ticketing systems, enhances efficiency. On a corridor-wide scale, cross-border connectivity, timetable synchronization, and public transport integration are essential for improving overall rail network connectivity. Improvements at all these scales can collectively enhance accessibility to railway stations.

The heterogeneity in station area contexts presents significant complexity for planners and policymakers interested in understanding existing TOD conditions, an area's TOD potential, and the relevant policy and planning interventions required to achieve planning goals (Higgins and Kanaroglou, 2016). In this perspective, a new GIS-based approach to identify where priority actions are needed to reduce spatial inequalities to access the railway service can be useful for increase the awareness of policymakers and public transport operators.

3. Methodology

Spatial inequalities to access the railway service were assessed combining two different approaches based on Geographic Information Systems (GIS). Firstly, a meso-scale walkability assessment was used, evaluating three indicators related to network connectivity: road density, intersection density, and Pedestrian Catchment Area Ratio (also known as Ped-shed ratio) as estimated by Schlossberg (2006). The description of these indicators and their impacts on walkability of railway station areas are reported in Table 1. These indicators are well-known in literature, can be easily calculated using a GIS software and represent different aspects of network connectivity. Although they may seem to be correlated, each of these different measures of connectivity may reflect subtle differences in the way in which the built environment influences pedestrian access to railway stations. In order to clarify this statement, Fig. 1 represents three different cases. Although usually high road and intersection density can lead to a better accessibility (Fig. 1a), high value of road density does not preclude that there may be few intersections and many roads with cul-de-sacs, not leading to a walkable area and forcing pedestrians to lengthen their routes (Fig. 1b). Moreover, although one would expect that areas with more roads would have more intersections, this cannot be true, as shown in Fig. 1b. Thus, on the one hand, analyzing road density is important to understand how much the road network is extensive and if there are alternative routes between origin and destination; on the other hand, analyzing intersection density is important because it gives insight into the connectivity of the road network that might not be evident from simply looking at the length of the network. Pedestrian Catchment Area ratio was chosen to evaluate how much the road network covers the 500m-buffer area around the railway station. This cannot be correlated to the road density and the intersection density as shown in Fig. 1c. The figure shows that having higher values of road density and intersection density doesn't mean that also the PCA ratio is higher. Moreover, Pedestrian Catchment Area ratio measures how much the urban fabric and land use can hinder accessibility.

Therefore, a well-connected network has many short links, numerous intersections, and minimal dead-ends providing continuous, direct routes to destinations, and covering the theoretical service area (buffer area) to the greatest extent possible.

We compared the values that these indicators assume across railway station areas to assess whether spatial inequalities in access to railway stations related to road connectivity exist. A network connectivity index for each station s (CI_s) was calculated according to the following equation:

$$CI_s = \frac{1}{3}\left[\frac{RD_s}{\max\ (RD_k)} + \frac{ID_s}{\max\ (ID_k)} + \frac{PCA_s}{\max\ (PCA_k)}\right]$$

where RDs, IDs and PCAs are the values that road density, intersection density and PCA ratio assume for the station s, while max (RD_k), max (ID_k), and max (PCA_k) are the maximum values reached by these indicators for the station k, considering all the railway station areas chosen as study areas. We considered equal weights for the three meso-scale indicators composing the network connectivity index since we wanted to assign the same importance to these indicators in assessing the road network connectivity, capturing different aspects of how road connectivity impacts walkability.

Moreover, we evaluated how the road network connectivity affects social equity considering that the impacts on access of residents

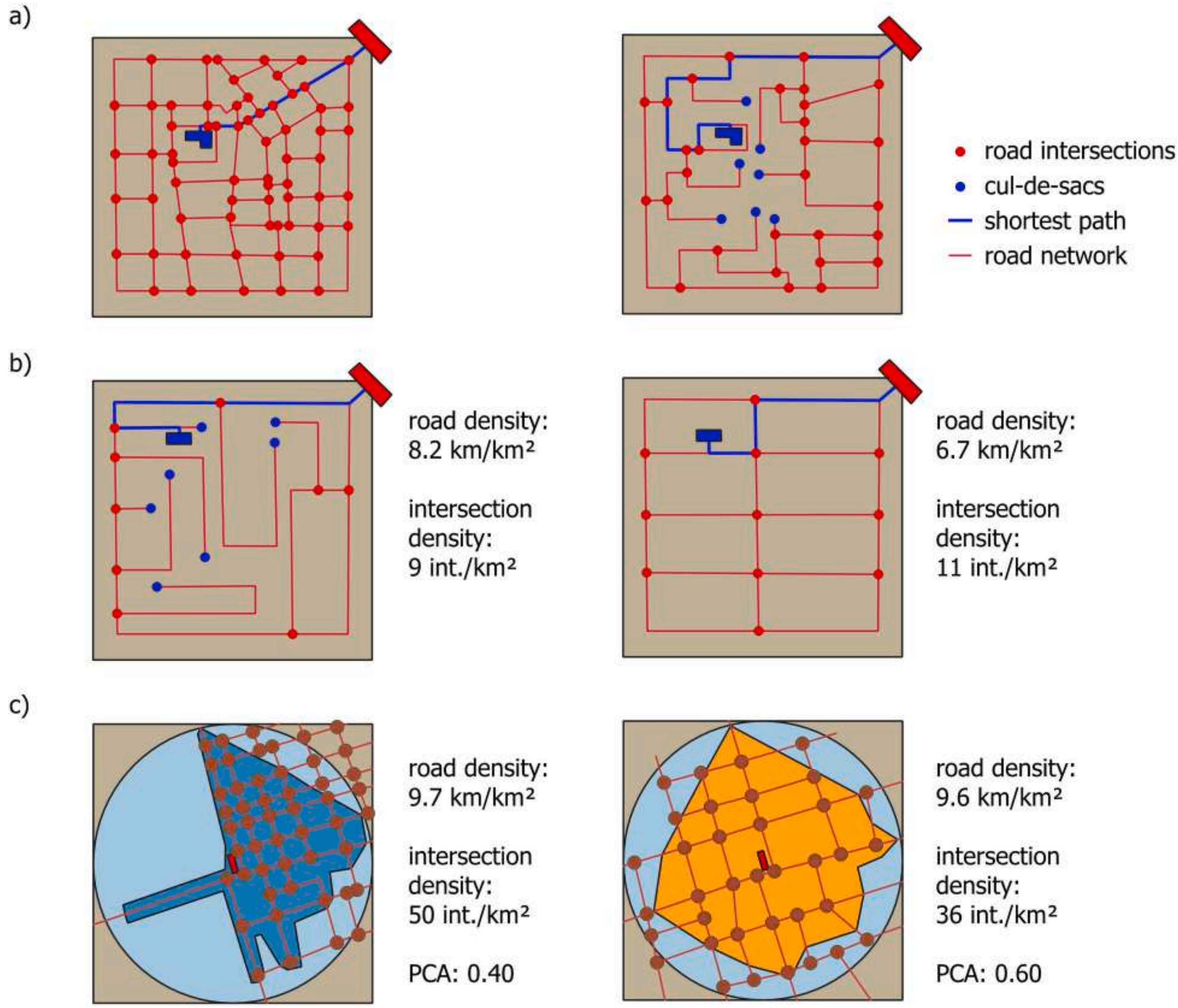

Fig. 1. The impacts of road density and intersection density on walkability.

and employees to railway stations depend also on the distribution of residential buildings and activities in the railway station areas. Indeed, as Fig. 2 shows, the impacts of road connectivity on the access to two railway stations having the same network-defined service area are not equal: a great number of people living and working in the buffer area of the railway station A (in the left) are excluded by the network-defined service area while the same road network connectivity has less impacts on exclusion of people living in the buffer area of the railway station B (in the right). For this reason, we calculated the percentage of people living and working in the buffer area that lives and works within and outside the network-defined service area. Living and working outside the network-defined service area means being excluded from access to the nearest station, being more than 500 m from it.

Finally, a second approach was adopted to investigate disparities in access to railway stations. Since pedestrians' walking experience is also influenced by several factors related to the quality of the pedestrian environment, a micro-scale walkability assessment

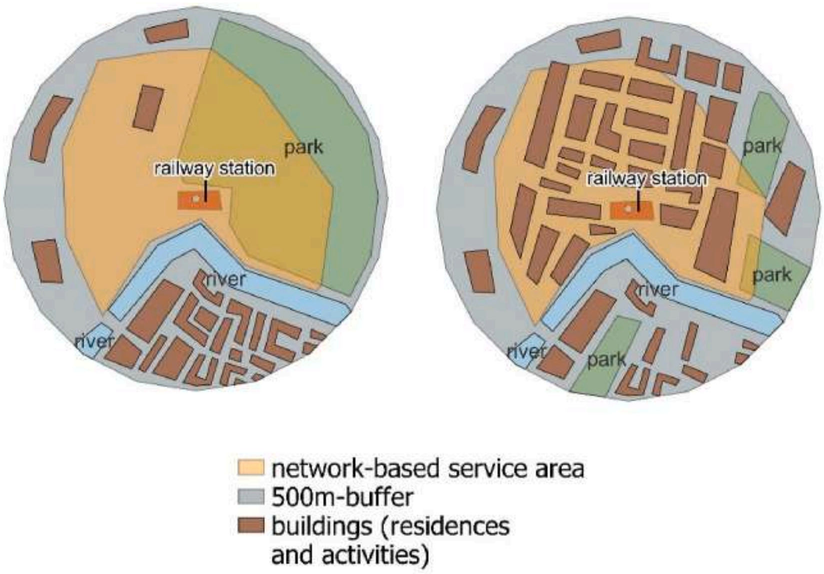

Fig. 2. Two railway stations having the same network-defined service area with different impacts on access.

was implemented to investigate how the quality of the pedestrian network at street level affects the access to railway stations. Indeed, also the people that live and work within the network-defined service area may experience a perception of unsafety and difficulties in accessing railway stations and give up on using the train service as the main mode of transport for their daily commute. For conducting a street-level walkability assessment, the pedestrian network must be built in GIS software as a layer, considering sidewalks and crosswalks (Fig. 3).

Once the pedestrian network was built, the micro-scale walkability assessment tool developed by D'Orso and Migliore (2020) was adopted to assess the quality of pedestrian infrastructure. Indicators related to practicability, safety and pleasantness of the pedestrian environment were considered and a score was assigned to them for each sidewalk, according to the rules listed in Table 2. The

Fig. 3. The pedestrian network: sidewalks (blue) and crosswalks (red).

Table 2
Micro-scale walkability indicators for sidewalks, as reported in D'Orso et al. (2023).

