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Rethinking road network hierarchy towards new accessibility perspectives

Stefanos Tsigdinos[a, *], Yannis Paraskevopoulos[a], Panagiotis Tzouras [a], Efthimios Bakogiannis[a] and Thanos Vlastos[a]

[a]*National Technical University of Athens, Heroon Polytechneiou 9, Zografou Campus, Athens 157.80, Greece*

Abstract

Conventional road network hierarchy has focused mainly on facilitating car movement, while (usually) neglecting the rest surface transport modes. This fact resulted in dysfunctional urban environments where a plethora of social, economic and environmental issues are encountered. In this context, serious inequalities regarding urban mobility arise (e.g., inaccessible areas without car, exclusion of vulnerable social groups from a fair transport system, etc.). Therefore, there is an urgent need to bring forth the notion of accessibility and the fair access to opportunities, in transport systems and specifically in road network hierarchy.
This study aspires to explore whether the rethinking/reformulating of the road network hierarchy can improve the accessibility level for sustainable modes (public transport and cycling/micromobility) in different transport future paths. To this end, 4 different scenarios that redefine the strategic road network of the study area are developed: 1) Business as Usual (BAU), 2) Car-oriented city, 3) Public Transport Priority, 4) Sustainable Modes Integration. Next, a combinatorial approach evaluating these scenarios is adopted: specifically, the spatial accessibility concerning cars, public transport and cycling/micromobility in each scenario is estimated. This method is applied to the metropolitan area of Athens, Greece which can be considered as a challenging example of a car-oriented metropolis. The main results indicate that the fourth scenario integrating all sustainable modes can improve the accessibility of public transport and cycling, while restraining car dominance in terms of access to opportunities. These findings are particularly useful for researchers and practitioners and could be taken into account for the making of human-oriented cities with a better level of mobility for all in the future.

Keywords: Road network hierarchy; scenario planning; accessibility; transport geography; Athens

* Corresponding author.
E-mail address: stef.tsigdinos@gmail.com

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1. Introduction

The notion of hierarchy seems a prevalent feature of both living and artificial systems (Corominas-Murtra, 2013) as it can be found in social relations and interactions, brain function, computer systems, natural environment such as rivers and trees and especially, cities and transport networks (Pumain, 2006;). When it comes to the latter, it shall be stressed that the majority of the roads in a given network, are considered as trivial, whereas the minority as vital (Jiang, 2009). This hierarchical structure is translated into road network hierarchy plans which clearly demonstrate the role of each road segment in the entire network (Eppell et al., 2001). The first relevant plan was conducted in the UK by Buchanan in 1963 who proposed two contrasting functions in the road network; movement/circulation against access (Gunn and Great Britain. Ministry Of Transport, 2015). This approach established 3 basic road categories; arterials (sometimes motorways as well), collectors or distributors and local roads, where arterials prioritize car movement, while local roads the access to properties (Levinson and Krizek, 2008). However, the once progressive thought of Buchanan, has now been transformed into an outdated conventional approach leading to dysfunctional urban areas with serious environmental and societal issues (Marshall, 2004). To be more precise, this car-oriented approach undermines the social dimension of roads (McCann, 2013), creates severe barriers to urban fabric and environmental degradation (Leurent and Windisch, 2011), while neglecting other transport modes (Liu et al., 2017).

Nonetheless, roads should not be destined solely for accommodating car movement (Marshall, 2005); on the contrary, since roads are multimodal entities (Stavroulaki and Berghauser Pont, 2020) and multimodality is an integral perspective of the future (Tsigdinos et al., 2022), the proper planning approach facilitating any possible transport mode, shall prevail (Tsigdinos and Vlastos, 2021). Towards this direction, recent literature underlines a notable shift from conventional to alternative approaches. For instance, transit-oriented hierarchy suggested by Marshall (2006), prioritizes public transport explicitly and embraces the cooperation between sustainable modes. Mehaffy et al. (2010) conceptualized an integrated planning approach, re-thinking road network hierarchy along with developing vital neighborhoods. Following this framework, Tsigdinos et al. (2021) proposed a coherent road network hierarchy method for formulating strategic multimodal corridors in Athens, Greece. Last, another notable paradigm is the "Link and Place" approach that adopts matrix-based hierarchy, attempting to take urban and transport dimension into consideration simultaneously (Jones and Boujenko, 2009).

