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# Exploring ways to determine an alternative strategic road network in a metropolitan city: A multi-criteria analysis approach

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ABSTRACT

Street functional classification comprises a principal element of urban road networks. However, the conventional approach that has dominated urban and transport planning, has given main priority on car movement. This condition lead to significant negative impacts on cities such as major severances to the urban fabric, low multimodality level, inaccessible road environment for pedestrians and cyclists. As a result, it is clear that we should embark into a new hierarchy system, enhancing and supporting sustainable transport modes.

The current research intends to develop a method that determines the strategic road network of a metropolitan region based on a multicriteria analysis process (MCA). More specifically, at first, we created 3 alternatives of redefining the current strategic road network of the study area. These alternatives propose 3 different strategic network classifications according to several parameters; i) connectivity properties, ii) route position in the road network, iii) urban interest, iv) existence of major public transport lines and metropolitan cycling routes, as well as v) their existing classification condition. Afterwards, we evaluate these alternatives using multicriteria analysis (REGIME method) in order to choose the most efficient one. The evaluation process uses various criteria which cover a considerable range of urban and transport issues. The selected alternative adopts a two-dimensional matrix approach, which addresses the significance of the routes and the modes prioritized. The method is applied to the metropolitan area of Athens in Greece.

It is worth noting that the selected alternative can bring about notable benefits for the Greek capital, such as increase of walking, cycling and public transport share, improvement of traffic safety level, greener mobility (less GHG emissions and energy consumption), enhancement of the urban realm, better accessibility and coherence of the urban fabric. The method proposed, is a human-oriented planning tool which provides priority to sustainable modes and could be replicated to other areas with similar characteristics as well.



## 1. Introduction

The intensive spread of car use, mainly after the 50s, created car-depended urban environments [1] where serious problems are encountered [2]. Specifically, car-oriented cities are suffering from road accidents, traffic congestion, urban sprawl, inaccessible public spaces, environmental degradation, etc. [3,4]. These circumstances, which cannot sustain an acceptable mobility level and a sufficient quality of life for all [5] need a sustainable planning perspective [6,7]. Therefore, cities should develop strategies including the proper policy measures, in order to limit this car-oriented reality and provide more priority to people [8].

Under the aforementioned circumstances, new perspectives discussing the future of cities has arisen. Among them, we encounter the well-known concept of "Sustainable Mobility" [9]. This concept describes a network that addresses contemporary mobility needs by improving walking, cycling, public transport and micromobility (e.g. e-scooters), aiming at enhancing social equity, economic performance and environmental protection [10]. However, the development of a sustainable transport system requires several critical steps. The adoption and, subsequently, the implementation of an integrated urban and transport planning approach [11] is an important prerequisite for the "beginning of this journey." A key element of this approach road network hierarchy or street functional classification [12], which organizes the movement of each mode of transport in a comprehensive way, and therefore introduces a discrete road network management system [12–14].

The current paper aims to explore multiple ways in order to redefine the strategic network of the study area in line with the principles of sustainable mobility. Specifically, the main objective of the research is to develop a method which formulates the strategic road network of a metropolitan city based on a multicriteria analysis process (MCA). The main research questions arising are the following; 1) what approach

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should be adopted? Alternative or conventional? 2) what should be the fundamental components of the proposed method? 3) which are the proper evaluation criteria for selecting the most efficient classification alternative? We will attempt to respond to each one in detail in the next sections. Finally, this research takes into consideration both the urban and transport dimension of the city, since urban areas are considered unified entities where land use and movement are in great interaction with each other [15].

## 2. Literature review

### 2.1. Road network hierarchy: towards new perspectives

The concept of hierarchy exists in several natural, social and technological systems, such as cells, branch of trees, languages, cities and computer networks [16]. Batty [17] argued that hierarchy is intrinsic in urban systems, and is either organic or established. Regarding transportation issues, we should mention that the way streets are connected with each other leads to a specific hierarchical structure [18,19], in which the majority of streets is considered trivial, whereas the minority is vital [20]. Road network hierarchy or street functional classification defines the way through which streets are grouped into classes, according to the function they serve [21]. Precisely, road hierarchy demonstrates the role of each street in the entire network [22].

