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Accessibility Measures to Evaluate Public Transport Competitiveness: The Case of Rome and Turin

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Abstract: The transport sector worldwide relies heavily on oil products, and private cars account for the largest share of passenger mobility in several countries. Public transport could represent an interesting alternative under many perspectives, including a decrease in traffic, pollutants, and climate emissions. However, for public transport to succeed, it should be attractive for final users, representing a viable alternative to private mobility. In this work, we analyse the spatial distribution of public transport service provision within two metropolitan cities, considering the three key dimensions of mobility, competitiveness, and accessibility of public transport. The results show that private car performs better than public transport in all scopes considered, and that performance indicators are highly variable among city areas, indicating inequalities in social and environmental sustainability in urban systems. The outcomes of the analysis provide interesting insights for policy makers and researchers that deal with similar topics, and can also be extended to other cities and countries.

Keywords: urban mobility; public transport; accessibility; equity

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1. Introduction

Globally, there is a clear trend towards increasing concentration of population in major cities [1]. Historically, cities are created also because the geographic concentration of productive activities allows an economic advantage through economies of scale and networks [2]. After reaching an optimal level of concentration, however, typical dis-economies of concentration emerge, including congestion and slower travel speeds. Urbanisation-related phenomena often include spatial expansion in the peri-urban area, also driven by rising real estate costs in the metropolitan centre, which may, in turn, be accompanied by increased land consumption, urban sprawl, and increased travel distances for a large share of the population. When these phenomena occur together, the conditions for increased car dependency are created. Among the possible consequences of urbanisation, the aggravation of phenomena of social stratification, between 'rich' and 'poor' neighbourhoods, is also significant.

The complexity of the objectives that contemporary societies should pursue and the interdependence of the variables at stake is evident: harmonising the city's conurbation economies with the reduction in congestion dis-economies, reducing the environmental impact, and reconciling principles of efficiency and economy in the management of public affairs with those of social equity.

Defining operational concepts such as 'mobility', 'competitiveness' of public transport (PT) services and 'accessibility' in cities, as well as measurable and repeatable indicators, thus provides important understandings. It can be useful both in the assessment of investment projects and in the analysis of the degree of success in the pursuit of environmental sustainability and social equity objectives.

This evaluation requires a benchmarking of PT against private car-based mobility, which is currently a default choice for users in several cities worldwide. The performance of PT services, and any future implementation, must confront the problem of car dependency, along with the underlying political-economic factors of car-dependent societies [3].

The objective of this study is to analyse the spatial distribution of PT service provision within two Italian metropolitan cities considering the three key dimensions of mobility, competitiveness, and accessibility of PT. Specifically, the paper focuses on the mobility during the morning peak hour in Rome and Turin to: (1) compare the local PT system to car mobility in terms of competitiveness and accessibility, and (2) identify possible conditions of territorial inequality with respect to mobility (see Section 3, Research Questions and Methodology).

Among the main results, the analyses show that, both in Rome and Turin, private car performs better than PT in all scopes considered (mobility, competitiveness, and accessibility). In all urban areas, a gap is identified, and in some of them it is significantly high. The spatial distributions of mobility by private car are mostly specular to those of mobility by public transport, and show a centre-periphery pattern in the spatial distribution of service efficiency. Significant variability in performance indicators among city areas are also identified, indicating inequalities in social and environmental sustainability in urban systems.

The innovative contribution of this work is the combined implementation of the above-mentioned key dimensions to present a comprehensive analysis of PT performance in the different areas of a metropolitan city by processing available data with a good level of spatial detail. The research on mobility is typically conducted through sectoral studies, which specifically analyse the sociological, economic, or technological aspects. In this work, we have instead adopted an interdisciplinary approach. The mapping of the cities of Turin and Rome was carried out by analysing, through the use of combined indices, the levels of mobility, competitiveness, and accessibility by private car and PT. Regarding the measure of accessibility, in particular, a new empirical metric was used through the combination of public transport availability and habitual trips, i.e., between supply and demand, considering travel time as a relevant parameter. The study, conducted using freely accessible databases, is the first to have used the approach proposed in the cities of Rome and Turin.

2. Literature Review on Mobility and Accessibility in Urban Areas

The study of mobility, understood in a more general sense, involves the evaluation of a complex combination of elements, ranging from individual factors (such as attitudes, values, intentions, available time and financial resources) to contingent factors (such as the cost and availability of different modes of transport, location of services, physical attributes of the built environment, social norms and culturally dominant values) [4–6].

The main reference models [4] are represented by different approaches:

1. Utility or rational choice theory, based on the evaluation of costs and benefits [7–12];
2. Accessibility theory, which evaluates spatial and temporal factors [13–18];
3. Socio-psychological theories, which consider the impact of attitudes, norms, values and emotions [19–23];
4. 'New mobility perspective' approach, which is largely based on the method of analysing social practices [24–27].

Urban mobility studies also include a strand that focuses its analysis on the idea of designing cities in which the car becomes less necessary, such as New Urbanism, Smart Growth, Transit-Oriented Development, Compact City, and the 15 min City [13]. This strand, on the one hand, seems to share the approach of the accessibility theory mentioned above, but on the other hand appears to refer specifically to the concept of avoidance of travelling by car, incorporating the "avoid" component of the A-S-I approach (which classifies and prioritise measures in "avoid", "shift", and "improve") [28,29]. Similarly, the issue of functional polycentrism of cities needs to be considered. Cities with more places with higher densities of economic and institutional activity would be able to generate lower overall travel demand and also greater preference for PT use. Polycentricity has become a key concept in regional studies [30], which proposes that cities develop a spatial distribution of population and economic activity around multiple urban subcentres. Its opposite is the monocentric city, with a metropolitan core with a high concentration of jobs that becomes increasingly dispersed as one moves away from it. A polycentric city is potentially characterised by shorter distances between home and work and less congestion [31]. Moreover, polycentricity, especially in large cities, appears to promote lower operating costs and greater PT efficiency because it ensures a minimum size scale at different points in the city [32].

A distinction must be made between the terms "mobility" and "accessibility". Mobility refers to the degree of ease of movement, i.e., the ease with which one can move through space using a transport mean [33]. Accessibility, on the other hand, refers to the ability of an individual to move around a given area according to his or her needs and desires. In particular, accessibility can be defined as the ability of an individual in a given place to participate in an activity or set of activities [34], or as the number of opportunities, such as work, shopping, etc., that can be reached from a given place in a given time by car, PT or non-motorised modes of transport [35]. It follows that the mobility and accessibility levels of a city or neighbourhood are not necessarily correlated [33].

In this perspective, accessibility corresponds to 'mobility capital': an extension of the classical concept of capital (physical, economic, cultural, and social), where mobility emerges as one of the resources for action [36], directly linked to the concept of life opportunities [37] and capability [38,39]. Accessibility as understood thusly directly involves equity and justice in transport, especially for PT. Moreover, accessibility can be seen as the key to an inclusive transport system [40].

The social dimension of transport is addressed in several documents and studies outlining the priority principles of the European Union [41,42].

The European Union pays special attention to accessibility of transport for specific socio-demographic segments (young people, people at risk of poverty, people with a low level of education, people with reduced mobility, people living in isolated areas [41]). Equal attention is paid to horizontal equity principles, such as reducing geographical disparities, ensuring that all regions can benefit from infrastructure development [42]).

Three different ways of understanding the term equity can be traced in humanistic theory [43]: (1) the egalitarian principle, (2) the utilitarian principle, and (3) Rawl's principle. The choice between one or the other, which falls within the sphere of the political evaluation, is full of implications for the implementation of PT plans. Under the egalitarian principle, each individual has equal rights. This implies that the provision of transport services should not differ from region to region. Under the utilitarian principle, on the other hand, the 'good' to be pursued is the maximisation of total aggregate utility. This can result in a focus on territorial areas with higher added value, more attractive journeys, and higher population and employment density. In the framework of Rawl's principle [44] inequalities are allowed only if they lead to benefits for each individual, while restorative justice intervenes to balance unsustainable situations.

On a practical level, following Rawl, a plan is to be chosen if it is able to ensure the best condition, among all plans, for a group or an area that is in the worst position. In the context of PT plans, however, Rawl's principle has had little application. Better success has been achieved in the application of the utilitarian principle [43], especially in the practice of Cost–Benefit Analysis (CBA), or also in the variant of Social Cost–Benefit Analysis (SCBA). SCBA shares with CBA the approach of assigning a monetary value to the effects of the planned intervention. Usually, the benefits estimated in the CBA include time savings, vehicle operating costs, journey costs, impacts on accidents, journey quality, greenhouse gases, and indirect taxes [45].