All these approaches, aspire, among other objectives as well, to shape accessible urban environments. But what exactly is defined as accessible, and how is this measured in the macro-scale? The notion of spatial accessibility, firstly introduced by Hansen (1959), is a complex and multidimensional concept that is explained by several factors (Barabino et al., 2020) and cannot be fully outlined by a single definition. Ingram (1971) mentions that "*accessibility is an inherent property of a place, associated with a certain form of overcoming the resistance of space*". Similarly, Dalvi and Martin (1976) noted that accessibility is the ease of accomplishing any activity, from any place, making use of a specific transport system. Thirty years later, Bertolini et al. (2005) discussed the concept of accessibility as "*what and how can be reached at a given point in space*", while Handy (2020) in her most recent work, referred to accessibility as the way of characterizing the available choices for multiple transport modes.

Regularly, the most prevalent ways of measuring accessibility into the macroscale are: a) cumulative opportunities, b) gravity models, c) random utility-based measures and d) distance (Handy and Niemeier, 1997; Adhvaryu, et al., 2019). When focusing on the gravity models category, it should be noted that spatial accessibility is defined as "*the potential of opportunities available for an individual (or groups) located at a certain location for interaction*" (Hansen, 1959). More recent studies remained in the same direction, underlining that the accessibility of a zone in a transport system is proportional to the spatial interaction between the origin trip zone and all other zones through a generalized travel cost decay function (Geurs and van Wee, 2004). Notably, the spatial interaction can be represented through multiple ways; one well-known attractiveness illustrator is the concentration of workplaces (Bocarejo and Oviedo, 2012; Karou and Hull, 2014), or the density of non-residential activities (Paraskevopoulos & Photis, 2020).

However, to date, there is not a relevant study examining how the rethinking of road network hierarchy influences the accessibility level of the various transport modes, especially when it comes to scenario planning. Particularly, this concern contextualizes the basic research question of this work. In this context, the present study strives to go one step beyond the existing literature that is mainly concentrated on individual changes like cycling lanes or new train/bus lines (e.g., Bocarejo and Oviedo, 2012; Geurs et al., 2016; Pritchard et al., 2019) via exploring how a multimodal-oriented road network hierarchy would affect the spatial accessibility of various modes (car, cycling and public transport). To this end, 4 scenarios related to different futures of the strategic road network in a metropolitan city, namely, Athens, Greece, are examined. For every scenario and for each different mode, the accessibility level is measured, indicating which scenario truly supports the sustainable modes, while restraining car dominance. This procedure will provide substantial insights on how road network reformulation could affect accessibility and whether it could function as a tool for improving the urban environment.

2. Methodological framework

This study used a quantitative approach that incorporates mainly spatial analysis. The proposed method followed is presented in the methodological flow diagram found in Fig. 1.