The conventional approach defines street categories based on the degree to which they give emphasis on the movement/circulation function against local access [23]. This approach has usually 3 basic categories; arterials, collector and distributors and local roads [24]. However, in various countries, the classification system is found to be either more specific e.g. principal or minor arterial in USA and China [22,25] or enhanced with more categories, for instance freeways or motorways in Spain, Canada and Greece [26–28]. The rationale introduced by the typical approach, considers that movement function is inversely correlated with access [13,29] and has as its main principle to facilitate car circulation [30]. Marshall [21] argues that this car-oriented approach leads to dysfunctional urban areas with critical environmental and societal issues. More specifically, classification systems deriving from this approach, are based on a strict segregation, thus excluding cyclists and pedestrians from streets [1]. Furthermore, major thoroughfares pass through significant central areas and therefore serious movement barriers are created. These barriers are considered as considerable severances to the urban fabric which restrain active ways of movement [31]. Moreover, Liu et al. [32] highlight that the conventional approach ignores the social dimension of streets and also undermines the role of other modes. Finally, this classification rationale does not encourage the existence of traditional arterial streets that constitute a mixed environment, accommodating both car movement and human activities [33].

However, streets should not be designed only for car movement; but instead they should be multimodal and vibrant places [23]. In a broader perspective, a street is not solely a linear passage, but it might also compose a capacitor of the urban realm, a political act and a cultural interface [34]. For this reason, the street classification system of the future, should recommend the transformation of roads from traffic conduits to spaces of interaction and communication where different modes and speeds co-exist [1]. Tellingly, there is an ongoing and noticeable research effort towards this direction. For example, Marshall [35] introduced a transit-oriented hierarchy, which prioritizes public transport and embraces the cooperation between sustainable modes. In addition, Strate et al. [36] composed a functional classification system for accommodating multimodal transport and the City of Portland recommended that a thoroughfare's main function could be established either as vehicle or as pedestrian mobility (or bike or transit), thus following an integrated approach [31]. Furthermore, a great number of scientific papers and technical guidelines adopted a matrix-based classification approach that takes into account both "Link" and "Place" functions [e.g. 30, 33, 37]. Lastly, Liu et al. [32] extended the bi-dimensional matrix approach and suggested a tri-dimensional classification system depending on Hierarchy, Activities and Mode, thus enhancing the integrity of the classification process.

### 2.2. Multi-criteria analysis: a brief review

Multi-criteria methodologies have emerged as a discipline of Operational Research (OR) and their main objective is to support decision making; particularly, in complex situations [38]. Decision making constitutes a challenge which includes uncertainty referring to results that could be generated according to established choices [39]. Multi-criteria analysis (MCA) constitutes a notable tool, since it allows for multiple aspects of a problem, to be accounted for in the decision process [40–42]. It is used in a variety of cases, including classification, ranking and evaluation of different alternatives or scenarios [43]. The key components of a multi-criteria analysis are a) the alternatives, b) the criteria and c) the weights regarding these criteria [44]. Tellingly, the scores achieved do not necessarily need to be conveyed in monetary terms; on the contrary they can simply be expressed in physical units or in qualitative terms. We should mention that multi-criteria analysis is increasingly used for decision-making, mainly due to the particular complexity of the current issues and the deficiency of other relevant tools such as Cost-Benefit Analysis (CBA) or Cost-Effectiveness Analysis (CEA) in taking into consideration all the impacts of policies or strategies [45].

Multi-criteria techniques are used in several transport policy case studies to address complicated decision problems where policy-makers are dealing with multiple different and even conflicting criteria [40,46–48]. For instance, the application of MCA in the transport sector addresses a wide variety of decisions problems such as public transport planning, infrastructure construction, mobility management, adoption of new and smart technologies, etc. [49,50].