In this context, some scholars [18,46] observe that the uncritical use of CBA in the evaluation of investment projects, which makes use of indicators such as travel time savings and property value by attributing a monetised value to them, can lead to unintended consequences. A focus on time value alone inevitably ends up favouring the fastest means of transport, the car, while a focus on economic value can lead to favouring regions with higher added value. A Social CBA could improve the evaluation process by analysing additional aspects, including safety, health and environmental and social impacts [18]. However, given the broad range of effects to be accounted for, this is rarely applied during the planning of mobility plans and infrastructure.

One of the risks of including CBA in mobility planning is associated with the possibility that the focus on the time-saving indicator becomes exclusive, overlooking other considerations. The risk is that the fastest mode of transport, i.e., the car, or high-speed railway lines serving commuting flows will be favoured [45].

An efficient PT system is one of the keys to success in improving overall mobility in modern cities. According to Thomson [47], 'all efforts to improve rush-hour car travel will fail unless public transport is also improved'. Efficiency levels must also not be excessively heterogeneous across urban areas.

In addition, the monetisation of achievable benefits, estimated by using territorial added value, could lead to increased territorial socio-economic gaps in investment [48].

The guiding rule is that CBA is to be regarded as a tool and not as a principle, instrumental in assessing the goodness of one plan against a similar competing one. It therefore should not be used to evaluate the best solution between investment projects in new private mobility versus public mobility [45]. Other evaluation tools also seem capable of broadening the horizon to non-monetary or non-monetisable benefits, such as landscape impact or reducing urban inequalities. These include, for example, Multi-Criteria Analysis, seen as a means for establishing trade-offs between different stakeholders involved in the project [49]. On a practical level, the criteria of economy and efficiency in the management of the PT systems may conflict with the criteria of justice and inclusiveness.

From a methodological point of view, the studies of mobility plans and investment projects consider PT accessibility according to three distinct notions: (1) "how easy it is to walk to a PT stop" from a given point in space, i.e., accessibility to PT [50]; (2) "how many people can be served by the PT service" [51]; and (3) "how many destinations people seek could be reached with the current PT offer", i.e., accessibility by means of PT [52].

The last notion appears to be the most valid for the purposes of this paper, having defined accessibility as the ability to visit places of activity (such as shops, workplaces, services, businesses, public spaces, etc.) using a particular transport system in an acceptable time or cost [53]. It also aims to intersect supply and demand for mobility [45], whereas the first two concepts of accessibility do not allow to go beyond the analysis of service supply. In some studies, the qualitative components of mobility demand are also captured with opinion surveys [52]. Another issue is how to measure service levels and/or accessibility of PT services within cities. Two main approaches emerge in the literature. The first one is the isochrones method [54], also complemented by the estimation of the number of opportunities reachable in a 30 or 40 min trip (e.g., [55]). The second is the gravity-based model method, aimed at measuring the travel costs (travel time and/or travel cost) between one zone and all others, weighted by the attractiveness of the respective zones (e.g., [56,57]). A third method is based on measures of transport network connectivity, although still relatively less used [58,59].

Travel time is often considered an intuitive measure that fits well with people's perception of distance friction [60–62]. Time, however, is not the only factor influencing modal choice decisions. Other elements include reliability, punctuality, comfort, vehicle/station characteristics and, considering PT, frequency, among others [5,63]. As an example, in a study conducted on metro users, Raveau et al. [64] indicate that users, given the same travel time, tend to favour linear and direct routes and routes that are better known or more heavily travelled. It follows that a PT trip involving more complex routes or the use of more vehicles, even if of shorter duration, may not be very competitive compared to the intrinsically "linear" route with one's own vehicle (car or motorbike). Empirical evidence in the research literature on the spatial distribution of PT supply shows a centripetal dynamic, with higher service levels in central areas. This evidence is valid for both European cities (such as Gothenburg, Paris, Madrid [65]), and non-European cities (such as Melbourne, San Francisco, Montreal, New York, Sydney and Boston [54,62,65]). Population density and demand levels to a good extent account for this dynamic. Available studies on the competition of PT versus the private vehicle in US and European cities show that the latter is able to provide a higher level of accessibility [54,66–72]. The spatial distribution of the level of accessibility is rather more complicated according to the empirical literature. Suburbs connected to public mobility corridors capable of satisfying part of the travel demand of its residents, for example, may exhibit a fair level of accessibility [73]. Mobility in Rome and Turin has been object of discussion and study in recent years. Greenpeace [74] has focused on urban development and mobility in Rome, amongst other things. They propose supply side measures: enhancing the supply of PT services, particularly rail transport; focusing on peripheral and more densely populated areas of residents; encouraging walking and bicycling; and disincentivising private car mobility (e.g., with traffic-restricted zones and 30 km/h speed limit zones). Lelo and Risi [75] focuses more on structural and morphological factors related to the history of urban development and socio-economic factors. He highlights, for example, how people residing in more suburban areas, where housing costs, population density and workplace are lower, are forced to make long commutes due to inefficient PT services. Within the framework of research on the 15 min city concept and its variants, such as the 20 min district, Staricco [76] developed a methodological framework to analyse levels of accessibility on foot to 20 types of local services from each census section in the city of Turin. Ceccato et al. [77] calculated accessibility in Turin using travel speed for car and PT.

Rome and Turin have already been the subject of analysis by this research group. In [78], the mobility habits and related energy consumption and emissions of remote workers during 2015–2019 were studied. A new survey of the mobility habits of a sample of remote workers (about 2200) who are based in Rome is underway.

3. Research Questions and Methodology

This work is part of a broader research activity aimed at assessing the adequacy of the PT system to meet the needs of users to travel for work and to reach services and places of interest (culture and art, sport, leisure and recreation, shopping, etc.) and at identifying the conditions of mobility inequalities in the main Italian cities. The paper focuses on the mobility during the morning peak hour in two Italian metropolitan cities: Rome and Turin. The choice of the two cities is due to the attention recently given to them in numerous debates and studies, and to their specific physical and historical-urban characteristics, which lead to different impacts on urban circulation and represent a challenge for initiatives aimed at improving transport sustainability (see Section 4).

This paper focuses on the following two main research questions:

1. How is the local PT system in the cities of Turin and Rome compared to the car with reference to the competitiveness indicator and the accessibility indicator of journeys made during the morning rush hour on working days?
2. Are there conditions of territorial inequality with respect to mobility during the morning rush hour on working days in the two cities?

The analysis was conducted by examining three main indicators (calculated from the isochrones of PT and car trips and origin/destination (O/D) trip matrices):

(1) The mobility index for PT and cars, seen as a measure of the degree of fluidity of the respective carriers in the urban territory (Equation (1));

(2) The index of competitiveness of PT with respect to the car, defined as the ratio between the respective mobility indexes (Equation (2));
(3) The degree of accessibility of PT, here considered as a measure of the possibility of travelling with PT the typical trips of the residents of the individual neighbourhoods (Equation (3)).

An isochrone is defined as the line joining points located at equal "distances" in terms of travel time from a given location. The isochrones, shown as areas overlapping territorial maps, enable us to visualise the proportion of territory that can be reached in a given time from the central point. They are typically computed by means of simulations and models based on the available infrastructure and the schedule of PT services [79]. In this work, isochrones are calculated through the analysis of location data provided by TravelTime [80] based on the PT schedules planned by the respective transport operators [81]. Since they do not take into account the inherent daily irregularity of travel times due to accidents, breakdowns, delays, and unusual traffic conditions, the degree of statistical uncertainty cannot be estimated. The isochrones are centred on the PT service stops, obtained from the Open Street Map repository [82,83], 2759 and 8659 PT stops in the cities of Turin and of Rome, respectively.

By centring the isochrones on the PT stops, the time due to multimodality, i.e., the time required to reach the stop on foot, by car, or by any other means, is not counted. This assumption, while not limiting the scope of the analysis or the significance of the results, avoids the choice of multimodality criteria. Such criteria, while used in some studies [84,85], may be overly arbitrary or complex, making the final results more difficult to be interpreted and compared.