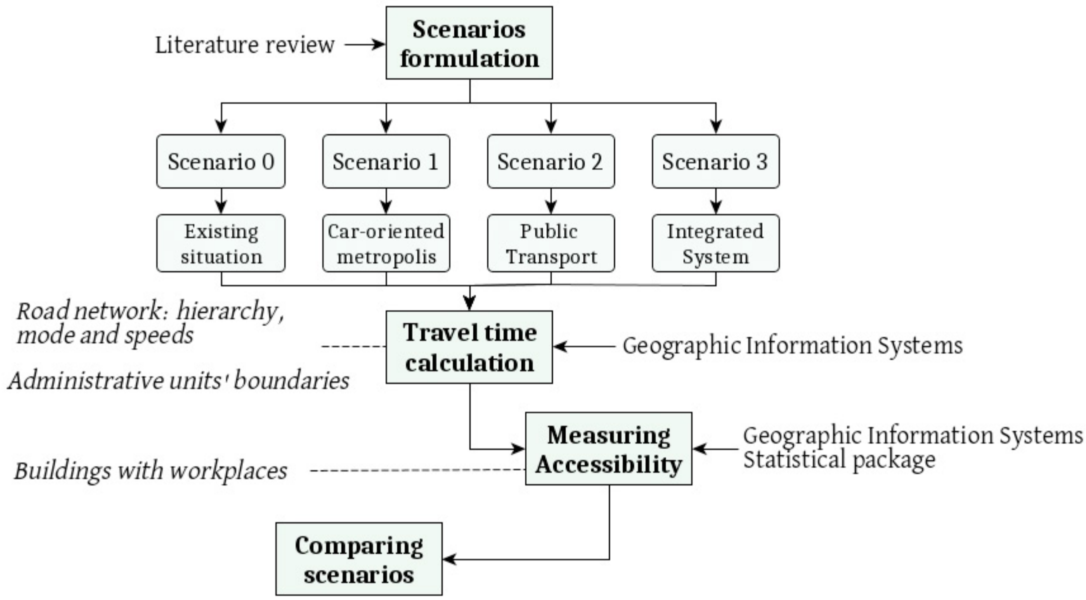

Fig. 1. Methodological framework

2.1. Study setting and dataset

The study area of the research is the Metropolitan Area of Athens (AMA), which contains 38 municipalities and 61 administrative units, including two metropolitan centers, i.e., Athens and Piraeus (see Paraskevopoulos, et al, 2022). Referring to the transport system, it shall be stressed that AMA has a car-oriented road network hierarchy system (Tsigdinos and Vlastos, 2021), where automobiles are the dominant transport mode, shaping the flows and the mobility culture in the urban realm (Deloukas and Apostolopoulou, 2017). As a result, the role of public transport and cycling is usually neglected. Surface public transport (tram, streetcars and buses) is not prioritized and lines are not well-structured, leading to a discordant system where services cannot meet the users' needs (Efthymiou and Antoniou, 2017). When it comes to cycling, conditions are far more difficult, calling for coherent policy measures and interventions that will bring prosperity to this certain transport mode by increasing its use (Milakis and Athanasopoulos, 2014).

The dataset used consists of 4 features utilizing secondary data, namely: 1) urban road network structure and attributes (e.g., road type, speed per mode, direction, etc.), 2) study area zone (municipalities and sub-entities) boundaries, 3) strategic road network for each scenario and 4) number of buildings with workplaces (offices and factories) per zone.

2.2. Scenarios

To explore the impacts of the road network hierarchy to the accessibility levels, we follow a scenario planning approach (Lyons et al., 2021), and consider four different scenarios for AMA, based on the work of Tsigdinos and Vlastos (2021). These scenarios were developed using the backcasting approach and are as follows:

Scenario 0: the do-nothing scenario, which represents the status-quo and is used as the basis to evaluate all other scenarios. The percentage of the strategic network in the entire city road network is around 9,80% (motorways are 22,0% and primary arterials are 78,0%), signifying that a substantial number of roads are devoted in facilitating the movement motor vehicles.

Scenario 1: “a city based on cars”. The first scenario develops a car-oriented vision that maintains the existing rationale, and therefore car-oriented streets have not been notably reduced. The main differences between the status quo and this scenario are the new strategic categories, the ring roads diverging through traffic and reduced speed limits in some urban arterial roads. The final categories in this classification system are three. Namely, 1) Regional Car/RC (27% of the new strategic), 2) Metropolitan Car/MC (65%) and 3) Citywide Car /CC (8%).