In particular, Yedla and Shrestha [51] examined the impact of including various qualitative criteria for the selection of alternative transportation options in Delhi. The authors use six different criteria for the evaluation: energy saving potential (energy), emission reduction potential (environment), cost of operation (cost), availability of technology (technology), adaptability of the option (adaptability) and barriers to implementation (barrier). Zubaryeva et al. [52] utilized a multi-criteria decision support method to assess the potential lead markets for electrified vehicles in Europe. The researches combine several economic, social, environmental, and transport-related factors. Barbosa et al. [53] evaluated the urban public transport system of Florianopolis in Brazil, through using both qualitative (e.g., convenience, service, safety) and quantitative (e.g., waiting time, the fare price) criteria. Gerçek et al. [54] used an MCA in order to evaluate the rail transit networks in Istanbul. A multiple criteria approach for the evaluation of the rail transit networks in Istanbul. Furthermore, multi-criteria methods can be used to analyze policy measures. Taefi et al. [55] explored policy measures related to the adoption of electric vehicles in urban road freight transport. Macharis et al. [56] applied multi-actor multicriteria analysis (MAMCA) in order to assess mobility and logistics policy measures in Flanders. Moreover, Lee [57] prioritized Advanced Public Transport Modes (APTM) in new towns of Korea using MCA based on data gathered from various transportation experts.

Nevertheless, despite the considerable use of MCA in the transport sector, there has only been limited attention paid to combining MCA with transport scenario/alternative analysis [58,59], and especially with the backcasting approach [60,61], which includes the development of normative scenarios aimed at exploring the feasibility and implications of achieving certain desired end-point [62]. However, the assessment of transport backcasting scenarios by using multi-criteria analysis (MCA) is seen here as a promising solution for the following reasons [61]:

Firstly, as we mentioned above, MCA has been traditionally used in transport sector to solve complex decision problems by constructing a hierarchy of criteria for evaluation [59]. Secondly, MCA can be used to rank the likelihood that a range of sustainability impacts (environmental, social, and economic) can be generated for the implementation of the proposed policy pathways in the longer-term [60]. Thirdly, MCA can be easily combined with other participatory methods, triggering a more flexible assessment framework that facilitates the engagement a wide range of stakeholders during the assessment process [52,63]. This last point is central in the context of shifting the paradigm towards more collaborative planning approaches, primarily based on stakeholders' participation and interaction [64].

## 3. Methodological framework

This study used a qualitative approach in order to develop the methodological framework that we followed. Specifically, we conducted a thorough literature review analysis, exploring relevant studies which propose transport scenarios or alternatives, and afterwards they evaluate them through multicriteria analysis (Section 2). This procedure enlightened our perception with the existing state of the art, thus contributing notably to the development of our methodological framework. This framework consists of five (5) distinct steps. The first one concerns the review of the current situation (urban and transport characteristics) in order to identify potentials. The second refers to the development of a method that formulates the new strategic road network. This method is applied 3 times, thus creating 3 classification alternatives. Each one has a different vision for the study area. The third step contains the multicriteria analysis which is based on a set of different criteria categories. This process will reveal the best alternative for our study area. Lastly, the final step of the methodological approach describes this selected alternative briefly (planning and design features), attempting to bridge the gap between strategic planning and its implementation.

### 3.1. Analysis

Initially, the analysis phase is divided into two parts of equal importance. The first part refers to the urban features, and namely the following: i) the urban interest of the existing strategic routes, ii) the determination of the compact urban core and iii) the identification of the most significant urban centers of the city. Focusing on each one separately, we should highlight the following: i) the urban interest indicates the land use mix, the functional density (land use per 100 m) and the existence of notable sites or buildings such as architectural monuments, squares, archaeological sites, sites of pedestrian attraction, etc. in a given road segment. If a segment has great land use mix and functional density (Shannon index ≥ 0,5 and density ≥ 5land uses per 100 m respectively) and at least one significant site or building, then this segment is characterized as “High interest”, otherwise as “Low Interest”; ii) the main urban core illustrates the compact area of the city. Specifically, it consists of municipalities with residential density surpassing the threshold of 200 residents per hectare; iii) finally, the major urban centers and their classification are retrieved from formal regional planning documents.