The territorial unit of analysis is the sub-municipal zone. The municipalities of Turin and Rome are subdivided into 94 and 153 urban zones, respectively, which approximately reflect the size of the city's 'neighbourhood'. The sub-municipal zones of Turin are statistical zones [86] resulting from the aggregations of several census sections as defined by the Italian National Institute of Statistics—ISTAT [87]. The sub-municipal zones of Rome derive from the subdivision of the municipal territory for statistical and spatial planning and management purposes [88].

TP includes all of the TP means operating in Rome and Turin: train, metro, bus and tram, while travels with car include private cars, as in [89].

All analyses are conducted by considering the 30 min outbound trips at 7 a.m., representing the peak-hour for morning commuting.

The isochrones are calculated on Wednesdays in May 2023, i.e., on a weekday during the school attendance period for all school orders. The month of May 2023 does not fall within the COVID and post-COVID period and, therefore, its effect on car travel mode is considered negligible. The choice of considering Wednesday as representative for all the working days is a common practice in the field, as the mobility demand during working days generally show little deviations from a day to another, as also confirmed by literature study on mobility patterns [90].

The O/D matrices between sub-municipal zones are calculated from TomTom [89] data, based on average weekdays (Monday through Friday) of October 2022. This period, although it does not coincide with the period for which the location data from Travel time are available, is used for the calculations without invalidating the results. A previous study on vehicle mobility profiles in Turin [90] shows that hourly mobility patterns have a very similar behaviour in May and October, especially during the morning peak hour (although considering pre-COVID trends).

The mobility index (MI), expressed in km^2, is calculated as the average area of the isochrones generated in each urban zone by the 30 min trips at 07:00 from each PT stop. The average area is calculated as the sum of the isochrones divided by the number of stops in each zone,

$$MI_z = \frac{\sum_i A_{i,z}}{S_z} \quad (1)$$

where z is the indicator of each zone (ranging from 1 to 94 in Turin and from 1 to 153 in Rome); S is the number of PT stops in z; $A_{i,z}$ is the area of the i^{th} isochrone in zone z.

The competitiveness index CI is calculated as

$$CI_z = \frac{MI_{z(PT)}}{MI_{z(car)}} = \frac{\sum_i A_{i,z(PT)}}{\sum_i A_{i,z(car)}} \quad (2)$$

where MI_z is calculated for both PT and private cars. In the latter case, to perform a consistent analysis, the isochrones' areas are calculated in each PT stop considering the trip in private car.

The accessibility index AI is calculated as

$$AI_z = \frac{n_z\left\{N, A_{i,(TP)}\right\}}{N_z} \quad (3)$$

where N is the number of trips made by car in each zone; $n_z\left\{N, A_{i,(TP)}\right\}$ is the subset of N that falls within the area of the PT isochrone.

The parameter CI has a minimum of 0, and an undefined theoretical maximum value. A value greater than 1 indicates that moving by PT is faster than moving by private means. In fact, it is rather unlikely that MI reaches and exceeds a value of 1. In practice, by comparing mobility by PT with that by private means, we assume that the latter constitutes a benchmark.

The parameter AI has a minimum of 0, and a purely theoretical maximum of 1. An hypothetical value of 1 would indicate that all habitual movements of residents could be fulfilled through a 30 min journey with PT.

The implementation of index AI is intended to enrich the isochrone concept. In this way, the isochrone loses its typical characteristic of anisotropy, in which all points in the space around the starting point have the same utility. Using the index proposed in this article, an isochrone is more 'relevant' the more it envelopes habitual movements of residents. As a consequence, this analysis implicitly allows different weights to be assigned to zones based on their importance, resulting in indicators that are more closely aligned with real mobility dynamics.

Moran's spatial mobility autocorrelation index has been used to estimate the significance of the PT mobility spatial trend. It indicates the cross-product statistic between the PT mobility index for a neighbourhood and its spatial lag, expressed in deviations from its mean.

4. Rome and Turin: Territorial Context and Characteristics

Rome is the capital of Italy, and its biggest city, both in terms of population, with 2.8 million inhabitants, and size, being almost 1300 square km (its density is around 2150 inhabitants/km^2). In an European context, Rome is also the eighth-largest city in terms of population. Rome shows a very important level of congestion, especially on the ring roads and consular radial roads, as the concentration of work opportunities in certain areas of the city has a strong impact on daily commuting patterns. Considering the demographic data for 2022 [87], the citizens of Rome are, on average, 46.4 years old, with 23.3% of the population being at least 65 years old (these figures are very similar to the national trend, with an average age of 46.2 and 23.8% of people being at least 65 years old). The total income per capita in Rome in 2022 is EUR 29,155 [91], with a 4.8% increase over 2021, much higher than the national average of EUR 20,039, but lower than the figure of Milan (EUR 37,734).

Rome is also one of the Italian cities with the highest motorisation rate (considering the ten largest cities), with 628 cars per 1000 inhabitants in 2021 [92]. The use of public transport in Rome remains limited, as in an average working day, the total trips are 0.72 million, which is less than 15% of the total trips [93].

Rome's public transport network includes 37 km of tram tracks, 32 km of trolleybuses, and 58 km of subway (the second in Italy after Milan), as well as 1960 buses (of which 25 are electric or hybrid, and 500 run on natural gas) [94]. The total offer of Rome's public transport stands at 8159 pkm per inhabitant, the third-highest value in Italy, after Milan and Venice. However, this indicator should be analysed by considering the fact that many non-residents use the public transport services, including tourists and commuters. The largest part of the pkm offer is from buses, 51% of the total, and from subway, 46% of the total.

Turin is the fourth-largest city in Italy, with 850,000 inhabitants, comparable to other European cities like Amsterdam, Marseille, Kraków, and Valencia. Turin is also in the top list for population density in Italy (considering cities with more than 50,000 inhabitants) with around 6525 inhabitants/km^2. As of 2022 [87], the citizens of Turin are, on average, 47.6 years old, with 26.0% of the population being at least 65 years old (these figures are both higher than the Italian ones). The total income per capita in Turin in 2022 is EUR 26,971 [91], with a 3.4% increase over 2021, which is higher than the national average of EUR 20,039, but lower than other large cities in central or northern Italy, including Florence (EUR 28,409) and Bologna (EUR 29,978). Turin has a motorisation rate of 581 cars per 1000 inhabitants in 2021, with an 11% decrease compared to 2018 [92].

The modal share of public transport in Turin is around 9% of the total daily trips, with an estimated value of 260 thousand trips per day in the city in 2022 [95]. These figures remain much lower compared to available data before the pandemic, with the modal share being around half of the 2013 level.

Turin's public transport is based on 73 km of tram tracks (the second city in Italy after Milan) and 14 km of subway, as well as 750 buses (of which 96 are electric or hybrid and 213 run on natural gas) [94]. The annual public transport offer is 4325 pkm per inhabitant, which is lower than average figures for provincial capitals in Italy (4748 pkm/inhab.) and Northern Italy (6048 pkm/inhab.). The pkm offer is mostly from buses, 58% of the total, followed by 22% from subway and 20% from tram.

In terms of land consumption, Rome and Turin are, respectively, in first and second place in the ranking of Italian provinces by area consumed. The metropolitan city of Rome has the largest area consumed in Italy in 2022, with more than 70,300 hectares, increased by a further 235 hectares in 2023. The province of Turin occupies about 58,500 hectares, with an increase of 168 hectares in 2023. The urban areas of Rome and Turin are reported in Figure 1.

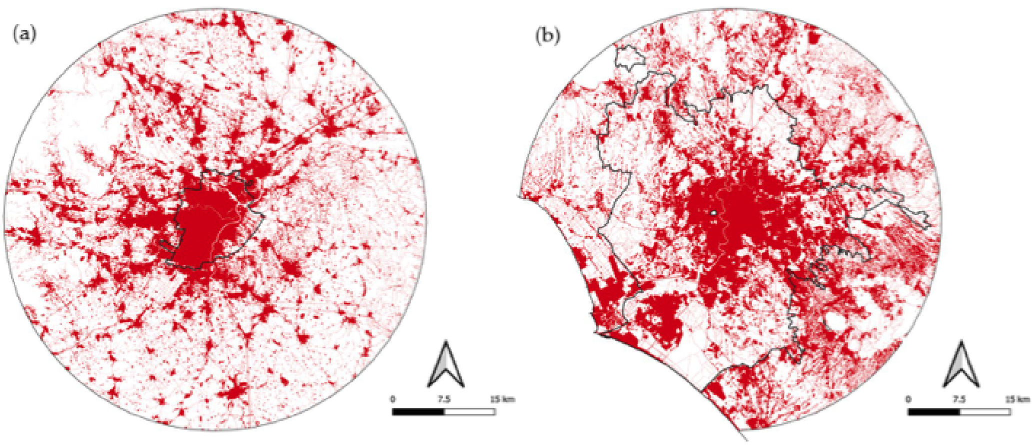

Figure 1. Urban areas in Turin (**case a, left**) and Rome (**case b, right**).