Category	Weight	Indicator	Value	Description
Practicability	0.3	Pavement slope	0	Steep slope for older people and wheelchair users (>5 %)
			1	Non-perceptible slope (<5 %)
		Pedestrian LOS	0	High pedestrian flows, insufficient sidewalk width or presence of obstacles (LOS = E, F)
			1	LOS = C, D
			2	Low pedestrian flows, adequate pavement width or absence of obstacles (LOS = A, B)
		Decay	0	Very degraded pavement
			1	Presence of some potholes or depressions
			2	No potholes or depressions, pavement in good condition
Pleasantness	0.3	Street furniture	0	Absence of litter bins, benches, and other elements of street furniture
			1	Presence of litter bins, benches, and other elements of street furniture
		Sun/Rain protection	0	Lack of shelter from the sun or rain
			1	Presence of shelters from sun or rain
		Green areas	0	Absence of flowerbeds or green areas
			1	Presence of flowerbeds or green areas
		Shops	0	Absence of shops
			1	Presence of shop windows and shops
		Architectural context	0	Degraded architectural context (presence of graffiti, degraded facades, industrial buildings or abandoned buildings)
			1	Pleasant architectural context (absence of graffiti, degraded facades, industrial buildings or abandoned buildings)
Safety	0.4	Lighting	0	Poor or no lighting
			1	Adequate and efficient street lighting according to UNI standard (UNI11248)
		Traffic flow and speed	0	High traffic volumes (>1000 vph) or high speeds (>50 km/h)
			1	In other cases
			2	Free flow (<300 vph) and low speeds (<30 km/h)
		Protection from vehicles	0	Absence of barriers to protect pedestrians from vehicles
			1	Presence of protection elements
		Driveways	0	Presence of driveways along the route
			1	Absence of one or more driveways

assessment of the scores is made mainly through site inspections. Google Street View can be used to expedite the assessment (making a pre-assessment to be checked after through a site inspection) and in order to collect data where a site inspection is not possible or safe. Obviously, Google Street View data have a limitation: they take a picture of the quality of the pedestrian network in a specific instant (the date of the picture on Google Street View) that cannot be up to date. The conditions that can be seen on Google Street View pictures can be different from the ones we have in the present day. However, Google Street View is largely used in walkability assessments (Lu and Chen, 2024; Aghaabbasi et al., 2018). Moreover, site inspections may also have the same drawback: the quality of pedestrian infrastructure that was measured is related to a specific instant and variation may occur after a short period of time; for example, furniture elements can be added few days after the site inspection and before completing the whole micro-scale walkability assessment.

Practicability focused on the practical aspect of walking considering indicators such as sidewalk slope, pedestrians' level of service (PLOS) and the evaluation of the surface quality of sidewalks. Similarly, pleasantness has been taken into consideration to assess visual aesthetic qualities, aesthetic appeal, interest and comfort of the pedestrian environment within the catchment area of the railway stations. Indicators as the availability of street furniture, benches, the sun/rain protection, and other amenities improving the comfort for pedestrians were included. Since pedestrians are vulnerable road users and at more risk of fatal crashes, safety-related indicators were examined, evaluating the presence of an adequate pedestrian-oriented lighting, the traffic volume and speed, the presence of barriers or objects to buffer pedestrians from traffic, the presence of driveways along the sidewalks. Weights were also attributed because practicability, safety, and pleasantness have a different impact on pedestrians' perception of the quality of the pedestrian

Table 3
Micro-walkability indicators for crosswalks, as reported in D'Orso et al. (2023).

Category	Indicator	Value	Description
Safety	Lighting	0	Poor or no lighting
		1	Pedestrian-oriented lighting
	Traffic flow and speed	0	High traffic volumes (>1000 vph) or high speeds (>50 km/h)
		1	In other cases
		2	Free flow (<300 vph) and low speeds (<30 km/h)
	Traffic lights	0	Absence of traffic lights at the crosswalk
		1	Traffic lights at the crosswalk but presence of conflicts between vehicles and pedestrians
		2	Traffic lights that eliminate conflict points between vehicles and pedestrians
	Visibility	0	No crosswalks or very poor crosswalk visibility
		1	Good crosswalk visibility
		2	Excellent crosswalk visibility

realm. The weights are the same reported by D'Orso and Migliore (2020), used in the Palermo area and derived from a literature review of walkability assessments performed in similar contexts (D'Alessandro et al., 2016; Ruiz-Padillo et al., 2018).

As already modified in D'Orso et al. (2023), some changes to the indicator scores and some crosswalk-specific safety indicators were considered (Table 3). Indeed, only safety-related indicators as lighting, traffic flow and speed, presence of signalized crossings and visibility were assessed for crosswalks.

Using a GIS software, a database of the pedestrian network quality was created and filled during site inspections with the score assumed by each indicator for each sidewalk and crosswalk. Indeed, we included indicators as new fields in the attribute table of the layer representing the pedestrian links; in this way, each row of the attribute table refers to each arc of the network, whereas each column corresponds to each indicator and their respective assigned score. For example, for the indicator "street furniture", after a site inspection, a 0-score was assigned if litter bins, benches, and other elements of street furniture were absent along the sidewalk, and a 1-score was assigned if they were present. Finally, a quality index was assessed for each crosswalk and each sidewalk, using the following formulas:

$$QI_{sw} = Praticability \text{ x } 0.3 + Pleasantness \text{ x } 0.3 + Safety \text{ x } 0.4 \quad (2)$$

$$QI_{cw} = Safety \ x \ \frac{5}{7} \quad (3)$$

Each sidewalk and crosswalk can obtain a quality index ranging from 0 to 5. For each railway station area, the percentage of km of pedestrian network having a quality index under a threshold was evaluated to identify the worst areas in terms of quality of pedestrian network.

Combining both the different walkability approaches, we identified the railway station areas having the lowest accessibility and may be creating the most disadvantaged communities.

4. Study area

The city of Palermo is located in Sicily, an island in the southern part of Italy. The city has an area of about 158.9 km^2 and is divided into 25 districts. According to the Italian National Institute of Statistics (ISTAT), the city had a population of 632,499 in 2022. Fourteen railway stations distributed throughout the city area were considered as a case study (Fig. 4). These stations are along the railway line connecting the nearest airport (Punta Raisi), located outside the city, to the city main station and from this to the Palermo Roccella station, in the south-eastern suburb of the city. This railway line extends for approximately 37 km, of which 20 are within the municipality boundaries. This railway line connects several neighborhoods, business hubs, commercial areas, and cultural attractions,

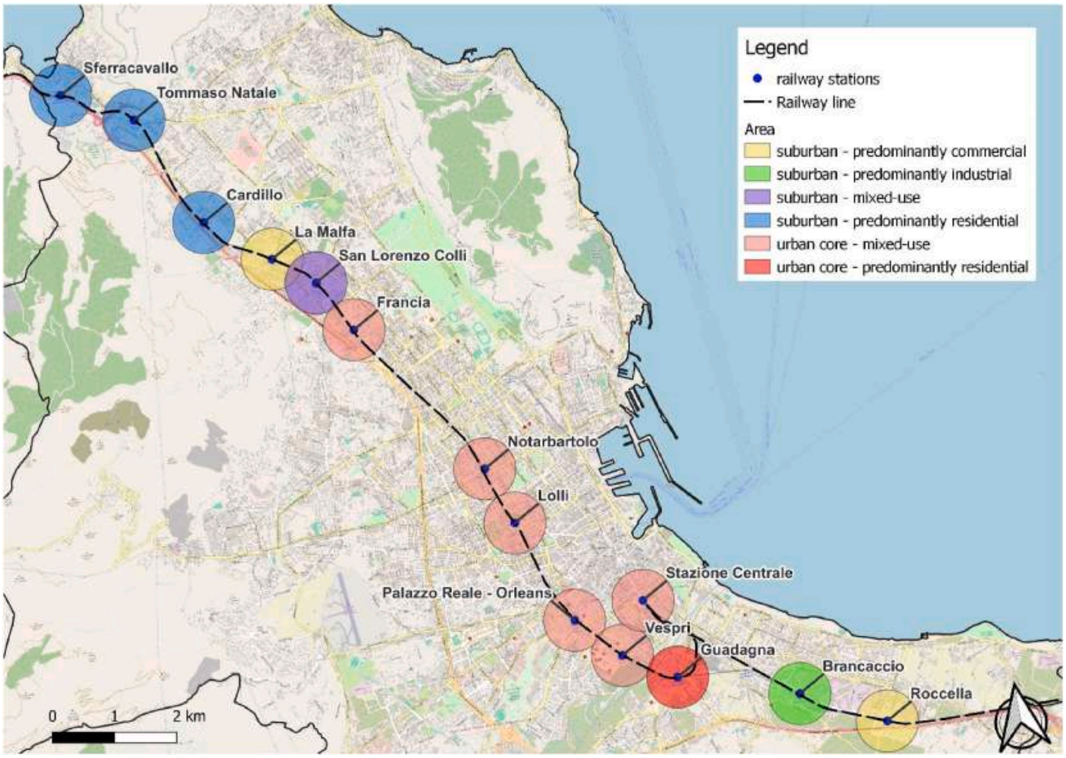

Fig. 4. Railway stations.

including many tourist spots, and therefore play a pivotal role in uplifting the city economy. Therefore, the railway service has great potential as a mode of transport for the city inhabitants and tourists visiting the city, representing a connection with the city center especially for people living in suburban areas.

However, a recent study conducted by D'Orso and Migliore (2020) highlighted that the pedestrian environment around the catchment areas of some railway stations in Palermo is not satisfactory. Poor walkability affects the pedestrian accessibility to the railway stations, also influencing the mode choice of residents for the first- and last-mile journey. Eventually, in some cases, this led to less usage of public transport and motivate people to use private vehicles, generating more traffic congestion and pollutant emissions.

It is therefore not surprising that the motorization rate of Palermo is 62.4 passenger cars per 100 inhabitants, showing that several neighborhoods are very car dependent. Also, according to the Sustainable Urban Mobility Plan of Palermo (Comune di Palermo, 2019), the modal share for private vehicles is 78 %. On the other hand, the modal share for public transport is 9 %, whereas for walking it is 12 %, manifesting much less usage of public transport by residents than private cars. Therefore, according to the TomTom Traffic Index Ranking, Palermo stands as the 77th most congested traffic city across the world in 2023, whereas INRIX ranked Palermo as the third most traffic congested city in Europe in 2022. The downtown streets of Palermo are so congested that drivers spend the equivalent of five days stuck in traffic in a year (INRIX, 2023).

Therefore, based upon the high motorization rate and consequent modal share, we chose the historical city of Palermo as a case study to measure the spatial inequalities to access the railway stations across the city and identify the disadvantaged communities.