The second part examines the transport characteristics and precisely the following: i) existing strategic network, ii) main public transport routes, iii) metropolitan cycling routes and iv) road width. Focusing on each one separately, we have to mention the following: i) the strategic network of a metropolitan city is retrieved from formal transport planning documents. Usually it consists of motorways and primary arterials, but this fact is not obligatory; ii) the main public transport routes including trunk bus lines and tramway lines that service metropolitan or intermunicipal trips; iii) the metropolitan cycling network is retrieved from formal urban planning document and includes either constructed or planned routes; iv) the road width represents the total width of a road segment (sidewalk, pavement, parking, median, etc.).

### 3.2. Development of a classification method

The paper used a qualitative approach in order to develop the proposed method for formulating the different classification alternatives. Precisely, the suggested method is based on an extensive literature review analysis regarding street classification, conventional or innovative. This method mainly adopts a spatial approach and requires both on-site observations and secondary data in order to identify the needs of the study area. Therefore, we recorded features such as land uses and road width. Furthermore, we acquired various secondary data such as road classification, public transport and metropolitan cycling network, so that we were able to gain a more comprehensive view of the current mobility status. After examining different types of classification methods in a combinatorial way, we adopt a bi-dimensional approach (dimension one-significance and dimension two-mode priority) which is mainly in line with innovative classification perspectives [35,37].

The proposed method is applied in 3 discrete ways, thus constructing 3 strategic network classification alternatives which represent different visions about the transport system of the future. These alternatives are the following: a) A1-car-oriented or conservative, b) A2-public transport-oriented or moderate and c) A3-sustainable modes-oriented or innovative. The rationale behind the formulation of 3 alternatives is that we aim to ensure a holistic approach regarding the prioritization of transport modes in the city. For instance, car-oriented planning signifies different classification needs compared to public transport or sustainable modes-oriented planning, and these needs are considered in the suggested method (see below sustainability potentials indicator-SPI). It should be noted that every alternative classification proposes a new strategic network which utilizes existing routes, so that potential costs and construction delays are limited. Furthermore, the method described in each case could be easily applied to road networks with radial-centric topology. Next, we describe the general criteria and the steps of our method.

#### 3.2.1. General features of the method for classification

The method applied to each alternative is composed by hierarchical three steps. The first defines the road segments of the new strategic network and their significance, the second determines the ring roads that divide the metropolitan area and the third assigns mode priority in every segment. Next, we describe the criteria used in each step.

*3.2.1.1. Road significance.* The first step deals with the network segments and their significance which represents the first dimension of the classification matrix. In the basis of the strong relation between urban and transport planning [15], we decided to link road significance categories with the size of the study area. As we deal with a metropolitan area, we selected to divide road significance into 3 categories. The first is Regional; the second is Metropolitan and the third Citywide. Of course, in case of different city size, the number of categories should change. The criteria used for choosing the routes (group of road edges) are the following (see Fig. 1):

a) Connectivity: Based on the assumption that the importance of a network segment depends on the importance of the places which are connected by this segment [65], we introduce this particular criterion to examine the significance of the connection between two places.
b) Geography or Location: We examine the location of a road segment in regards with the main urban core.
c) Current classification in the existing network: This criterion examines if a road segment belongs to highways or primary arterials.
d) Sustainability potentials indicator: It is indicator depicting the