5. Results

Figures 2 and 3 show the PT mobility index (PT-MI) and car mobility index (car-MI) in Turin and Rome on weekdays at peak hour (7 a.m.). In both cases, the degree of car mobility in all urban zones appears to be higher than that of PT (see Figure 4), confirming the results from studies conducted in other cities [54,63,66–71]. In none of the urban zones of the two cities is PT actually giving a better mobility service when compared to private cars at morning peak hours. Moreover, in absolute terms, the maximum PT-MI is lower than the minimum car-MI, with values of 56.2 km^2 against 62 km^2 in Turin and 52.6 km^2 against 67 km^2 in Rome.

PT mobility is higher in Turin than in Rome. On average, in Turin, a journey of 30 min at 7 a.m. is equivalent to an isochrone of 34 km^2, while in Rome, the same is 18 km^2. In parallel, mobility by car is greater in Rome than in Turin (233 km^2 and 189 km^2, respectively).

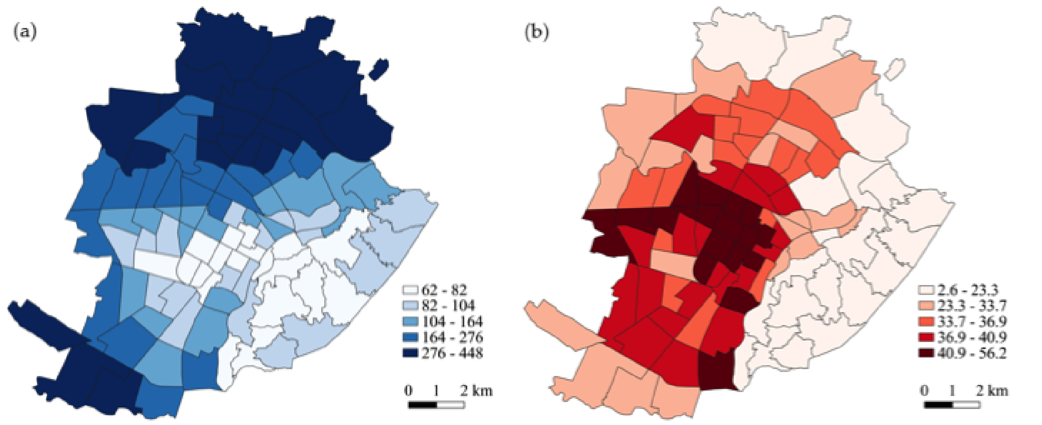

Figure 2. Mobility index (km^2) of (**a**) car and (**b**) PT trips in the city of Turin—average isochrone area (at 07:00 on weekdays).

More specifically, in Turin (Figure 2) the maximum PT isochrone does not exceed 56.2 km^2, while the maximum isochrone for car travels is about eight times higher. The zones characterised by the highest car-MI are those close to the motorway network and ring roads. However, also without taking these areas into account, a degree of mobility by car that is almost five times higher than the one by PT is observed. Large portions of the city territory (corresponding to the hill areas—in the East—and peripheral areas) show values of less than 23.3 km^2 for PT. Some of them are industrial or green/forested areas, while others are low-density residential zones in the hilly part of the city.

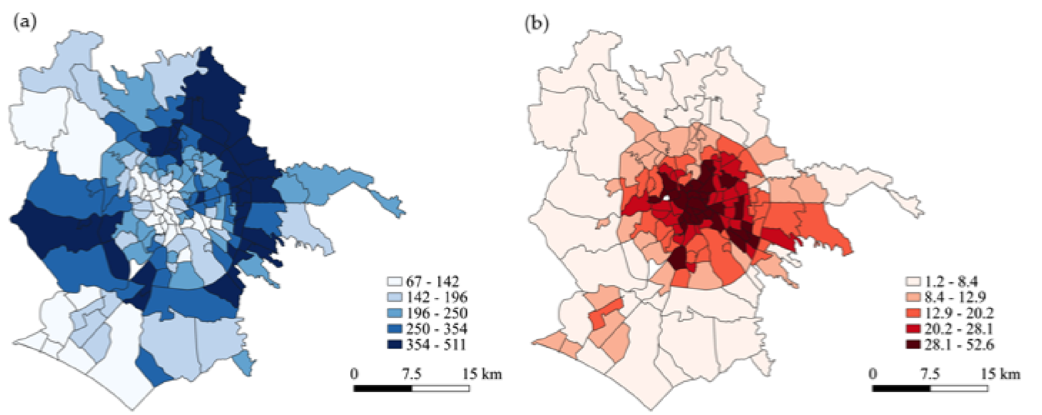

Figure 3. Mobility index (km^2) of (**a**) car and (**b**) PT trips by (**a**) car and (**b**) PT in the city of Rome (at 07:00 on weekdays).

In the case of Rome (Figure 3), the gap between the mobility index of PT and cars is even more evident. Again, the areas with maximum car mobility are close to the ring road and highway connections. Large peripheral urbanised areas show very low PT mobility degrees, with a 30 min coverage area of at most 8.4 km^2.

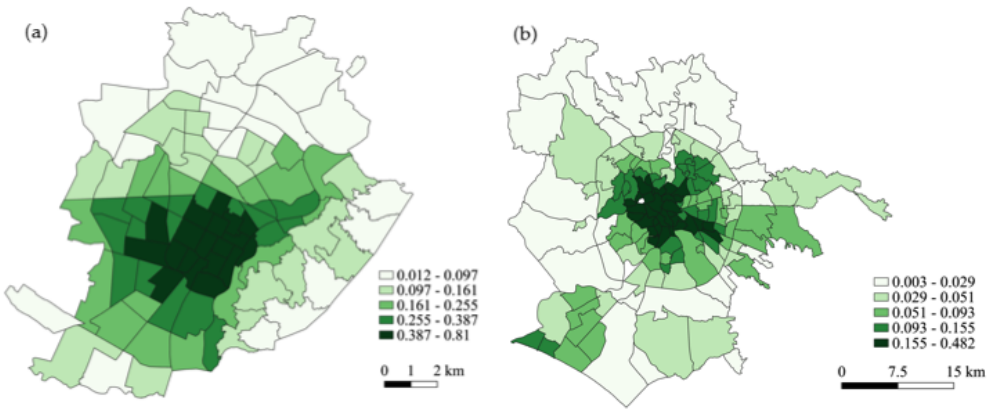

Figure 4. Competitiveness index of public versus car transport in (**a**) Turin and (**b**) Rome.

Analysing the spatial distribution in the two cities, a clear trend emerges with respect to the centre/periphery dimension. The peripheral urban zones show a lower PT-MI than the central ones. At the same time, peripheral areas appear to be more efficient in private transport. Both findings agree with other studies in the literature [54,63,66–71]. The degree of statistical dispersion of mobility in neighbourhoods is high, the coefficient of variation relative to PT isochrones being 0.36 in Turin and 0.60 in Rome, while for car isochrones the values are 0.61 and 0.44, respectively.

Moran's spatial mobility autocorrelation index for both cities is positive (0.640 for Turin and 0.478 for Rome) and significant ($p < 0.01$ after 999 permutations), suggesting a geographical distribution not attributable to a random spatial process. A more detailed representation of the mobility index of PT and car trips for each city is provided in Appendix A.

The competitiveness index (CI), calculated as the ratio between isochrones (Equation (2)), is shown in Figure 4. Overall, the average ratio between the degree of competitiveness of PT and that of car (calculated on all PT stops) is 0.18 for Turin and 0.08 for Rome. In other words, for the two cities, the average isochrone of PT has an area equal, respectively, to 18% and 8% of that relative to travels by car. A more detailed representation of the CI is provided in Appendix A.