Scenario 2: “public transport to stimulate urban mobility”. The second scenario shapes a public transport-oriented vision that changes slightly the existing rationale. For instance, measures like bus lanes in radial arterials and ring roads are prioritized. Hence, the strategic road network consists of 4 categories: 1) Regional Car/RC (27% of the new strategic), 2) Metropolitan Car/MC (20,16%), 3) Metropolitan Public Transport/MPT (42,84%) and 4) Citywide Public Transport/CPT (10%). The first two categories emphasize on car, whereas the rest on public transport.

Scenario 3: “building an integrated system by bringing sustainable modes to the forefront”. The third scenario envisages a future where sustainable modes (public transport, active modes and micromobility) are the centerpiece of the city’s transport system, thus transforming the existing car-oriented rationale considerably. To be more specific, this scenario supports multimodal arterials, ring roads and decisive speed limit reduction. The strategic road network consists of 6 categories: 1) Regional Car/RC (28% of the new strategic), 2) Metropolitan Car/MC (41,79%), 3) Metropolitan Public Transport/MPT (18,42%), 4) Metropolitan Active Modes/MAM (0,79%), 5) Citywide Public Transport/CPT (9,98%) and 6) Citywide Active Modes/CAM (1,02%). The first two categories prioritize car-movement, while the rest give emphasis on sustainable modes and specifically, categories 3 and 5 on public transport and 4 and 6 on active modes (the slow speed found in these categories, allows autonomous buses as well).

2.3. Travel time calculation

Travel time is a fundamental parameter for measuring the accessibility of each mode in every scenario. Thereupon, following the development of the strategic network according to each scenario, the overall travel time i.e., T_{ij}, from every centroid zone to any other is calculated. The generated network includes all the fastest paths with using one mode individually. This assumption is made to compare the accessibility between the different modes. Possible delays in the case of public transport services have been considered in the final speed limits. To this end, the QNEAT plugin of QGIS was used, leading to the creation of an origin-destination matrix (61x61), containing the travel times of the fastest path between each zone. This plugin necessitates speeds and, on this basis, certain attention was paid to the definition of the appropriate speed limits that will respect the vision of each scenario. For instance, public transport vehicles reduce their speed by 0,6km per stop (Kieu et al., 2015), while n case of an exclusive lane, speed can increase by approx. 10-15% (Zyryanov and Mironchuk, 2012). Also, cycling in exclusive lanes is found to have a free-flow speed equal to 15 km/h (Dozza and Werneke, 2014).

To be more specific, the certain speed values differing in each scenario were assigned. In scenario 0, car speed limit in motorways equals to 110km/h and in primary road network to 70km/h. Public transport speed limits in motorways are 90km/h and in primary roads they operate at 50km/h. Finally, cycling is not permitted in motorways, while in primary arterials speed limits are 5 or 10km/h. In scenario 1, car speed limit in RC roads equals to 108km/h, in MC roads to 88km/h and in CC roads to 69km/h. Public transport speed limit in RC is 95km/h, whereas in MC roads, the vehicles operate at 67km/h and in CC roads at 57km/h. Last, cycling is not permitted in RCl roads, on the contrary, the rest roads speed can be up to 5 or 10km/h. In scenario 2, car speed limit in RC roads equals to 100km/h, in MC roads to 78km/h, in MPT roads to 65km/h and in CPT road to 60km/h. Public transport speed limit in RC is 95km/h, while in MC roads, the vehicles operate at 69km/h, in MPT roads at 60km/h and in CPT roads at 53km/h.