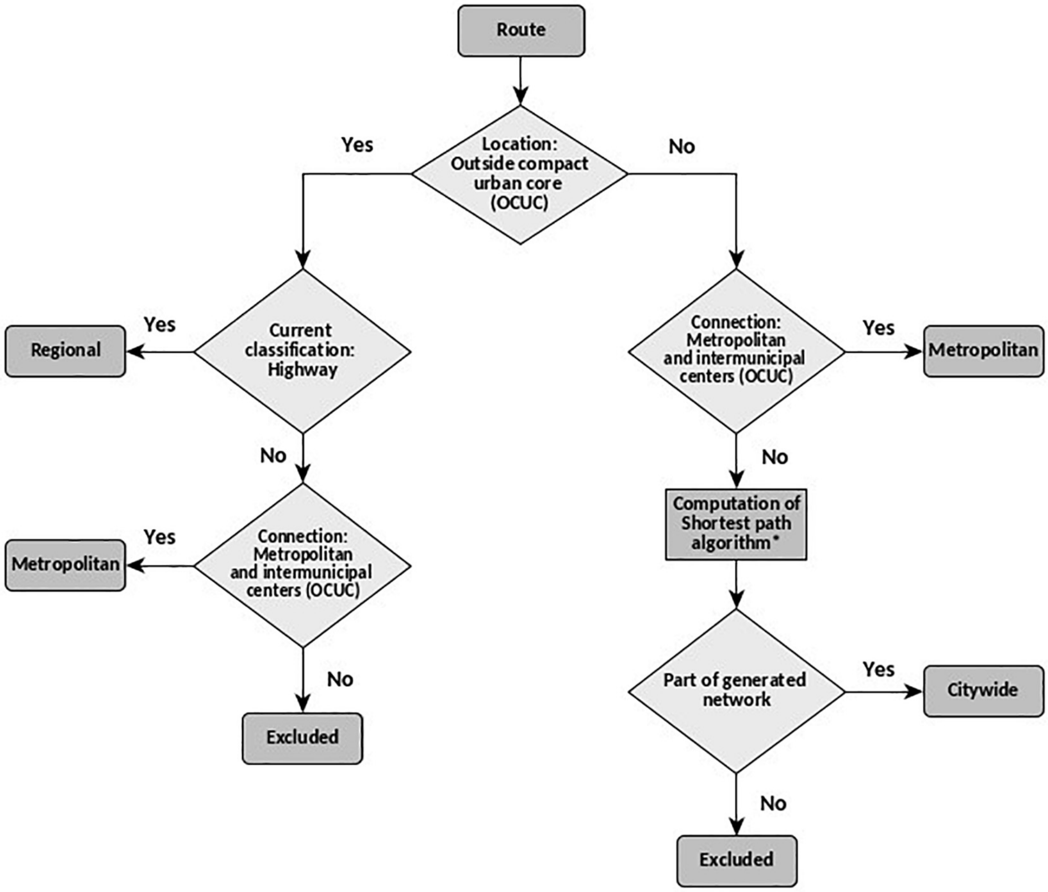


**Fig. 1.** Process for assigning significance to routes.

potentials for sustainable transport modes. The formula is the following:

$$SPI = a*UI + b*TW + c*PT + d*CL \quad (1)$$

Where:

SPI is the sustainability potentials indicator (values 0 to 4),

a, b, c and d are coefficients depicting when a factor is considered (value = 1) or not (value = 0).

UI is the urban interest (value = 0 when urban interest is high and value =1 when urban interest is low).

TW is the total width of a road segment (value = 0 when road with is lower than 25 m and value =1 otherwise).

PT is the existence of main public transport line (value = 0 when public transport line is absent and value = 1 otherwise).

CL is the existence of metropolitan cycling route (value = 0 when cycling route is absent and value =1 otherwise).

e) Shortest path algorithm: this criterion contains the application of "v.net.allpairs" tool in the software GRASS GIS which generates the shortest path between all pairs of nodes in a given network (urban centers within the main urban core in particular). This algorithm connects two centers with one route, thus increasing the robustness of the proposed strategic network [65]. It is worth noting that this algorithm uses as cost the sustainability potentials indicator (SPI), which is different in each alternative. Thus, when a street has high value of this indicator, then this segment has higher possibilities of being chosen.