Finally, Figure 5 shows the accessibility index (AI) in relation to 30 min trips made at 7 a.m. It represents a measure of the amount of everyday trips that can theoretically be satisfied by PT. On average, a 30 min PT trip in Turin would satisfy 74% of regular commuters in the morning rush hour. In Rome, the percentage is considerably lower, around 41%. The centre/periphery dynamic of variation still seems to be confirmed, but with some attenuation with respect to the MI. This evidence appears to be in line with other studies (e.g., [73]). Some peripheral areas appear to be less disadvantaged. For example, those in the eastern districts in the city of Rome, as well as a sort of ridge in the city of Turin identified by rail transport and by the subway. Moreover, Moran's accessibility autocorrelation index, when compared with Moran's mobility autocorrelation index, shows an even greater gap between the two cities (0.412 for Turin and 0.234 for Rome). This figure seems to suggest that, in a larger city such as Rome, the attenuation of the spatial trend in terms of accessibility is even greater. A more detailed representation of the AI in Rome and Turin is available in Appendix A.

The distribution of the PT indicators (MI, CI, and AI) is variable between the different areas of the two cities. This is indicated by high values of the coefficient of variation, calculated as the ratio between the standard deviation and the mean after weighting the administrative areas by their respective resident population. This dispersion indicator is particularly high for the PT competitiveness (the coefficient of variation of CI is 0.93 for Turin and 1.25 for Rome), and slightly lower for the accessibility indicator (the coefficient of variation of AI is 0.81 for Turin and 1.04 for Rome). The statistical results indicate the presence of significant territorial inequalities in the attractiveness of PT supply.

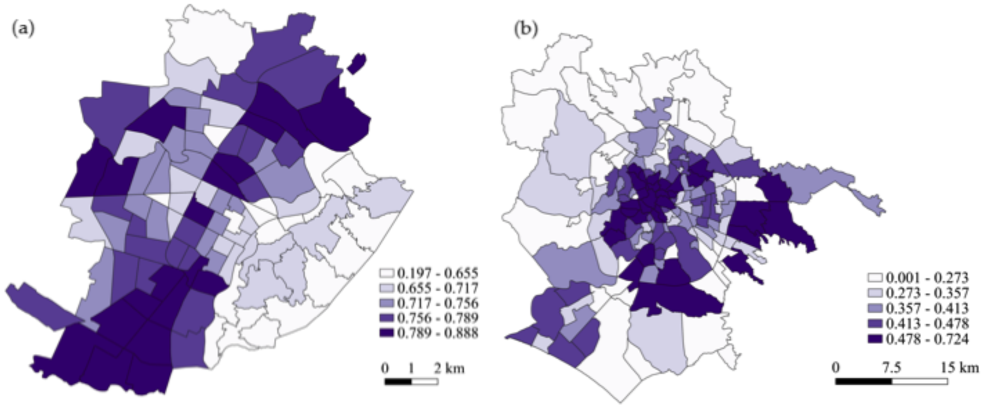

Figure 5. Accessibility index of public transport in (**a**) Turin and (**b**) Rome.

6. Discussion

The results of the analysis show that, in all of the urban zones of the cities examined, the degree of mobility allowed by car is higher than the one by PT.

With respect to the competitiveness indicator proposed (see Equation (2)), we observe that, in Turin and Rome, the PT is never more competitive than travelling by car, with CI remaining always far lower than 1. In both cities, there is also a large gap in PT competitiveness between central city areas and peripheral areas (Figures 2–4), in line with some empirical evidence in the literature for Melbourne, San Francisco, Gothenburg, Paris, Montreal, New York, Madrid, Sydney, and Boston [54,62,65,96]. The centripetal pattern in the spatial distribution of PT competitiveness is the result of economic drivers, urban policy choices and long-standing historical events. First, historically, central neighbourhoods are also those with the highest population density. A service typically based on density, such as PT, is certainly more efficient when provided to the most highly populated neighbourhoods. In addition, central districts are those that concentrate most economic activity and are sites of institutional and governmental offices. They generate inbound work and study trips in the morning peak and, therefore, receive more attention in PT planning. Spatial disparities in the distribution of PT services are influenced by the morphology of the cities' road network, which often has a radial structure, as in the case of Rome. This has negative effects especially for road PT, which is forced to proceed on highly congested road axes. In both Turin and Rome, the aforementioned conditions of disadvantage are added to other forms of social inequality, such as the lack of services in peripheral areas and lower average incomes. Moreover, road congestion in urban areas can have a negative impact on measures to alleviate PT saturation on roads. In fact, the expansion of PT services on roads, unless the lane network is increased, would lead to less improvements than expected.

Rome's post-war demographic growth was characterised by illegal or unapproved housing developments sector that led to the growth of neighbourhoods that lacked services and infrastructure [97–100]. In the case of Turin, urban development was conditioned by the presence of Fiat, Italy's largest industrial company at the time, around which grew sleeping neighbourhoods for workers employed by the company and its suppliers. Although with different causes and in different ways, the development of the two cities has led to high land use without adequate infrastructure and quality services. In suburban areas, where the results of the analysis show large gaps in PT competitiveness (Figure 4), the lowest socio-economic indicators of quality of life (such as the percentage of college graduates, the unemployment rate, the percentage of households with potential economic hardship and the social hardship index) are also found [75].

In newly urbanised areas, PT development is often forced to 'follow' building construction, mostly delayed, prioritising road transport, which is easier to implement, but has low competitiveness. In such cases, it is difficult for the people to avoid using private vehicles. The problem is accentuated when new neighbourhoods have a low population density, are residential, and are far from central areas.

Regarding the PT mobility index, some peripheral areas seem to be less disadvantaged. For example, those in the eastern districts of the city of Rome and a kind of backbone of the city of Turin identified by rail and metro transport. In these cases, the rail PT system makes a positive contribution. This is true for the eastern area of Rome, where discrete levels of mobility, PT competitiveness, and accessibility are noted. Lelo and Risi indicate [101], in these same neighbourhoods, some of the highest indices for unemployment, the lowest number of graduates and a high socio-economic disadvantage, and suggest a trend linking illegal construction practices in the city of Rome with social and economic marginality. In this context, the importance of an integrated interpretation of the various dimensions of analysis is therefore evident, including the type of PT (road or rail).

Looking at the AI, considered as a percentage of habitual journeys that in theory can be satisfied by PT (see Equation (3)), the trend dominated by the centre/periphery dimension observed for CI appears more nuanced for both Rome and Turin. This is due to the presence of metro and train stops and probably a combination of other behavioural and choice factors. At the same time, the lower degree of accessibility that characterises the city of Rome compared to that of Turin seems likely to be attributable to the higher incidence of daily commuting and the greater distances to be travelled.

When analysing the competitiveness of PT in different areas of the same city with reference to travel time, the empirical literature mostly seems to suggest that it is greater in central areas. This has been highlighted for Melbourne [54], San Francisco [67], Gothenburg [96], Paris, Montreal, New York, Madrid, Sydney, and Boston [65]. Chia and Lee [73], in a study on the Australian city of Brisbane, find that when the accessibility measure considers not only travel time, but also the potential effect of transfer location, the previous trend is not confirmed, some outer-city suburbs located along major bus corridors have a relatively higher level of accessibility. This also holds true for our map of Rome, when considering TomTom trips: some suburbs, especially those served by metro lines, see an improved level of accessibility through PT.

The results indicate the presence of significant territorial inequalities in the attractiveness of PT supply. The inequalities seem to be less significant when considering accessibility, which may incorporate other factors such as proximity to public rail transport or the role of people's housing choices in favouring shorter commuting times. The findings also show that he policy actions need to be tailored to the specific area of the city based on quantitative evidence.

In urban planning policies, the issue of mobility should not be a sectoral policy involving only experts. We believe that an integrated approach is needed, pursuing an integration between urban development and mobility plans and including socio-economic sustainability and environmental sustainability as indispensable elements in the definition and implementation of effective spatial planning and urban regeneration policies. Urban regeneration policies (in particular combining a set of actions in different fields of intervention), in order to be effective and contribute to the concrete reduction in inequalities, shall combine innovative practices of governance, active citizenship participation, methods, and approaches to improve the access to common goods and public spaces and services.

PT should be planned and operated in a way that makes it more accessible, and provide a competitive service compared to private mobility, not only on the economic dimension. To make PT service more effective, it might be appropriate to introduce some forms of incentives for PT companies so that they are motivated to transport more passengers, and not just to provide a service. Analysis of available data and information on users' mobility should be encouraged, also by making big data publicly available.