For each railway station, a walkable catchment area considering a 500-m straight line distance from the railway station was assessed. Indeed, catchment areas are generally defined as buffers with a radius that is usually calculated as the distance that the residents are willing to walk to the railway stations, assuming they are all able to walk. Therefore, we created a buffer having a radius of 500 m around each railway station using QGIS, an open-source GIS software. The characteristics of the railway stations in terms of population within the walkable catchment area, number of job opportunities (employees), number and type of points of interest (POIs), and land use, are reported in Table 4.

The census data were derived from the 15th Italian General Census of Population and Housing (ISTAT, 2011). The employee data were derived from the 9th Italian General Census of Industry and Services (ISTAT, 2015). These data, although not up-to-date, represent the most complete available to the public. Thus, some changes in the population and employees data may occur in the recent period. A decrease in the population occurred, particularly in the city center of Palermo due to the suburbanization and urban sprawl which are especially located around the coastal areas of the city.

ISTAT also provided the shapefiles of the census zones in which the city is divided. We used the Intersection tool in QGIS to find the census zones falling within the walkable catchment areas.

Starting from the shapefile data representing buildings as polygonal features provided by the Municipality of Palermo (https://opendata.comune.palermo.it), having as attributes the height, the floor area and the volume of each building, using the Intersection tool, we created a layer including all the buildings within the walkable catchment areas and then classified them into residential and non-residential. We calculated how many people live in the railway station areas, using the following GIS apportioning method. First, we apportioned the population data of the census zones into the buildings falling within them in proportion to the volume of the buildings; then, we considered only the buildings falling within the walkable catchment areas and calculated the population living in

Table 4
Railway stations metrics.

Railway station	Population	Employees	Number of POIs	Main POIs	Land use
Brancaccio	2508	3545	4	Industrial area, supermarket	Suburban – predominantly industrial
Cardillo	2414	417	1	Supermarket	Suburban – predominantly residential
Francia	5086	3265	36	Supermarket, cinema, school, pharmacy, local shops	Urban core – mixed use
Guadagna	9780	1579	11	Groceries, school, post office	Urban core – predominantly residential
La Malfa	2347	3207	12	Shopping malls, supermarkets	Suburban – predominantly commercial
Lolli	15648	6429	198	Cinema, theater, school, restaurants, local shops	Urban core – mixed use
Notarbartolo	13184	6207	78	Cinema, theatre, school, local shops	Urban core – mixed use
Palazzo Reale - Orleans	9503	7285	84	University, groceries, small shops, tourist spot	Urban core – mixed use
Roccella	78	138	23	Shopping mall	Suburban – predominantly commercial
San Lorenzo Colli	1995	5293	51	Supermarkets, restaurants	Suburban – mixed use
Sferracavallo	2871	451	13	Restaurants, post office	Suburban – predominantly residential
Stazione Centrale	13543	6343	169	Restaurants, small shops, churches, government agencies	Urban core – mixed use
Tommaso Natale	6089	977	9	Groceries, small shops, cinema, post office	Suburban – predominantly residential
Vespri	8762	6056	34	Hospital, local shops	Urban core – mixed use

each railway station area.

For the employee data, a different GIS apportioning method was followed; we gathered and apportioned data from the census zones based on the proportion of the census zones falling within the catchment area. For example, considering a census zone having 100 employees, if 50 % of this census zone falls within the railway catchment area, we considered 50 employees (50 % *100) in the calculation of the number of total employees working within the catchment area.

The POIs for pedestrians within the catchment areas were imported and counted using the QuickOSM plugin, selecting "amenity" as key. We considered as POIs several types of amenities: schools, universities, hospitals, banks, postal offices, public buildings, theatres, cinemas, groceries, and tourist spots.

To understand the main land use in each walkable catchment area we considered the percentage of residential buildings in relation to the total number of buildings, the number of employees and POIs.

As it can be noted, 7 railway stations are located in suburban areas and 7 in the urban core. The railway station areas located in the northern suburbs are predominantly residential. La Malfa and Roccella areas are predominantly commercial since shopping malls are located in these areas. Except for the Guadagna area, the railway station areas in the urban core are mixed-use with high population and activity densities.

Considering the data reported in Table 4, we can see that the overall accessibility of the railway service in Palermo is not very good: only 15 % (93,806) of the people living in Palermo and 27 % (51,190) of the employees live and work respectively within the 500m-buffers around the stations.

5. Results

In this section, we reported the results of the application of our methodology to the case study.

5.1. Road density

In order to assess the road density and the intersection density for each railway station area, a square area of 1 km^2 around each railway station and centered on it was evaluated using QGIS. The 1 km^2 square area around railway stations is representative enough of the pedestrian environment that transit users can experience. Different studies in literature recommend 500 m as optimum to define the railway station catchment area, and no more than 1 km of actual walking distance, including all detours (ITDP, 2017). A distance of 500 m represents about a 10-min walk, and a distance of 1000 m represents about a 20-min walk at an average urban speed of approximately 3 km per hour, including wait time at intersections.

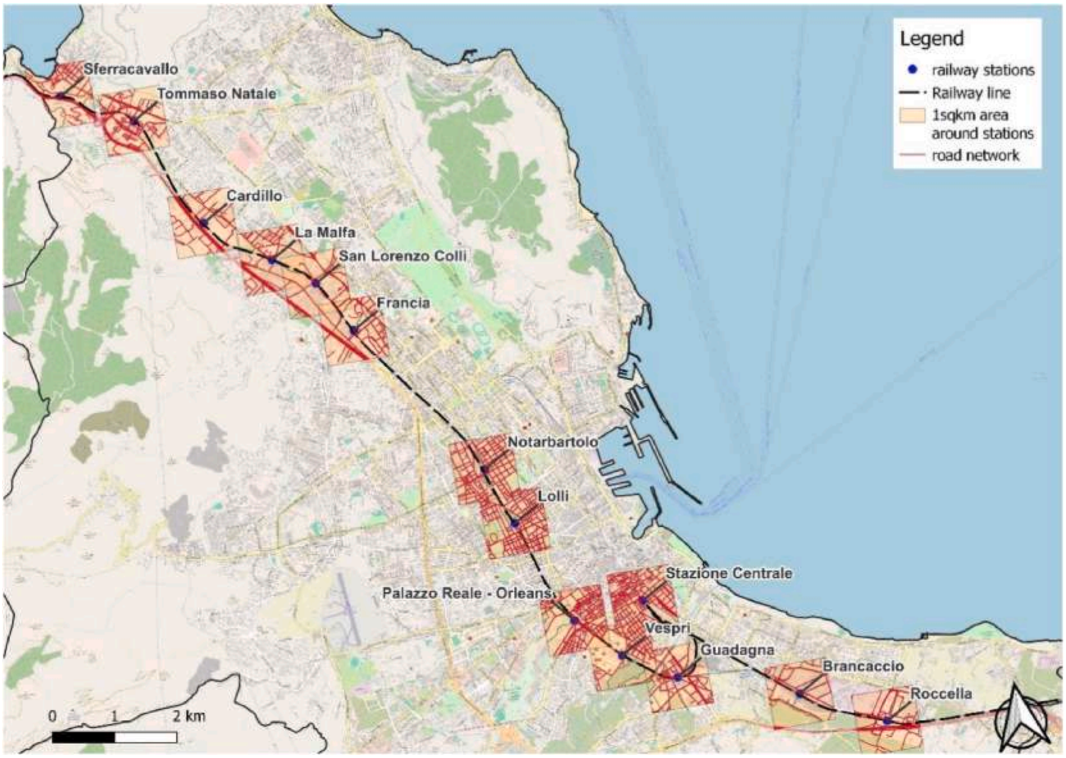

Fig. 5. Road density calculation.

Table 5
Road density.

Railway stations	Road density [km/km^2]
Brancaccio	**9.104**
Cardillo	**11.998**
Francia	14.692
Guadagna	14.586
La Malfa	13.179
Lolli	**22.437**
Notarbartolo	**20.647**
Palazzo Reale - Orleans	**22.796**
Roccella	14.653
San Lorenzo Colli	**9.836**
Sferracavallo	13.345
Stazione Centrale	**25.9**
Tommaso Natale	17.981
Vespri	13.142

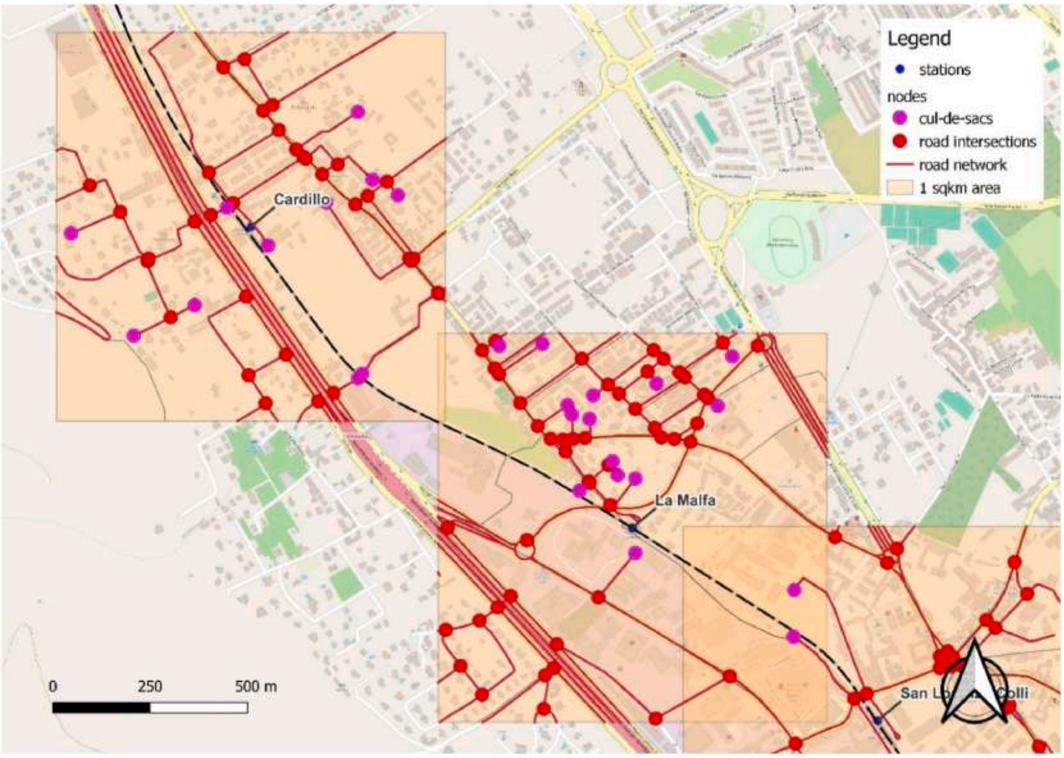

Fig. 6. Intersection density calculation.