*3.2.1.2. Ring roads.* The second step determines ring roads (outer, intermediate and inner-central) for the study area by considering three criteria which are the following:

a) Significance: This is the significance that was determined in the previous step.
b) Geometry: This criterion concerns the geometrical structure of segments, examining if they radial or circumferential to the metropolitan center of the city.
c) Geography or Location: We examine the location of a road segment in regards with the main urban core, the high-residential area inside the compact area and the basic metropolitan center.

The process for formulating ring roads is the following: The central-inner ring road is composed by circumferential routes that have metropolitan significance and they have the greatest proximity to the central area of the city. This ring road protects the commercial and historic center. The intermediate ring road of circumferential routes within the main urban core which have metropolitan significance as well, but they have the second greatest proximity to the central area. The zone created encompasses areas with high residential density (greater than 250–300). Lastly, the outer ring road is formulated either by regional roads or metropolitan circumferential routes and its main objective is to accommodate the diversion of regional through traffic.

*3.2.1.3. Modes priority.* The final step refers to the second dimension of the classification matrix and divides road segments into different categories depending on the modes they prioritize. Hence, in case of prioritizing only car, there is one category on the matrix, in case of prioritizing either car or public transport, there are two categories, and in the last case of giving priority to either car or public transport or sustainable modes, there are three categories. Of course, in case of different modes prioritized, the number of categories should change. The criteria used for assigning priority are the presented below (See Figs 2 and 3):

a) Significance: This is the significance that was determined in the previous step.
b) Geography or Location: We examine the location of a road segment in regards with the ring road zones that were defined in step 2.

*3.2.1.4. Final classification.* The final categories occur from the bi-dimensional matrix. If we take into consideration each dimension, we can mention the following: The first alternative should have maximum of three categories (1*3), the second 6 categories (2*3) and the third 9 categories (3*3). However, it is possible to determine even empty cells, when it comes to risky combinations.

### *3.3. Multicriteria analysis*

The multicriteria analysis method used is the REGIME method, which constitutes a distinct multi-criteria evaluation process that accepts both qualitative and quantitative data [40]. This method, that was initially introduced by Hinloopen, Nijkamp, and Rietveld in 1983 [66], is a multiple attribute qualitative method which solves the problem based on a pairwise comparison of all alternatives. The REGIME method is considered as one of the most important methods for experts in multiple attribute decision making to rank alternatives, due to the lack of direct use of qualitative attributes. In fact, the strength point of this method is the REGIME matrix formation, which is a combination of quantitative and qualitative attributes at penultimate stage (Fig. 4). It allows decision makers to use this technique in many cases without any need to convert the qualitative attributes into quantitative attributes. The application of the method is based upon two kinds of input data: the evaluation (impact) matrix and a set of political weights [67,68].