7. Conclusions

In this work, we analysed the spatial distribution of PT service provision in two metropolitan cities in Italy according to mobility, competitiveness, and accessibility indices calculated during the morning rush hour. In this context, accessibility is intended as a metric of the extent to which PT can be used for the typical commute of residents in different neighbourhoods.

The results show that private car use in the two cities offers higher levels of mobility, competitiveness, and accessibility than PT. In all urban areas, the car mobility index is higher than the PT mobility index in both Rome and Turin and, in absolute terms, the maximum value PT-MI is lower than the minimum value of car-MI. The gap is very high, even excluding areas close to the motorway network and ring roads, and is higher in Rome than in Turin.

The spatial distributions of mobility by private car are mostly specular to those of mobility by public transport. People use the car more because they are close to high traffic roads and/or the public offer is not satisfactory. There is also a clear centre-periphery trend in the spatial distribution of service efficiency: PT is more efficient in the centre, and decreases moving towards the periphery; the opposite trend occurs for cars. The PT mobility index is higher in Turin than in Rome, while the car mobility index is higher in Rome than in Turin. In terms of competitiveness, the average PT isochrone is 18% and 8% of that for car travel in Turin and Rome, respectively. On average, a 30 min PT trip in Turin would satisfy 74% of the morning rush-hour commute. In Rome, the percentage is considerably lower, around 41%.

The joint analysis of regular commuting by residents and isochrone areas shows a better assessment of PT accessibility in some peripheral areas of cities. For example, for Rome, in particular those served by the metro lines (eastern suburbs of Rome) and those with a high level of self-contained commuting (the 'city within a city' districts of the Roman coastline). The results also show significant variability in performance indicators between city areas, implying issues of social equity and environmental sustainability of urban systems. The distribution of PT indicators is variable between different areas of the two cities. The distribution of PT indicators is variable between different areas of the two cities, especially with regard to PT competitiveness, which indicates the presence of significant spatial inequalities in the attractiveness of PT supply. Critical aspects in mobility in the cities of Turin and Rome, in part associated with the specific historical and socio-economic context in which the cities have developed in recent decades, impact the levels of equity and quality of life of residents.

The indicators presented in this paper are based on figures related to the morning peak hour, which is the most critical for congestion in most Italian cities. However, the analysis of the evening peak hour may lead to different results and insights. For this reason, a future application of this model will address other hours of operation to shed light on the effect of different times over the day. The proposed methodology can be usefully applied to other cities, so as to also identify any common patterns or elements that suggest correlations. Integrating the analysis with big data and more comprehensive sets of information also regarding the other dimensions involved (social, economic, structural aspects, etc.) is an interesting development scenario and a useful tool to support urban policies.

The indicators presented in this paper are based on figures related to the morning peak hour, which is the most critical for congestion in most Italian cities. However, the analysis of the evening peak hour may lead to different results and insights. For this reason, a future application of this model will address other hours of operation to shed light on the effect of different times over the day.

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Abbreviations

The following abbreviations are used in this manuscript:

AI	accessibility index
car-MI	car mobility index
CBA	cost–benefit analysis
CI	competitiveness index
MI	mobility index
PT	public transport
PT-MI	public transport mobility index
SCBA	social cost–benefit analysis
SUMP	Sustainable Urban Mobility Plan

Appendix A

Appendix A.1

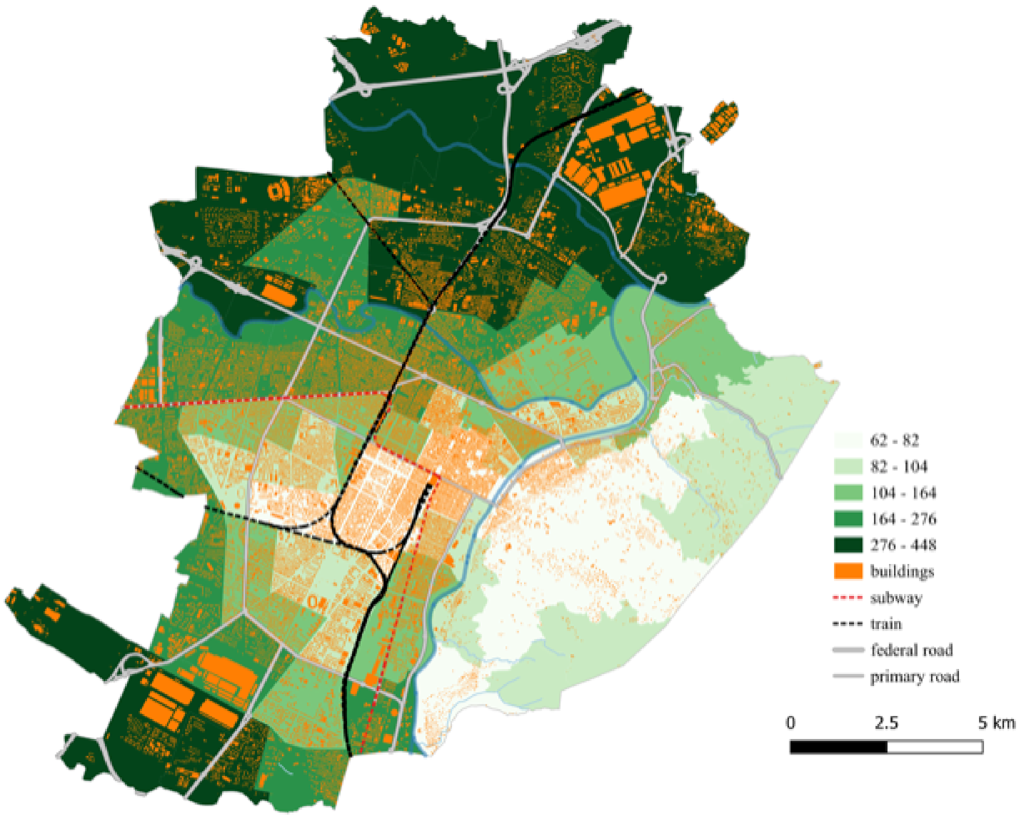

Figure A1. Mobility index (km^2) of car trips in the city of Turin (at 07:00 on weekdays).

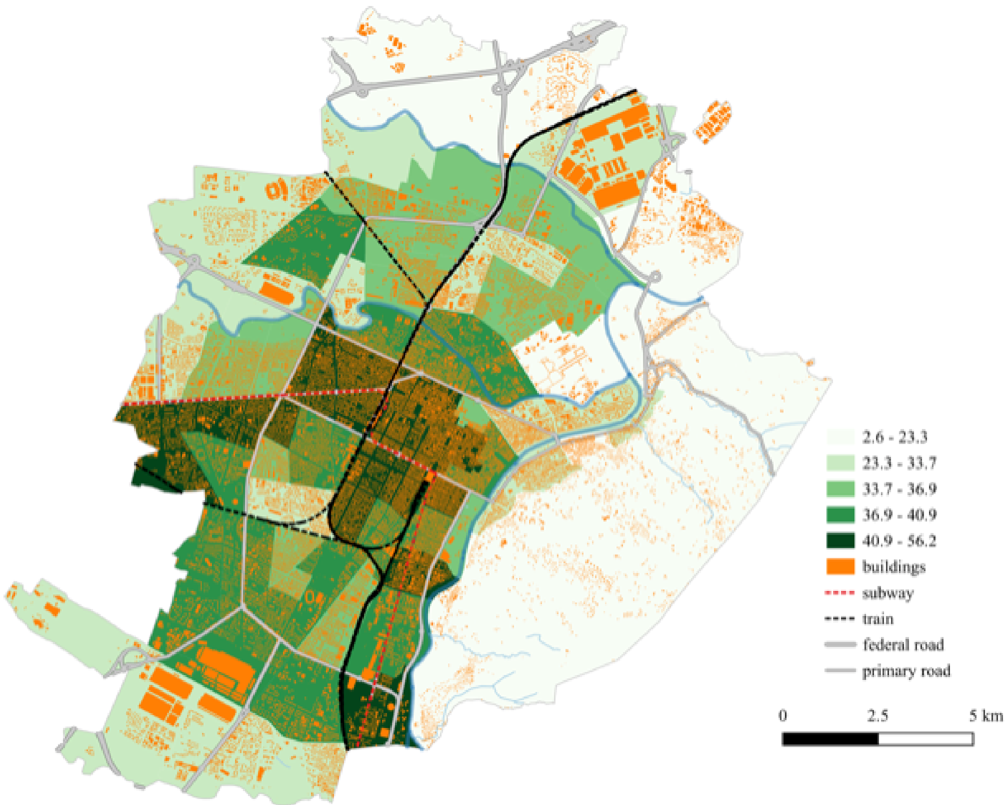

Figure A2. Mobility index (km^2) of TP trips in the city of Turin (at 07:00 on weekdays).