Last, cycling is not permitted in RC roads, while the rest roads speed can be up to 5-10km/h. Last, in scenario 3, car speed limit in RC roads equals to 100km/h, in MC roads to 75km/h, in MPT roads to 50km/h, in MAM roads to 30km/h, in CPT roads to 50km/h and in CAM roads to 20km/h. Public transport speed limit in RC is 95km/h, in MC roads, the vehicles usually operate at 66km/h, in MPT roads at 64km/h, in MAM roads at 50km/h, in CPT roads at 44km/h and in CAM roads at 40km/h. Last, cycling is restricted in RC roads, on the contrary, in MC roads cycling have a speed up to 10km/h, while in the rest roads, speed increases to 15km/h.

2.4. Measuring accessibility

For each scenario we measure the accessibility level of 61 administrative units in the AMA. This study adopts the definition that considers accessibility as the access to job opportunities from a zone i to all other areas of the Athens Metropolitan Area (j), taking into account that zones with fewer or more distant job opportunities will be less attractive. Particularly, a location-based accessibility model (Geurs and van Wee, 2004) is utilized. To this end, we employ the following formula (eq. 1) (Guzman, Oviedo and Rivera, 2017):

$$A_i = \sum O_j * \exp\left(-C_{ij}\right) \quad (1)$$

where:

O_j: represents the opportunities existing in zone j. We set the number of buildings with workplaces per zone to describe the significance of each zone j.

C_{ij}: is the cost function, i.e., travel time in hours from zone i to zone j per mode using the shortest path. It is assumed that all motorized modes respect speed limits, and therefore they operate at the maximum value per road category. Tellingly, traffic congestion is not considered in the estimation of travel time (especially for cars or buses).

3. Results

Spatial accessibility is an indicator that does not have a specific unit of measurement; therefore, this work focuses on the proportional differences of accessibility considering different scenarios. Notably, accessibility clearly differs among travel modes, namely: car, public transport and cycling/micromobility. Furthermore, significant differences are encountered in the spatial distribution of accessibility because of the new road hierarchy structure. That is why, this section presents the results of both the statistical and spatial analysis.

Considering the existing road network of Athens, private car seems to be the transport mode that ensures better accessibility compared to the other two examined modes. Indeed, in the do-nothing (i.e., scenario 0), car has higher by 7.2% and 53.9% mean accessibility value in comparison with public transport and cycling, respectively. Scenario 1, which proposes a road network hierarchy that prioritizes car movement, leads to merely lower travel times and therefore higher accessibility by only 0.45%. By performing a Wilcoxon signed-rank (paired but not normally distributed data), we conclude that this difference is significant for a confidence interval of 95%; yet, in public transport and cycling, this change seems to be insignificant. Public transport as a transport mode is slightly reinforced by scenario 2; this is an unexpected outcome. Based on the statistical results, accessibility of public transport modes increases by only 0.95% compared to the do-nothing scenario; yet, this difference is proved to be significant for the same confidence interval, while in cycling, no significant changes are observed. Scenario 3 results in shorter travel times both for public transport modes and cycling/micromobility. It is an approach which significantly fosters all sustainable/green modes, leading to an increase of the overall accessibility of cycling and public transport by 18% and 1.6%, respectively. On the contrary, the overall accessibility of private car as a transport mode in this scenario, is significantly reduced by 5.6%. It is intriguing that when taking into account all accessibility values of all modes and estimating the means, the differences seem to be quite small. Indeed, even in scenario 3, the reduction of the overall accessibility considering all modes is lower than 1%; yet, this change is significant for a confidence interval of 95%, while in other scenarios, no significant reductions (or increases) are observed. The statistical analysis also implies the emergence of heterogeneity in terms of accessibility among the zones of the study area. That is why, its spatial differences should be discussed as well. Fig. 2 displays the proportional differences between the proposed scenarios and scenario 0 in each zone.