Then, we uploaded the road network of Palermo derived from OpenStreetMap (www.openstreetmap.org) using the QuickOSM plugin, and we clipped it considering the square areas as an overlay layer, as it can be seen in Fig. 5. Finally, we calculated the length of all the road segments falling within the square area of 1 km^2 around each railway station. Table 5 shows the road density for each railway station area. It can be noted that Stazione Centrale, Palazzo Reale – Orleans, Lolli and Notarbatrolo areas – all located in the urban core – have the highest values of road density. In contrast, the suburban railway station areas of Brancaccio, San Lorenzo Colli and Cardillo have the lowest ones.

5.2. Intersection density

Using the "Build Graph" tool of the Networks plugin in QGIS, we created a new layer representing all the nodes (road intersections and cul-de-sacs) considering the road network as input. The layer has two attributes: an id number and the number of road segment converging in the node (nb). We used this last attribute to simply distinguish road intersections and cul-de-sacs in the map (Fig. 6). Road intersections are the junctions at which three or more road segments intersect (nb > 3), while cul-de-sacs were identified as nodes

Table 6
Intersection density.

Railway stations	Intersection density [int/km^2]
Brancaccio	**34**
Cardillo	**33**
Francia	65
Guadagna	92
La Malfa	48
Lolli	**209**
Notarbartolo	171
Palazzo Reale - Orleans	**247**
Roccella	**33**
San Lorenzo Colli	**39**
Sferracavallo	55
Stazione Centrale	**286**
Tommaso Natale	96
Vespri	90

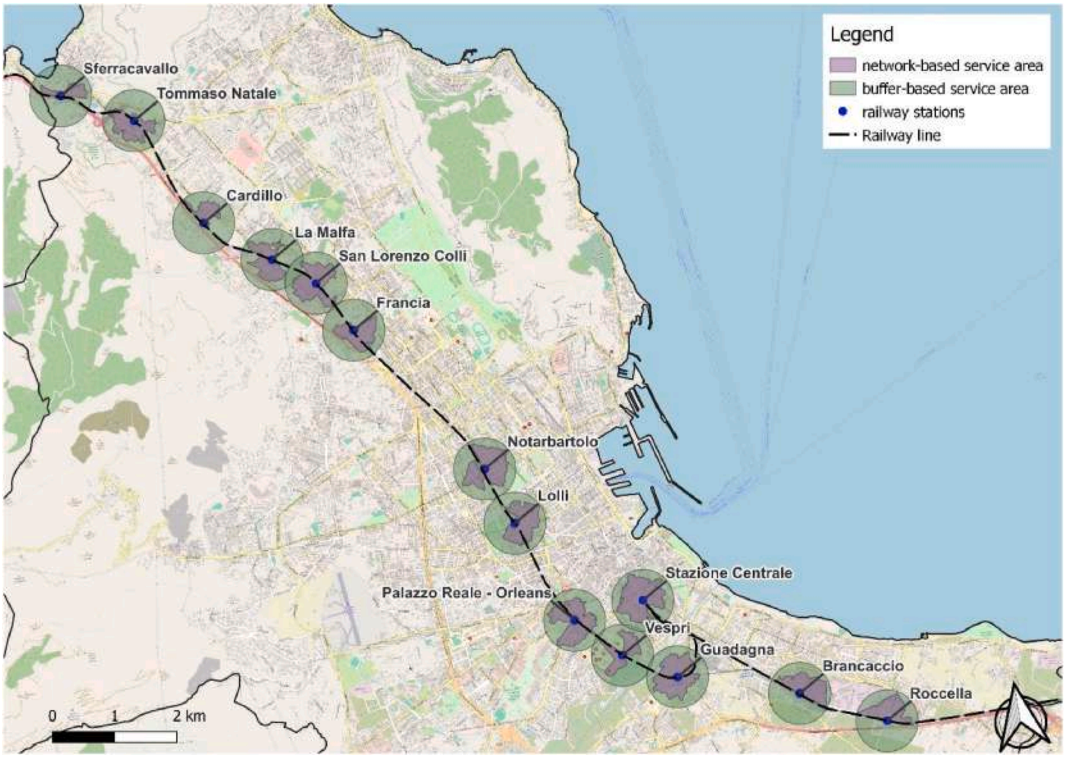

Fig. 7. Pedestrian Catchment Area ratio.

where only a road segment converges (nb = 1). The value of intersection density for each railway station area is reported in Table 6. As it can be noted, Stazione Centrale, Palazzo Reale – Orleans, and Lolli areas in the urban core have the highest values while Roccella, Cardillo, Brancaccio, and San Lorenzo Colli – all located in suburban areas – have the lowest ones.

5.3. Pedestrian Catchment Area ratio

Using Buffer and Service Area tools in QGIS, we estimated the theoretical service area and the network-defined service area of the railway stations, respectively (Fig. 7). Indeed, we identified the portion of the road network within 500 m from the station, using the Service Area tool. Then, we built the network-defined service areas as polygons, considering the parcels and the building that can be accessed from the portion of the road network within 500 m from the railway stations. The PCA ratios for each railway station area are reported in Table 7.

All stations have poor pedestrian accessibility, reaching a PCA ratio below 0.5. This finding is related to the presence of some context-specific conditions. For example, many railway stations (like Sferracavallo, Tommaso Natale, Cardillo or Francia) are near

Table 7
Pedestrian Catchment Area ratio.

Railway stations	PCA ratio
Brancaccio	0.28
Cardillo	**0.08**
Francia	0.21
Guadagna	**0.44**
La Malfa	0.18
Lolli	0.33
Notarbartolo	**0.44**
Palazzo Reale - Orleans	**0.42**
Roccella	0.27
San Lorenzo Colli	0.27
Sferracavallo	**0.09**
Stazione Centrale	**0.49**
Tommaso Natale	0.26
Vespri	0.22

Table 8
Network connectivity index.

Railway stations	Network Connectivity Index
Brancaccio	0.347
Cardillo	0.247
Francia	0.408
Guadagna	0.594
La Malfa	0.348
Lolli	0.757
Notarbartolo	0.764
Palazzo Reale - Orleans	0.867
Roccella	0.411
San Lorenzo Colli	0.356
Sferracavallo	0.297
Stazione Centrale	1
Tommaso Natale	0.520
Vespri	0.424

Viale Regione Siciliana, a primary road with two separate carriageways having a speed limit of 70 km/h and few pedestrian underpasses or overpasses located only in specific points; this road can be considered as a pedestrian-hostile road, limiting the pedestrian accessibility of these railway stations. Another element limiting the access is the presence of the railway tracks and occupy a large area that is unpassable for pedestrians. This is valid not only for suburban railway stations (like Brancaccio) but also for Stazione Centrale which is the main railway station in the urban core. Possibly, an infrastructure improvement (such as the construction of overpasses or underpasses) can help in mitigating these limitations to pedestrian accessibility and can enhance the PCA ratios reaching the optimal threshold. The railway station areas of Cardillo and Sferracavallo are the most inaccessible, as the network-defined service area is reduced right by the presence of Viale Regione Siciliana. Once again, the railway station areas in the city centre (Stazione Centrale, Guadagna, Notarbartolo, Palazzo Reale – Orleans) appear to have the highest values.

5.4. *Impacts of network connectivity on social equity*

To assess the level of network connectivity for each railway station area, we calculated the network connectivity index, using Eq. (1). The network connectivity index for each station is reported in Table 8. As it can be noted, Cardillo, Sferracavallo, Brancaccio, La Malfa, and San Lorenzo Colli areas – all located in suburban areas – have the lowest values of network connectivity index. Lolli, Notarbartolo, Palazzo Reale – Orleans and Stazione Centrale, on the other hand, have the highest values.

However, network connectivity affects the spatial access to the railway stations in a way that depends on the distribution of residential buildings and activities in the service area. Thus, we evaluated the impacts of network connectivity on social equity. First, the population residing in residential units within a 500m buffer zone was determined. Subsequently, the number of residents within the network-defined service area, delineated by a 500m network distance from each railway station, was assessed (Table 9). The difference between the population living within the 500m buffer and the network-defined service area represents the excluded population, i.e. the number of people living beyond the 500 m from the railway station and at risk of social exclusion. We considered some demographic characteristics identifying vulnerable social groups such as older people, unemployed and foreigners to understand the impacts of network connectivity on social exclusion. With the term "foreigners" we mean the people residing in Palermo coming from outside countries and not having the Italian citizenship. This social group may be at most risk of social exclusion. Indeed, foreigner people are most likely to not have a private vehicle and being more dependent on public transportation; thus, providing a good access to railway station is crucial in order to prevent their exclusion in community. As it can be noted in Fig. 8 (top), Brancaccio,

Table 9
Population within the 500m buffers and the network-defined areas.

	Within the 500m buffer					Within the network-defined service area				
	Population	Female	People over 65	Unemployed	Foreigners	Population	Female	People over 65	Unemployed	Foreigners
Brancaccio	2508	1290	367	131	13	31	16	7	0	0
Cardillo	2414	1239	328	117	34	943	482	129	45	12
Francia	5086	2762	1451	150	44	1750	957	553	48	17
Guadagna	9780	5102	1710	470	93	7172	3722	1193	369	82
La Malfa	2347	1231	264	135	19	469	247	50	26	5
Lolli	15648	8430	3011	601	1408	6092	3243	1139	236	646
Notarbartolo	13184	7363	3311	390	280	6041	3406	1470	181	152
Palazzo Reale - Orleans	9503	4870	1658	451	469	3399	1746	612	162	158
Roccella	78	37	9	2	2	33	17	4	1	2
San Lorenzo Colli	1995	1069	403	87	59	735	392	135	32	19
Sferracavallo	2871	1463	512	157	51	374	189	58	18	8
Stazione Centrale	13543	6825	2200	621	2802	6459	3237	1034	286	1581
Tommaso Natale	6089	3107	775	371	49	3346	1720	436	205	32
Vespri	8762	4610	1696	405	390	1977	1051	416	71	38