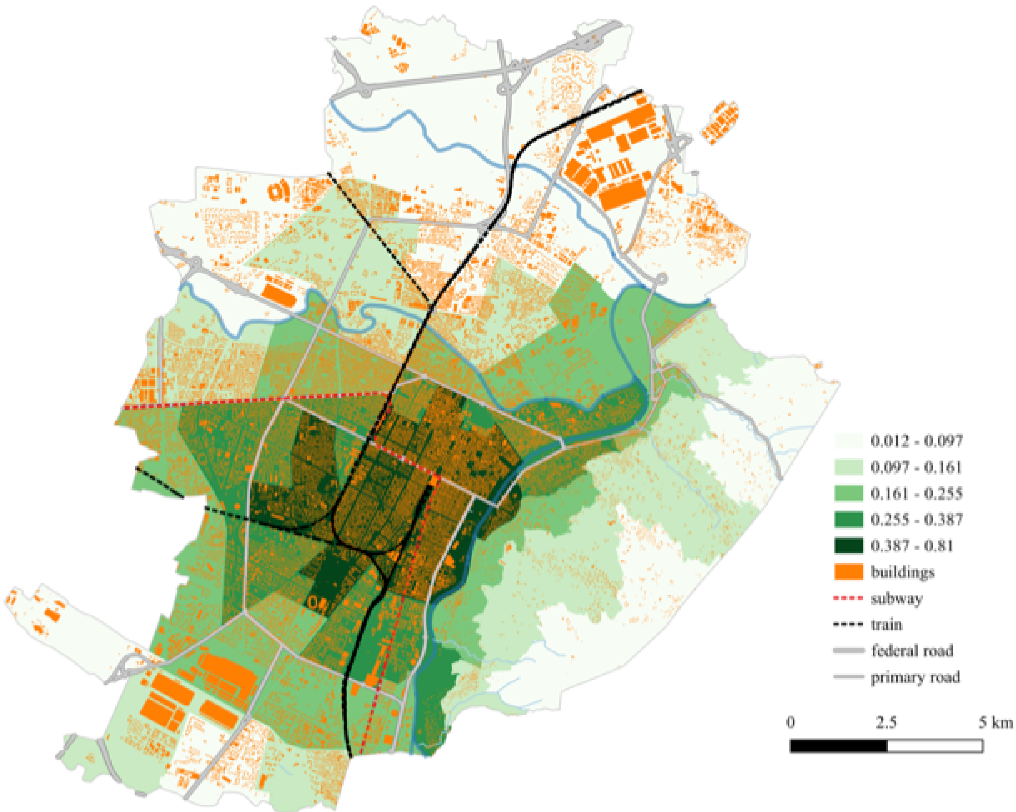

Figure A3. Competitiveness index in the city of Turin (at 07:00 on weekdays).

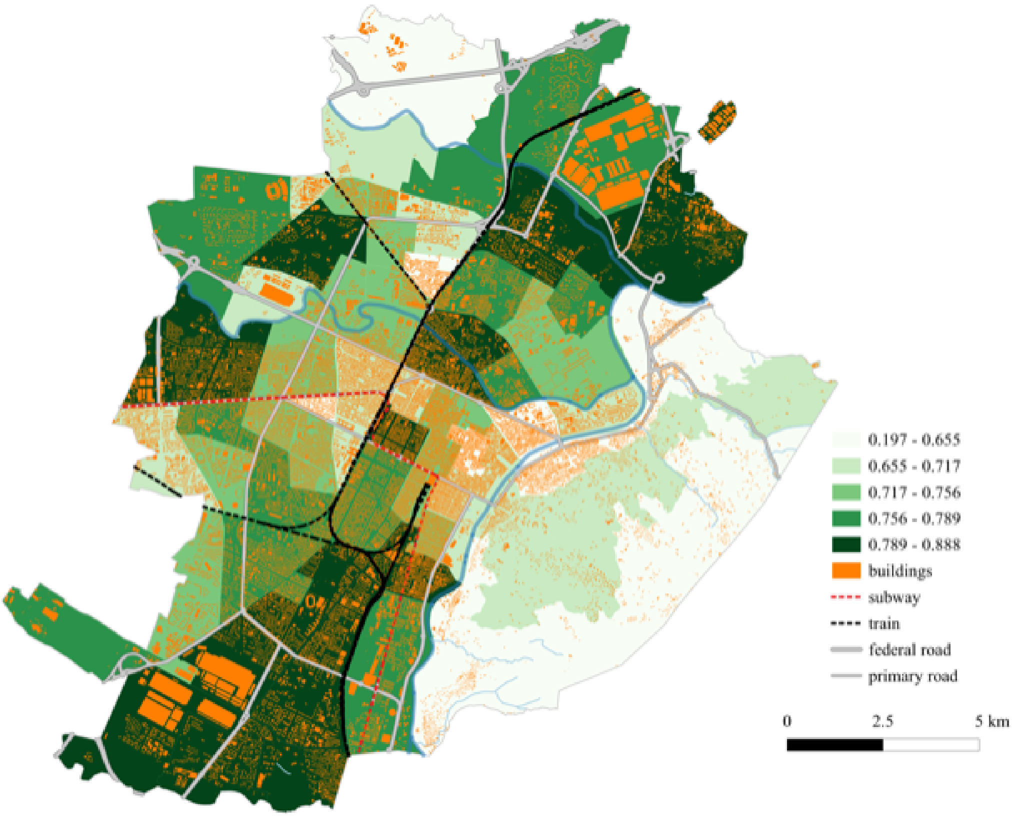

Figure A4. Accessibility index in the city of Turin (at 07:00 on weekdays).

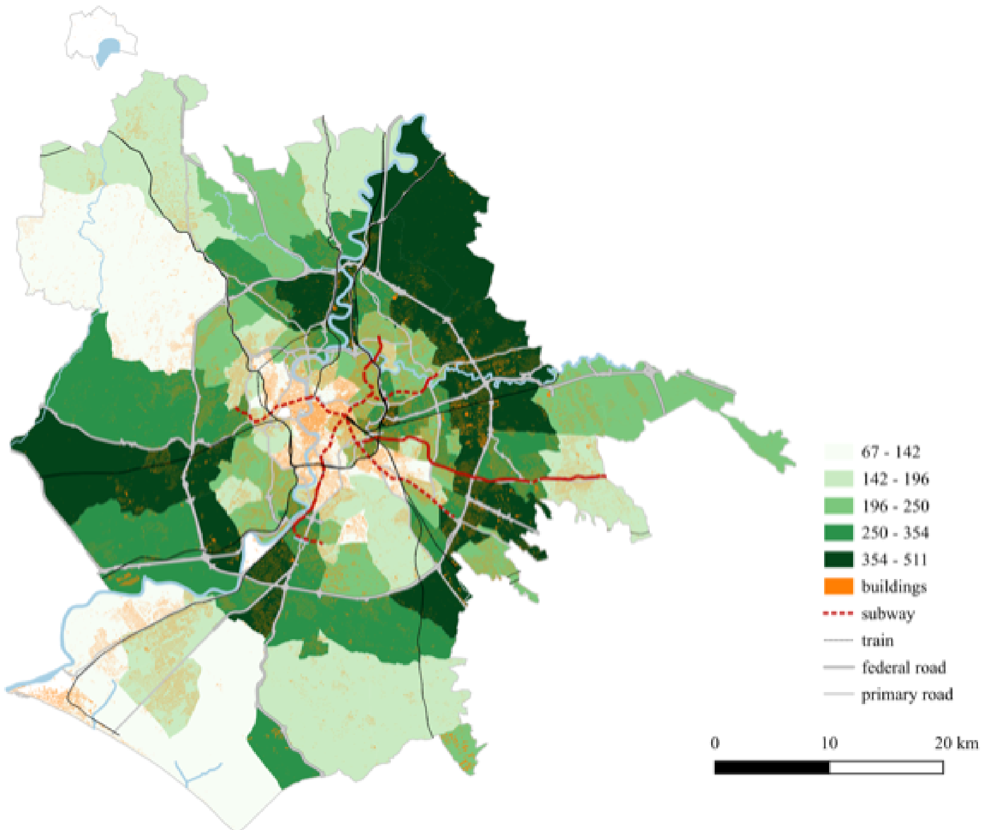

Figure A5. Mobility index of car trips in the city of Rome (at 07:00 on weekdays).