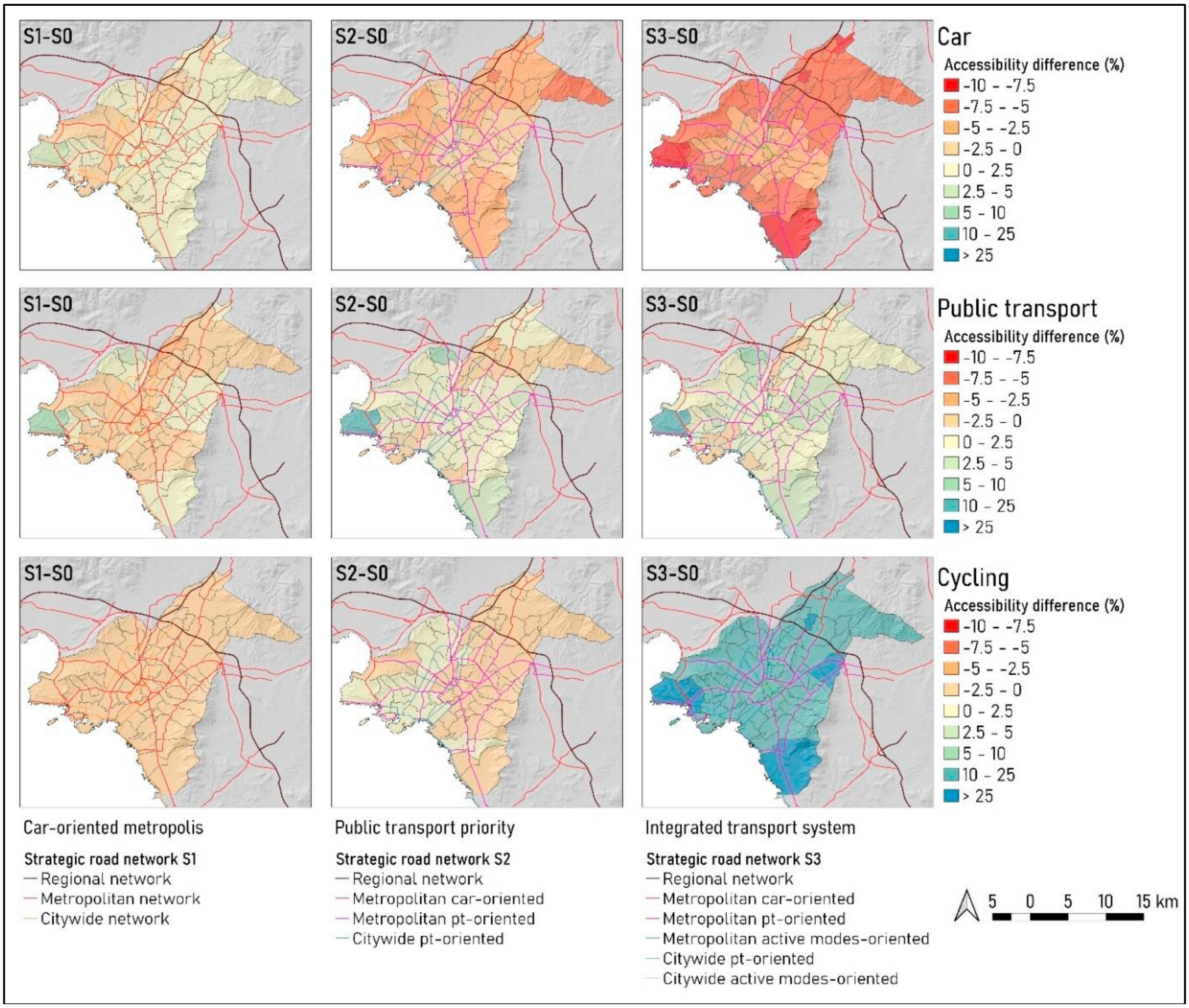

Fig. 2. Proportional differences of accessibility per mode and per scenario

It is demonstrated that scenario 1 slightly increases the accessibility of private car in the majority of zones in Athens; yet in west Attica, it causes small drops of maximum 2.5%. One exception to this is the zone Perama at the southwest, where a new metropolitan network road is introduced. Scenario 2 has the potential to reinforce accessibility by maximum 5% of public transport modes in the suburbs of Athens (i.e., Glyfada, Argiroupoli, Elliniko, Ag. Paraskevi, etc.) that can be found at a considerable distance from the city center. In the same zones, the private car accessibility is simultaneously decreased by 2.5% to 7.5%. Scenario 3 causes significant changes in the spatial distribution of accessibility, which is seemingly illustrated in the maps. In all zones of the study area, accessibility using bicycle rises by at least 10%. On the other hand, car accessibility is significantly reduced by approximately 2.5% in the city center and zones around it, and by approximately 7.5% (or even 10%) in the suburbs.

4. Discussion and conclusions

Accessibility is a broad and complex issue that has various conceptual and methodological definitions, derived from the different disciplines addressing this subject. Regarding urban-transportation accessibility, the different – and sometimes contradictory- aspects outlining this concept, question the capability of accurately quantifying it, since there is not an accessibility indicator with a specific unit of measurement. To this end, in this article we have developed a reproducible research approach based on multiple scenarios illustrating different levels of accessibility; by introducing road network hierarchy and multimodality as structural elements of urban-transport accessibility. This entails the main research gap filled by this research, since the existing state-of-the-art on the subject mostly focuses on how specific transportation changes (cycling, public transport lines, etc.), affect accessibility (e.g., Bocarejo and Oviedo, 2012; Geurs et al., 2016; Pritchard et al., 2019). In more detail, four scenarios have been developed framing various futures for the accessibility of Metropolitan Athens, by assigning different role/priorities for its strategic road network. In Scenario 1, a car-oriented road network classification is described; Scenario 2 shapes a public transport-oriented vision that changes slightly the existing rationale, while Scenario 3 outlines a future where sustainable modes are the backbone of the city's transport system; and all three scenarios are compared with the baseline Scenario 0 which represents the existing status-quo.