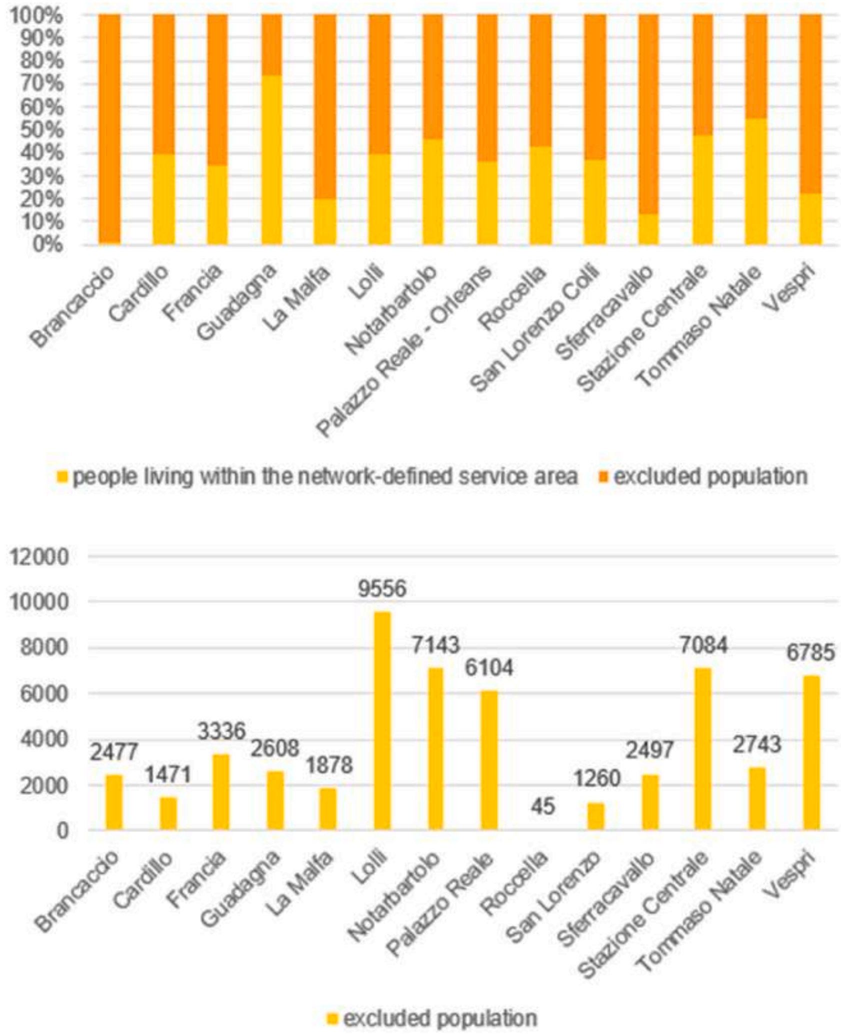

Fig. 8. Top: Percentage of people living in the buffer that live within the network-defined service area and outside it (excluded population). Bottom: excluded population.

Sferracavallo, and La Malfa areas have the highest percentage of excluded population. The Brancaccio railway station is inaccessible to all foreigners, to all the unemployed and to the 95 % of people aged over 65 living within the 500 m buffer, and this means that the use of the train service is precluded or made difficult for groups already at risk of social exclusion.

However, if the absolute numbers are considered, Lolli, Notarbartolo, and Stazione Centrale have the highest numbers of excluded population. This is reasonable because core areas have higher population density than suburban ones.

Given the railway service's potential as a mode of transportation for reaching job opportunities and POIs, the next step involved estimating the number of employees within both the 500m buffer area and network-defined service area (Table 10). As Fig. 9 (top) shows, we found that Sferracavallo, Francia, and Cardillo have the highest percentage of excluded employees. However, Palazzo Reale, Lolli, and Vespri have the highest number of excluded employees (Fig. 9, bottom). This is reasonable because urban core areas have higher activity density than suburban ones.

5.5. Quality of the pedestrian network

Considering the network-defined service areas around the railway stations, the micro-scale approach was followed. First, the pedestrian network was developed using QGIS, identifying all the sidewalks and crosswalks. Using the QuickMapServices plugin, we imported the Google Satellite map as a base map into QGIS to identify the location of sidewalks and crosswalks and build the network as a new linear layer. The layer attribute table contains as many records as the number of sidewalks and crosswalks within the railway network-defined service areas and as many columns as the number of indicators to be evaluated. The level of practicability, safety, and pleasantness of each pedestrian link (sidewalk or crosswalk) was assessed, assigning a score to each indicator (see Tables 2 and 3) based on objective assessments and quantitative measures of the existing conditions conducted through site inspections or using

Table 10
Employees within the 500-m buffers and the network-defined areas.

	Within the 500-m buffer							Within the network-defined service area						
	enterprises	employees (ENT)	No Profit Organizations	employees (NPO)	public institutions	employees (PI)	total employees	enterprises	employees (ENT)	No Profit Organizations	employees (NPO)	public institutions	employees (PI)	total employees
Brancaccio	190	3265	9	20	3	260	3545	79	1814	1	3	0	3	1820
Cardillo	116	415	5	1	0	0	417	24	75	1	0	0	0	75
Francia	384	1459	33	27	10	1779	3265	107	229	13	1	4	73	303
Guadagna	267	1039	13	16	9	523	1579	180	759	8	1	6	114	874
La Malfa	169	1791	9	156	6	1259	3207	54	847	2	66	2	295	1208
Lolli	1769	4502	116	260	17	1667	6429	704	1615	44	122	6	214	1952
Notarbartolo	1697	3940	98	126	23	2141	6207	878	1924	41	42	7	472	2438
Palazzo Reale - Orleans	430	1252	53	104	25	5929	7285	209	716	22	51	9	594	1360
Roccella	12	49	0	0	1	89	138	4	16	0	0	0	10	26
San Lorenzo Colli	211	2835	11	122	9	2336	5293	80	1168	3	56	4	457	1682
Sferracavallo	120	286	5	3	3	162	451	10	37	1	1	1	6	44
Stazione Centrale	1237	3670	60	76	26	2596	6343	764	2554	41	43	17	1264	3861
Tommaso Natale	150	788	15	2	3	188	977	77	331	7	0	1	8	339
Vespri	339	874	20	72	7	5109	6056	118	338	6	20	2	1365	1724

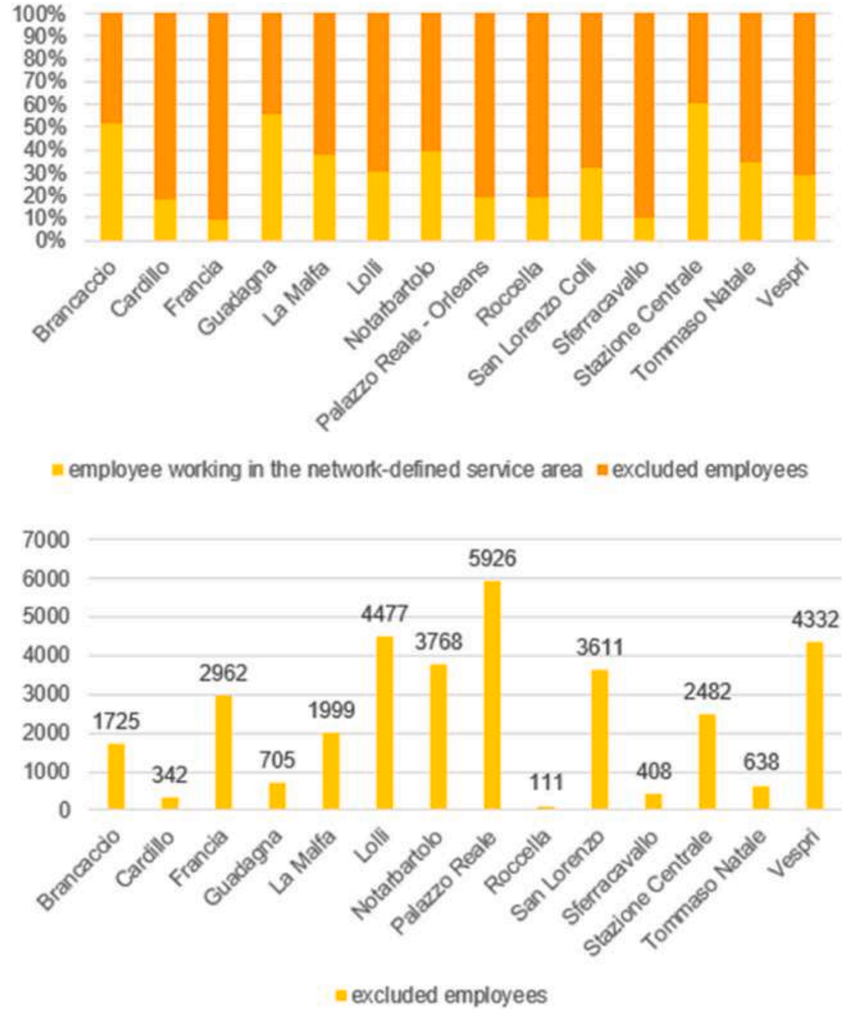

Fig. 9. Top: Percentage of employees working in the buffer that work within the network-defined service area and outside it (excluded employees). Bottom: excluded employees.

Google Street View where the site inspection was not possible, without considering perceptions or opinions. The weights for practicability, pleasantness and safety were considered equal to 0.3, 0.3 and 0.4, respectively, since safety has a bigger impact on walkability for users. Finally, a Quality Index was calculated for each pedestrian link. The assessment of the quality of pedestrian infrastructure within the network-defined service areas of the railway stations was a time-consuming process, as the pedestrian network was composed by 4299 pedestrian links. At the end of the process, the quality map was built (Fig. 10).

As it can be noted in Table 11, Brancaccio, Cardillo, and Sferracavallo areas have more than 70 % of kilometres of pedestrian network having a quality index below 2. La Malfa and San Lorenzo have more than 50 % of kilometres of pedestrian network below this threshold. On the other hand, Lolli has a good-quality pedestrian network (more than 50 % of the pedestrian network having a quality index over 3).

6. Discussion

Combining the two walkability assessment approaches, we found that the railway station area of Lolli has a good level of network connectivity and the highest level of quality of the pedestrian infrastructure. Stazione Centrale has the highest level of network connectivity but a quality with middle values: only 26 % of pedestrian network has a quality index over 3, while more than 40 % has a quality index ranging from 2 to 3. These two railway station areas are both located in the urban core. On the other hand, the railway station areas in suburbs (Brancaccio, Cardillo, La Malfa, San Lorenzo Colli and Sferracavallo) have poor road network connectivity and quality of pedestrian infrastructure.