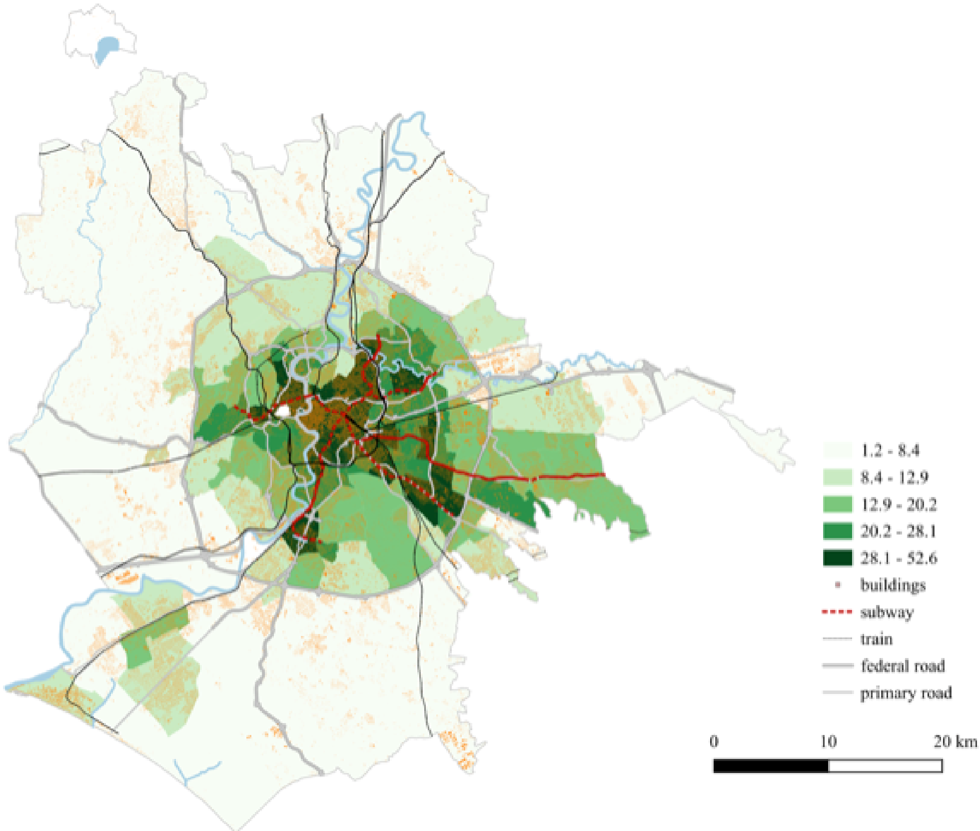

Figure A6. Mobility index of TP trips in the city of Rome (at 07:00 on weekdays).

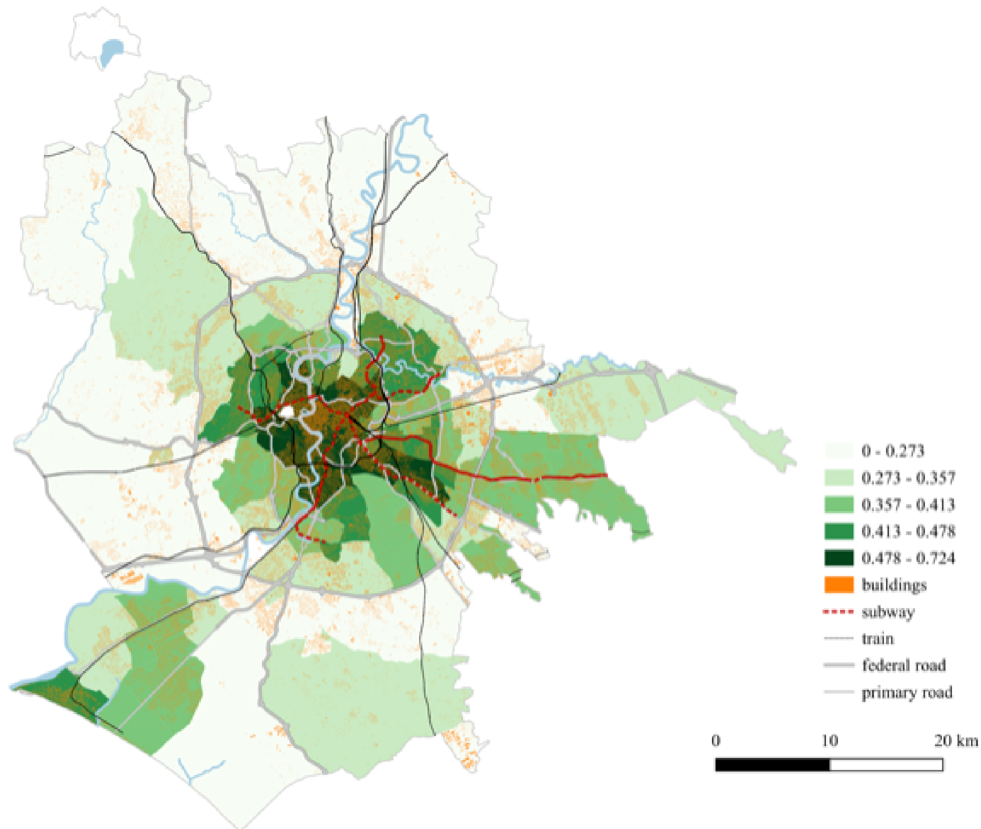

Figure A7. Competitiveness index in the city of Rome (at 07:00 on weekdays).

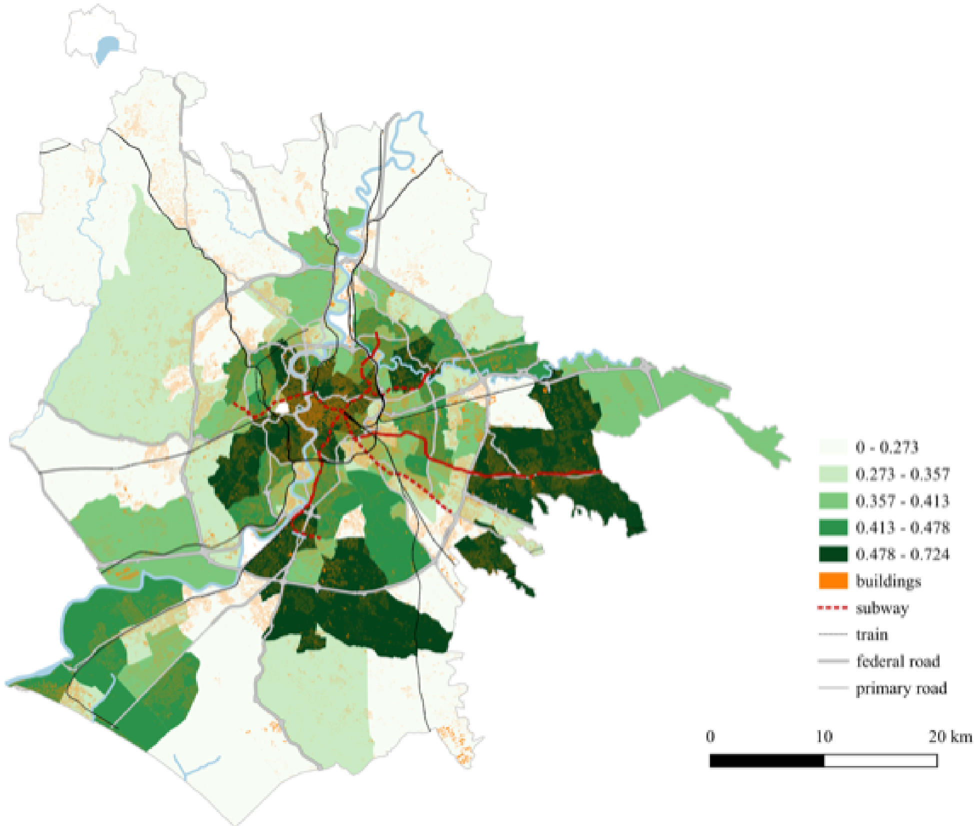

Figure A8. Accessibility index in the city of Rome (at 07:00 on weekdays).

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