The main finding of this work is that expectedly the final multimodal scenario (S3) prioritizing both public transport through bus lanes, cycling and micromobility through cycling lanes or tracks as well as walking through widening of sidewalks, seems to improve the accessibility of public transport and cycling considerably, while restraining car dominance in terms of access to opportunities. However, perhaps the most intriguing outcome, is that car still ensures better accessibility for Athens in this sustainable-centric scenario compared to the existing situation (S0), which highlights the car-oriented urban form and structure of Metropolitan Athens. Moreover, this dominant scenario (S3) notably results in shorter travel times both for public transport modes and cycling/micromobility, while improving accessibility in all zones of the study area. Noticeably, the results imply that transforming road network hierarchy towards sustainable mobility is indeed a great facilitator for enhancing spatial accessibility of the sustainable modes, and therefore supports the transition to viable mobility futures.

It is apparent that this research can be used as a diagnostic tool for accessibility, in the framework of an integrated urban-transport planning approach towards inclusive and sustainable cities. Precisely, it could function as a useful decision support tool, quantifying how the different planning interventions affect accessibility. However, further research could advance the utility of this research, especially since accessibility is a transdisciplinary subject. Including socio-demographic population characteristics would be important to describe the social fabric of the city and address a fundamental aspect of socio-spatial accessibility. Furthermore, a more detailed unit of analysis could shed light in the inter-municipal accessibility differences, while a more comprehensive outline of public transport (frequency and diversity of public transport routes) would be critical to describe more accurately the role of this certain mode in the transport system. Additionally, more scenarios could be tested, with the aim to glimpse other hidden possible future paths incorporating other modes as well (shared mobility, air mobility, etc.). Moreover, a composite index for evaluating scenarios incorporating various aspects like safety, feasibility, environmental impact, modal share, etc. would be surely beneficial. Finally, the proposed methodological framework could be applied to other European Metropolitan Areas by developing different scenarios and compare their accessibility levels.

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