In particular, Brancaccio, Cardillo and Sferracavallo railway stations are the more inaccessible and disadvantaged areas, having both poor network connectivity and pedestrian network quality. We focused on these three areas to underline the issues and propose

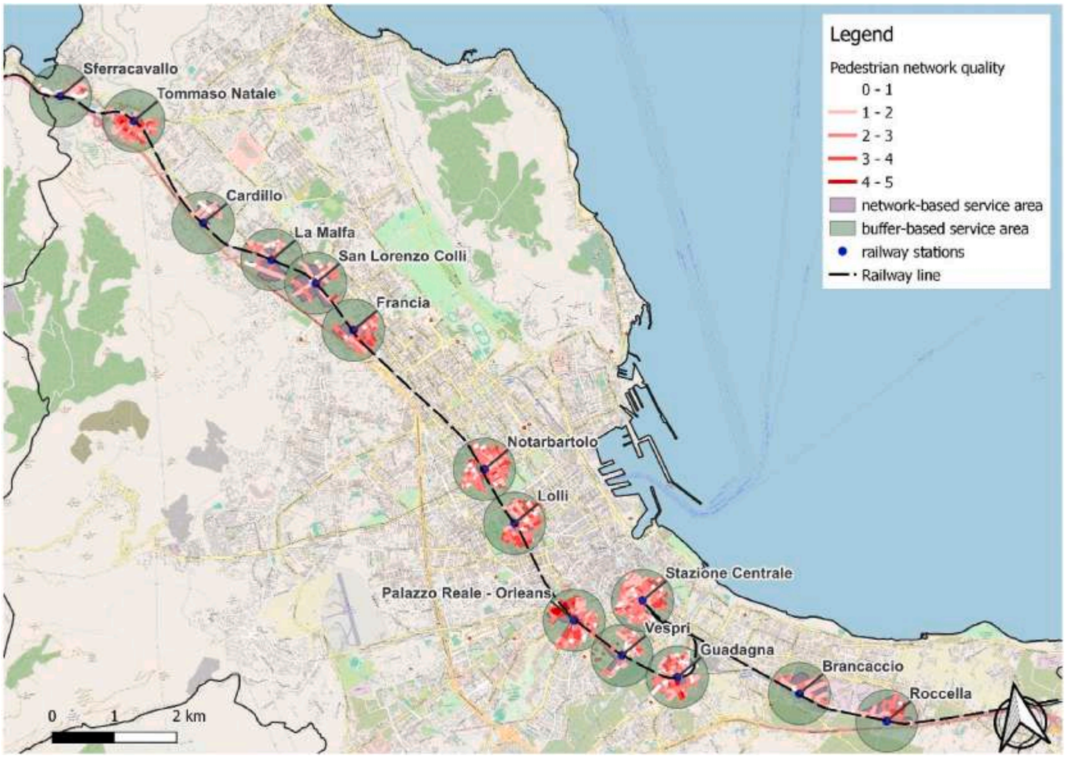

Fig. 10. Quality of the pedestrian network.

Table 11
Percentage of km of pedestrian network within the network-defined service area having a quality index falling within a given range.

Railway stations	0–1	1–2	2–3	3–4	4–5
Brancaccio	**7.3**	**61.8**	30.3	0.5	0.0
Cardillo	**10.4**	**73.2**	16.3	0.1	0.0
Francia	1.9	13.1	65.3	19.5	0.3
Guadagna	18.0	18.8	45.0	14.4	3.7
La Malfa	**4.6**	**50.1**	38.0	7.3	0.0
Lolli	1.6	6.8	32.1	**58.0**	**1.5**
Notarbartolo	1.8	8.9	47.2	35.7	6.3
Palazzo Reale - Orleans	7.3	18.2	42.0	22.7	9.9
Roccella	5.1	19.0	60.7	11.8	3.5
San Lorenzo Colli	**6.9**	**49.6**	37.5	5.9	0.1
Sferracavallo	**21.0**	**57.8**	17.2	4.0	0.0
Stazione Centrale	9.1	22.9	42.0	24.4	1.7
Tommaso Natale	1.2	38.1	33.3	19.9	7.5
Vespri	12.2	31.5	45.6	10.6	0.0

solutions, identifying the priority actions to be implemented.

Brancaccio station (Fig. 11) is characterized by a network-defined service area that is reduced due to the absence of roads that go beyond the railway tracks and connect the more densely populated southern part with the station. A pedestrian overpass over the rail tracks could be constructed to provide safe and direct access to the station to a broader number of people. Moreover, sidewalks have insufficient width and are frequently obstructed by garbage and tree roots. Also, the pedestrian crossings are not well maintained.

Cardillo station (Fig. 12) is characterized by a reduced network-defined service area due to the presence of Viale Regione Siciliana. In front of the station entrance there are no crosswalks and sidewalks; there is only a pedestrian lane with insufficient width. The main road of the area, Via Tommaso Natale, having high traffic volumes, have sidewalks with insufficient width and poor maintained pedestrian crossings.

Finally, the access road to the railway station of Sferracavallo (Fig. 13) is a high-speed road with no sidewalks and crosswalks. The main road of the railway station area, Via Sferracavallo, has sidewalks with degraded surface or insufficient width. Also in this case, the network-defined service area is limited by the presence of Viale Regione Siciliana.

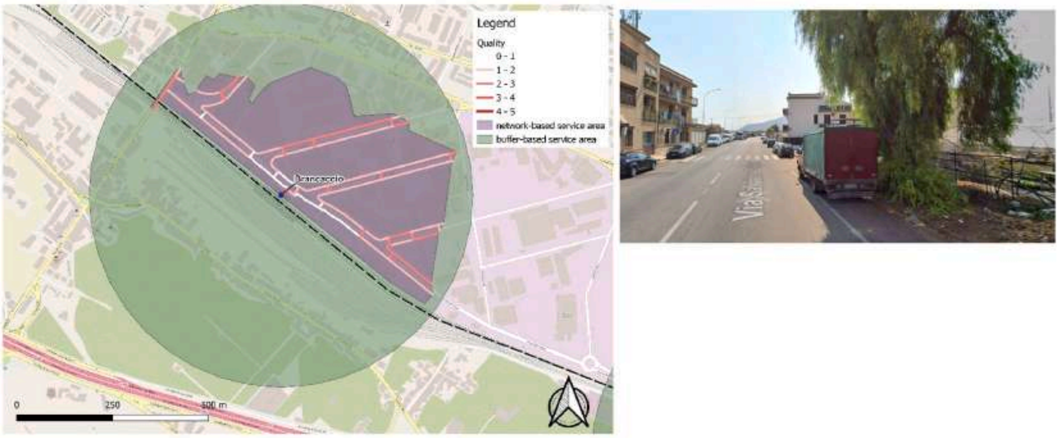

Fig. 11. Brancaccio railway station area.

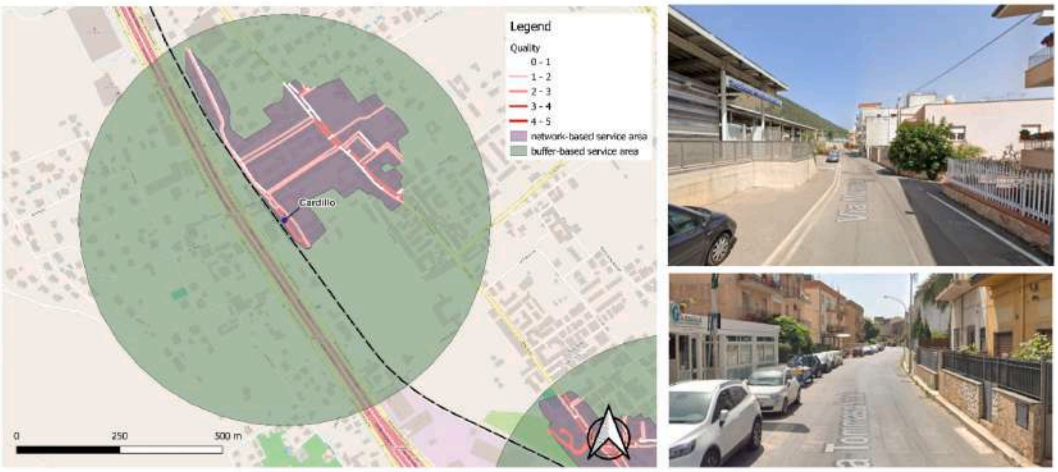

Fig. 12. Cardillo railway station area.

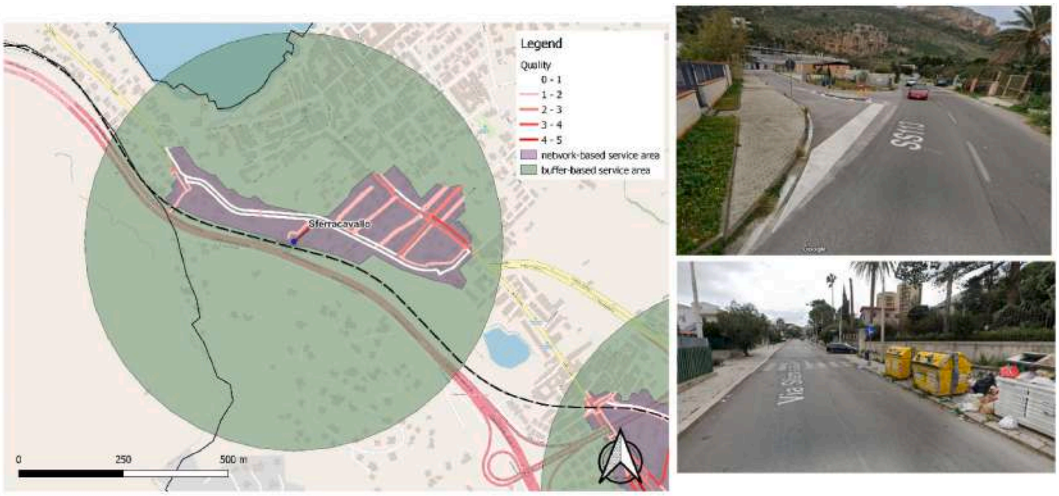

Fig. 13. Sferracavallo railway station area.

7. Conclusion

In recent years, policymakers and local authorities are paying more attention to active mobility and its link with public transport, trying to transform urban areas from car-dependent to walkable and cyclable neighborhoods. There is a growing awareness that spending large public resources to improve public transportation without simultaneously building or improving pedestrian and cycling infrastructure makes these interventions ineffective. On the other hand, even improving pedestrian access to a public transport service having low performance could be equally useless. Thus, interventions on pedestrian and cycling infrastructure need to be incorporated into larger projects involving public transport, road infrastructure or urban regeneration interventions. Therefore, a vision that considers walking as a complementary mode to public transport and a focus on walkability can help policymakers exploit the opportunities offered by these larger projects. Moreover, big disparities seem to exist in many cities between urban areas and suburban areas, as found by Bruno et al. (2024), Murgante et al. (2024) and Akrami et al. (2024). The case study of Palermo, Italy, was chosen since this city is one of the less pedestrian-friendly cities in Europe according to the walkability assessment made by Bartzokas-Tsiompras et al. (2023). Thus, the development of a set of indicators to assess pedestrian accessibility and the social impacts of poor levels of network connectivity and quality of the pedestrian realm was urgently needed to identify the gaps and the priority interventions.

Big disparities in accessibility between railway stations located in suburban areas and the city centre were found in the case study. Areas around suburban railway stations, such as Sferracavallo, Cardillo, and Brancaccio, are characterized by poor network connectivity, having low values of PCA ratio, road density and intersection density. New pedestrian links should be constructed to improve road connectivity and reduce the number of excluded population and employees. Indeed, suburban areas have the potential for expanding the road network thanks to the presence of low-density areas or undeveloped land. However, in absolute terms, poor network connectivity has more impacts on people living and working in railway station areas in the urban core, having higher population and activity densities. Furthermore, while railway station areas in the urban core have a good quality pedestrian network, suburban railway stations are characterized by poor walkability in terms of the quality of the pedestrian infrastructure, considering safety, practicability, and pleasantness as indicators. This is a consequence of several factors. First, due to funding limitations, local authorities invest more in projects aimed at improving the pedestrian environment of the city center because it is more frequented by residents and tourists. Moreover, in middle-size Italian and European cities, the historical urban centre usually has the conveniently built structure of a 15-min city, supporting walking with a grid-like network of narrow streets, high population density, and high proximity to services. Thus, in the city centers, less efforts are needed to improve pedestrian access to essential services and transit hubs. On the contrary, the complexity of suburban development led to unbalanced and unequitable situations, resulting in residential neighborhoods that serve few other purposes than housing and require long travel times for residents to satisfy their daily needs. Therefore, the poor quality of the pedestrian network in suburban areas represents a social equity problem, undermining the effectiveness of rail services as an equitable and sustainable mode of transport, especially considering that few mobility options are available for all in suburban areas. These areas are forced to become car dependent and non-car ownership may correspond to a greater risk of social exclusion of some social groups. Especially, older people, young students and low-income households not owning a car may be limited in their independence to make trips.

The findings from our study can be generalized to other middle-size Italian and European cities, having an historical urban core like Palermo and facing modern urbanization challenges in expanding towards suburban areas. Indeed, in many Italian and European cities, the historical urban centre is usually characterized by a grid-like road network, with high population and building density and high diversity. This means that city centers usually have the conveniently built structure of a 15-min city and few efforts are needed to improve pedestrian accessibility to essential services and transit hubs.

However, the method can be applied in every context, since the indicators are related to pedestrian needs (practicability, pleasantness and safety) and are not context specific. These indicators can also be considered in assessing the quality of the pedestrian network in large modern cities or rural areas as well.

For these reasons, the proposed approach can be a decision-support tool to recognize the disparities in access to railway station in different city areas, considering different aspects and scales related to walkability, identifying what priority measures are needed and where to improve the quality of the pedestrian network to support public transport use. Starting from these evaluations, policymakers can identify the railway station areas having a poor accessibility or low quality of the pedestrian environment around them and elaborate strategies and actions to solve or mitigate these issues. Moreover, the paper shows how to assess the impact of poor accessibility on social equity, calculating the excluded population and employees (who lives or works outside the 500 m network-defined service area). 15-minute city and TOD concepts have developing neighborhoods that promote walking and making walking to transit convenient and accessible as core principles. Identifying critical areas and priority interventions is therefore useful to extend the application of these planning concepts beyond the urban core. Indeed, as also shown in different studies like the one presented by Akrami et al. (2024) related to the city of Oslo (one of the five most pedestrian-friendly city centers according to the walkability assessment made by Bartzokas-Tsiompras et al., 2023), city centers are already 15-min neighborhoods, but many suburban areas have low accessibility scores, and, according to the plans, will likely not change much in the future. Thus, our methodology can be applied in the framework of the 15-min city concept as a diagnostic approach to assist planning in rapidly changing areas or city extensions. The proposed indicators can aid policymakers and local authorities in several aspects: (i) identifying areas that can be targeted for urban regeneration initiatives; (ii) identifying critical aspects of the spatial configuration of the road network that determine an impedance influencing access to essential services; (iii) defining targeted strategies, considering the improvement of network connectivity and quality of the pedestrian realm as main objectives; and (iv) evaluating the impacts of the actions on pedestrian infrastructure, calculating how many people are positively affected by the improved conditions.

However, our study has several limitations: first, the micro-scale walkability assessment is not very time-consuming for small areas like the network-defined service areas around the railway stations, but it could be possibly time-consuming if a street-level walkability assessment is required at a city level. Moreover, it doesn't consider the temporal variation of some indicators, which may vary during the day, the week or the seasons, such as the pedestrian LOS or the traffic volumes and speed. While developing the scoring system, we considered the pedestrian LOS that could be measured during the peak hours of an average day. Also, the traffic volumes and speeds are the ones that could be measured during the peak hours of an average day. However, traffic volumes and pedestrian flows can be very different between day and night or in different seasons, thus if we consider a quality index varying according to the temporal variation of the indicators, a sidewalk having a lower quality index during the day may have a higher quality index during the night (having a higher pedestrian LOS and lower traffic volumes). Also, specific events may have an impact on walkability, like a football match or a concert, reducing the pedestrian LOS for the sidewalks around the stadium. Thus, in future studies, the temporal variation of the quality index (time of the day, weekdays/weekends, winter/summer) can be considered.

Another limitation is in the use of the weights in the walkability assessments. Different weights could be used for the micro-scale indicators (pavement slope, pedestrian LOS, etc …) and not only for the three categories (practicability, pleasantness, and safety). In this respect, AHP method or a Stated Preference surveys could be used to assign these weights, understanding if and which indicators are more important than the others. Moreover, considering different social groups (differentiated by age, gender, disabilities), a further step could be the assessment of different weights for these indicators in order to highlight that users may have different needs and may rank the importance of the indicators differently. For example, older people may prefer to have flat footpath which are also clear from obstacles, benches for resting, and, from safety perspective, lower traffic volumes and speed, giving these indicators greater weights than the others. Future studies can also be performed to assign different weights for connectivity indicators, using AHP or Delphi method involving a panel of experts.

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CRediT authorship contribution statement

Gabriele D'Orso: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Muhammad Yasir:** Writing – original draft, Software, Formal analysis, Data curation. **Marco Migliore:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no relevant financial relationships with ineligible companies or personal relationships that could have appeared to influence the work reported in this paper.

References

Aghaabbasi, M., Moeinaddini, M., Shah, M.Z., Asadi-Shekari, Z., 2018. Addressing issues in the use of Google tools for assessing pedestrian built environments. J. Transport Geogr. 73, 185–198. https://doi.org/10.1016/j.jtrangeo.2018.10.004.

Akrami, M., Sliwa, M.W., Rynning, M.K., 2024. Walk further and access more! Exploring the 15-minute city concept in Oslo, Norway. Journal of Urban Mobility 5, 100077. https://doi.org/10.1016/j.urbmob.2024.100077.

Appleyard, B.S., Frost, A.R., Allen, C., 2019. Are all transit stations equal and equitable? Calculating sustainability, livability, health, & equity performance of smart growth & transit-oriented-development (TOD). J. Transport Health 14, 100584. https://doi.org/10.1016/j.jth.2019.100584.

Avila-Palencia, I., Int Panis, L., Dons, E., Gaupp-Berghausen, M., Raser, E., Götschi, T., Gerike, R., Brand, C., de Nazelle, A., Orjuela, J.P., et al., 2018. The effects of transport mode use on self-perceived health, mental health, and social contact measures: a cross-sectional and longitudinal study. Environ. Int. 120, 199–206.

Baghestani, A., Nikbakht, M., Kucheva, Y., Afshar, A., 2024. Assessing spatial and racial equity of subway accessibility: case study of New York City. Cities 155, 105489. https://doi.org/10.1016/j.cities.2024.105489.

Bartzokas-Tsiompras, A., Bakogiannis, E., Nikitas, A., 2023. Global microscale walkability ratings and rankings: a novel composite indicator for 59 European city centres. J. Transport Geogr. 111, 103645. https://doi.org/10.1016/j.jtrangeo.2023.103645.

Behbahani, H., Nazari, S., Kang, M.J., Litman, T., 2019. A conceptual framework to formulate transportation network design problem considering social equity criteria. Transport. Res. Pol. Pract. 125, 171–183. https://doi.org/10.1016/j.tra.2018.04.005.

Birkenfeld, C., Victoriano-Habit, R., Alousi-Jones, M., Soliz, A., El-Geneidy, A., 2023. Who is living a local lifestyle? Towards a better understanding of the 15-minute-city and 30-minute-city concepts from a behavioural perspective in Montréal, Canada. Journal of Urban Mobility 3, 100048. https://doi.org/10.1016/j.urbmob.2023.100048.

Bivina, G.R., Gupta, A., Parida, M., 2020. Walk accessibility to metro stations: an analysis based on meso- or micro-scale built environment factors. Sustain. Cities Soc. 55, 102047. https://doi.org/10.1016/j.scs.2020.102047.

Borghetti, F., Colombo, C.G., Longo, M., Mazzoncini, R., Cesarini, L., Contestabile, L., Somaschini, C., 2021. 15-Min station: a case study in North Italy city to evaluate the livability of an area. Sustainability 13 (18), 10246. https://doi.org/10.3390/su131810246.

Bruno, M., Monteiro Melo, H.P., Campanelli, B., Loreto, V., 2024. A universal framework for inclusive 15-minute cities. Nature Cities 1, 633–641. https://doi.org/10.1038/s44284-024-00119-4.

Bhuiya, M.M.R., Rafiq, R., Morshed, K.N.M., et al., 2023. Suitable bus stop locations for a proposed bus rapid transit corridor in a developing country city: an analytical hierarchy process approach. Transp. in Dev. Econ. 9, 10. https://doi.org/10.1007/s40890-023-00179-6.
Calthorpe, P., 1995. The Next American Metropolis: Ecology, Community, and the American Dream, third ed. Princeton Architectural Pr.
Cavallaro, F., Bruzzone, F., Nocera, S., 2020. Spatial and social equity implications for High-Speed Railway lines in Northern Italy. Transport. Res. Pol. Pract. 135, 327–340. https://doi.org/10.1016/j.tra.2020.03.028.
Collins, K., Der Wartanian, R., Reed, P., Chea, H., Hou, Y., Zhang, Y., 2023. Social equity and public transit in the inland empire: Introducing a transit equity analysis model. Transportation Research Interdisciplinary Perspectives 21, 100870. https://doi.org/10.1016/j.trip.2023.100870.
Comune di Palermo, 2019. Sustainable Urban Mobility Plan -. Piano Urbano della Mobilità Sostenibile, Quadro conoscitivo.
Dill, J., 2004. Measuring Network Connectivity for Bicycling and Walking. 83rd Annual Meeting of the Transportation Research Board, Washington, D.C.
D'Alessandro, D., Appolloni, L., Capasso, L., 2016. How walkable is the city? Application of the walking suitability index of the territory (T-WSI) to the city of Rieti (Lazio region, Central Italy). Epidemiol Prev 2016 40 (3–4), 237–242.
D'Orso, G., Migliore, M., 2020. A GIS-based method for evaluating the walkability of a pedestrian environment and prioritised investments. J Transp Geogr 82, 102555. https://doi.org/10.1016/J.JTRANGEO.2019.102555.
D'Orso, G., Minaudo, L., Migliore, M., 2023. Comparing macroscale and microscale walkability indicators to establish pick-up/drop-off locations for a microtransit service in a suburban area. Infrastructures 8, 165. https://doi.org/10.3390/infrastructures8120165.
Dutheil, F., Pélangeon, S., Duclos, M., Vorilhon, P., Mermillod, M., Baker, J.S., Pereira, B., Navel, V., 2020. Protective effect on mortality of active commuting to work: a systematic review and meta-analysis. Sports Med. 50, 2237–2250. https://doi.org/10.1007/s40279-020-01354-0.
Fazio, M., Borghetti, F., Giuffrida, N., Le Pira, M., Longo, M., Ignaccolo, M., Inturri, G., Maja, R., 2023. The "15-minutes station": a case study to evaluate the pedestrian accessibility of railway transport in Southern Italy. Transp. Res. Procedia 69, 536–543. https://doi.org/10.1016/j.trpro.2023.02.205.
Ferrer, S., Ruiz, T., 2018. The impact of the built environment on the decision to walk for short trips: evidence from two Spanish cities. Transp. Policy 67, 111–120. https://doi.org/10.1016/J.TRANPOL.2017.04.009.
Foth, N., Manaugh, K., El-Geneidy, A.M., 2013. Towards equitable transit: examining transit accessibility and social need in Toronto, Canada, 1996-2006. J. Transport Geogr. 29, 1–10.
Freiberg, G., Giannotti, M., Bittencourt, T.A., 2024. Are mass transit projects and public transport planning overlooking uneven distributional effects? Empirical evidence from Sao Paulo, Brazil. J. Transport Geogr. 116, 103825. https://doi.org/10.1016/j.jtrangeo.2024.103825.
Guo, J., Brakewood, C., 2024. Analysis of spatiotemporal transit accessibility and transit inequity of essential services in low-density cities, a case study of Nashville, TN. Transport. Res. Pol. Pract. 179, 103931. https://doi.org/10.1016/j.tra.2023.103931.
Gupta, A., Bivina, G.R., Parida, M., 2022. Does neighborhood design matter for walk access to metro stations? An integrated SEM-Hybrid discrete mode choice approach. Transp. Policy 121, 61–77. https://doi.org/10.1016/j.tranpol.2022.03.010.
Ha, J., Ki, D., Lee, S., Ko, J., 2023. Mode choice and the first-/last-mile burden: the moderating effect of street-level walkability. Transport. Res. Transport Environ. 116, 103646. https://doi.org/10.1016/j.trd.2023.103646.
Hamer, M., Chida, Y., 2008. Walking and primary prevention: a meta-analysis of prospective cohort studies. Br. J. Sports Med. 42 (4), 238–243. https://doi.org/10.1136/bjsm.2007.039974.
Higgins, C.D., Kanaroglou, P.S., 2016. A latent class method for classifying and evaluating the performance of station area transit-oriented development in the Toronto region. J. Transport Geogr. 52, 61–72. https://doi.org/10.1016/j.jtrangeo.2016.02.012.
INRIX, 2023. 2022 INRIX Global Traffic Scorecard. Available online: https://inrix.com/scorecard-2022/.
Institute for Transportation and Development Policy (ITDP), 2017. TOD Standard, third ed. ITDP, New York.
Istituto Nazionale di Statistica (ISTAT), 2011. 15° Censimento generale della popolazione e delle abitazioni: Dati definitivi [15th General Census of Population and Housing: Final data]. Available online: https://www.istat.it/statistiche-per-temi/censimenti/censimenti-storici/popolazione-e-abitazioni/popolazione-2011/.
Istituto Nazionale di Statistica (ISTAT), 2015. I distretti industriali 2011: 9° Censimento dell'industria e dei servizi e Censimento delle istituzioni non profit [Industrial districts 2011: 9th Census of Industry and Services and Census of Non-Profit Institutions]. ISBN 978-88-458-1859-2. Available online: https://www.istat.it/produzione-editoriale/i-distretti-industriali-2011/.
Jeffrey, D., Boulangé, C., Giles-Corti, B., Washington, S., Gunn, L., 2019. Using walkability measures to identify train stations with the potential to become transit oriented developments located in walkable neighbourhoods. J. Transport Geogr. 76, 221–231. https://doi.org/10.1016/j.jtrangeo.2019.03.009.
Jehle, U., Coetzee, C., Büttner, B., Pajares, E., Wulfhorst, G., 2022. Connecting people and places: analysis of perceived pedestrian accessibility to railway stations by Bavarian case studies. Journal of Urban Mobility 2, 100025. https://doi.org/10.1016/j.urbmob.2022.100025.
Kamruzzaman, M., Baker, D., Washington, S., Turrell, G., 2014. Advance transit oriented development typology: case study in Brisbane, Australia. J. Transport Geogr. 34, 54–70.
Kelly, P., Kahlmeier, S., Götschi, T., Orsini, N., Richards, J., Roberts, N., Scarborough, P., Foster, C., 2014. Systematic review and meta-analysis of reduction in all-cause mortality from walking and cycling and shape of dose response relationship. Int J Behav Nutr Phy 11, 1–15. https://doi.org/10.1186/s12966-014-0132-x.
La Paix, P.L., Geurs, K., 2014. Adaptive stated choice experiment for access and egress mode choice to train stations. World Symposium of Land Use and Transport Research (WSTLUR).
La Rocca, R.A., 2009. Soft mobility and urban transformation. Tema J Land Use Mobil Environ 2, 85–90. https://doi.org/10.6092/1970-9870/125.
Li, K., Zhang, X., 2024. Does high-speed railway promote horizontal equity within and between cities? Evidence from China. Land Use Policy 144, 107217. https://doi.org/10.1016/j.landusepol.2024.107217.
Lu, Y., Chen, H.M., 2024. Using google street view to reveal environmental justice: Assessing public perceived walkability in macroscale city. Landscape and Urban Planning 244, 104995. https://doi.org/10.1016/j.landurbplan.2023.104995.
Martens, K., 2017. Transport Justice: Designing Fair Transportation Systems. Routledge, Taylor & Francis Group, New York/London.
Martens, K., Singer, M.E., Cohen-Zada, A.L., 2022. Equity in accessibility: moving from disparity to insufficiency analyses. J. Am. Plann. Assoc. 88 (4), 479–494. https://doi.org/10.1080/01944363.2021.2016476.
Mohiuddin, H., 2021. Planning for the first and last mile: a review of practices at selected transit agencies in the United States. Sustainability 13 (4), 2222. https://doi.org/10.3390/su13042222.
Moreno, C., Allam, Z., Chabaud, D., Gall, C., Pratlong, F., 2021. Introducing the "15-minute city": sustainability, resilience and place identity in future post-pandemic cities. Smart Cities 4, 93–111. https://doi.org/10.3390/smartcities4010006.
Murgante, B., Patimisco, L., Annunziata, A., 2024. Developing a 15-minute city: a comparative study of four Italian cities-cagliari, perugia, pisa, and trieste. Cities 146, 104765. https://doi.org/10.1016/j.cities.2023.104765.
Otsuka, N., Welsch, J., Delmastro, T., Delpiano, R., Pensa, S., 2022. Beyond start and end points: accessibility of railway stations on a multi-spatial scale. Transp. Res. Rec. 2676 (12), 468–484. https://doi.org/10.1177/03611981221096116.
Pae, G., Akar, G., 2020. Effects of walking on self-assessed health status: links between walking, trip purposes and health. J Transp Health 18, 100901. https://doi.org/10.1016/j.jth.2020.100901.
Poorthuis, A., Zook, M., 2023. Moving the 15-minute city beyond the urban core: the role of accessibility and public transport in The Netherlands. J. Transport Geogr. 110, 103629. https://doi.org/10.1016/j.jtrangeo.2023.103629.
Raza, A., Zhong, M., Akuh, R., Safdar, M., 2023. Public transport equity with the concept of time-dependent accessibility using Geostatistics methods, Lorenz curves, and Gini coefficients. Case Studies on Transport Policy 11, 100956. https://doi.org/10.1016/j.cstp.2023.100956.
Ruiz-Padillo, A., Pasqual, F.M., Larranaga Uriarte, A.M., Cybis, H.B.B., 2018. Application of multi-criteria decision analysis methods for assessing walkability: a case study in Porto Alegre, Brazil. Transp. Res. Part D Transp. Environ. 63, 855–871. https://doi.org/10.1016/J.TRD.2018.07.016.
Schlossberg, M., Brown, N., 2004. Comparing transit-oriented development sites by walkability indicators. Transp. Res. Rec. 1887 (1), 34–42. https://doi.org/10.3141/1887-05.

Schlossberg, M., 2006. From TIGER to audit instruments: measuring neighborhood walkability with street data based on geographic information systems. Transp. Res. Rec.: J. Transport. Res. Board 1982, 48–56.

Staricco, L., 2022. 15-, 10- or 5-minute city? A focus on accessibility to services in Turin, Italy. Journal of Urban Mobility 2, 100030. https://doi.org/10.1016/j.urbmob.2022.100030.

United Nations, Department of Economic, Social Affairs, 2019. Population Division. In: World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). United Nations, New York.

United Nations General Assembly, 2016. New Urban Agenda. United Nations, New York. Available online: https://habitat3.org/the-new-urban-agenda/. (Accessed 26 March 2024).

United Nations, 2015. Transforming our world: the 2030 Agenda for sustainable development. Available online: https://wedocs.unep.org/20.500.11822/9814.

Vale, D., Lopes, A.S., 2023. Accessibility inequality across Europe: a comparison of 15-minute pedestrian accessibility in cities with 100,000 or more inhabitants. npj Urban Sustain 3, 55. https://doi.org/10.1038/s42949-023-00133-w.

Wan, T., Lu, W., Sun, P., 2023. Equity impacts of the built environment in urban rail transit station areas from a transit-oriented development perspective: a systematic review. Environ. Res. Commun. 5, 92001. https://doi.org/10.1088/2515-7620/acf8b2.

Zhao, Y., Hu, S., Zhang, M., 2024. Evaluating equitable Transit-Oriented development (TOD) via the Node-Place-People model. Transport. Res. Pol. Pract. 185, 104116. https://doi.org/10.1016/j.tra.2024.104116.