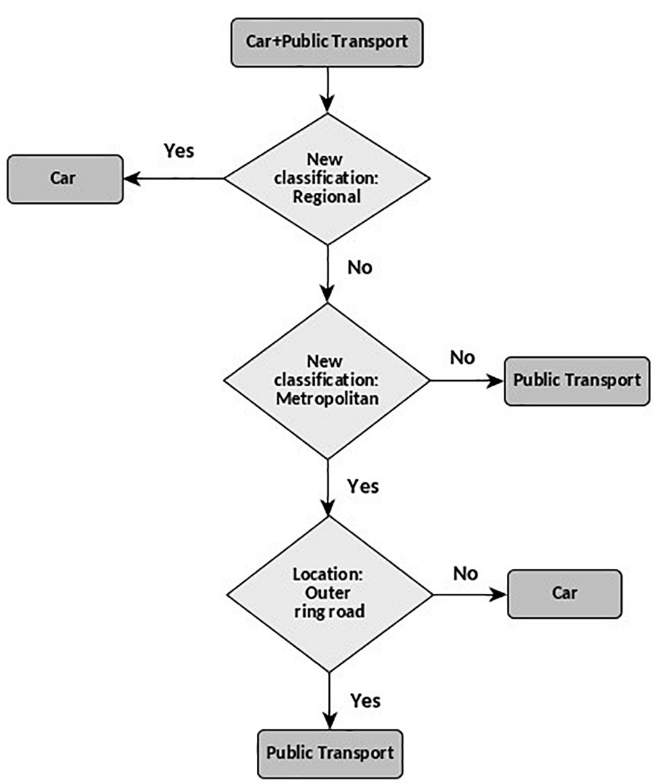


**Fig. 2.** Process for modes' prioritization (Part I).

#### *3.3.1. Presentation of criteria*

This analysis is based on a set of different criteria that are divided into 4 categories according to their role. The selection of criteria is directly correlated with the aim of the research and covers a wide range of environmental, social and economic characteristics occurring in a metropolitan city. The main contribution to the definition of the criteria was a detailed literature review [e.g. 69–73]. Each criterion was selected carefully and was calculated or estimated according to some basic principles, even the qualitative ones. These criteria along with their calculation/estimation description, are presented in detail inTable 1

The first category includes two criteria: readability and simplicity. The first one depicts the readability of the network, representing the easiness of the users to understand and use the network. The value of this criterion is the number of categories of each network. Greater number of categories reduces the readability of the proposed classification. The second criterion in this category is the simplicity of the new strategic network, meaning that a network with less length is robust and simple. The value of this criterion is calculated through the absolute value of reduction rate of the existing strategic network and it demonstrates a positive direction.

The second category includes two criteria: feasibility and traffic safety. The first one represents the cost of the proposed classification, in terms of required interventions and policy measures. It is a qualitative criterion. Higher feasibility occurs when a few interventions are necessary, and the direction of this criterion is positive. The second criterion concerns traffic safety, which is calculated by the percentage of car-oriented streets' length reduction. In this research, we define car-oriented streets as features where the available space for other modes is limited (e.g. narrow sidewalks, absent of cycle lanes, no bus or tram lines, illegal on-street parking, etc.) or there is a lack of the appropriate measures that ensure prioritization of collective transport, for instance no signaling priority for buses or trams.

The third category encompasses three criteria: new mobility culture, multimodality and impact to environment. The first one reflects the conditions to embrace sustainable and greener modes. It has a binary value, illustrating whether each proposed classification system includes categories prioritizing cycling and walking or public transport. The second criterion concerns multimodality, which is a crucial aspect of future transport systems. Multimodality is calculated via the entropy (Shannon) index that measures the mix level of different categories (for instance car-oriented and public transport oriented) based on their length. The values vary from 0 to 1 and it has positive direction. The final criterion refers to the environmental impact of every alternative. It is a qualitive criterion with negative direction which depicts traffic congestion level, GHG emissions, air and noise pollution, etc., that is possible to happen due to the application of each classification system.

The fourth category contains three criteria: central areas' protection, unification of urban fabric and vitality enhancement. The first criterion concerns the reduction of friction points, which is a central urban area of metropolitan or intermunicipal significance, where movement and access functions confront. In other words, these areas have notable vitality and intense pedestrian flows due to the activities and land uses; but at the same time, they are penetrated by major thoroughfares. Therefore, the reduction of these areas means that we protect these centralities by diverging the through traffic or by changing the hierarchy of the roads passing by. It is calculated via the absolute value of reduction rate of friction points and it has a positive direction. The second criterion is the unification of urban fabric that is calculated via the length (km) of traffic barriers (existing arterials) which are eliminated due to each classification system. The final criterion is vitality enhancement which refers to the possibility of a road segment to encourage pedestrian friendly land uses and facilitate public and shared transport, in order

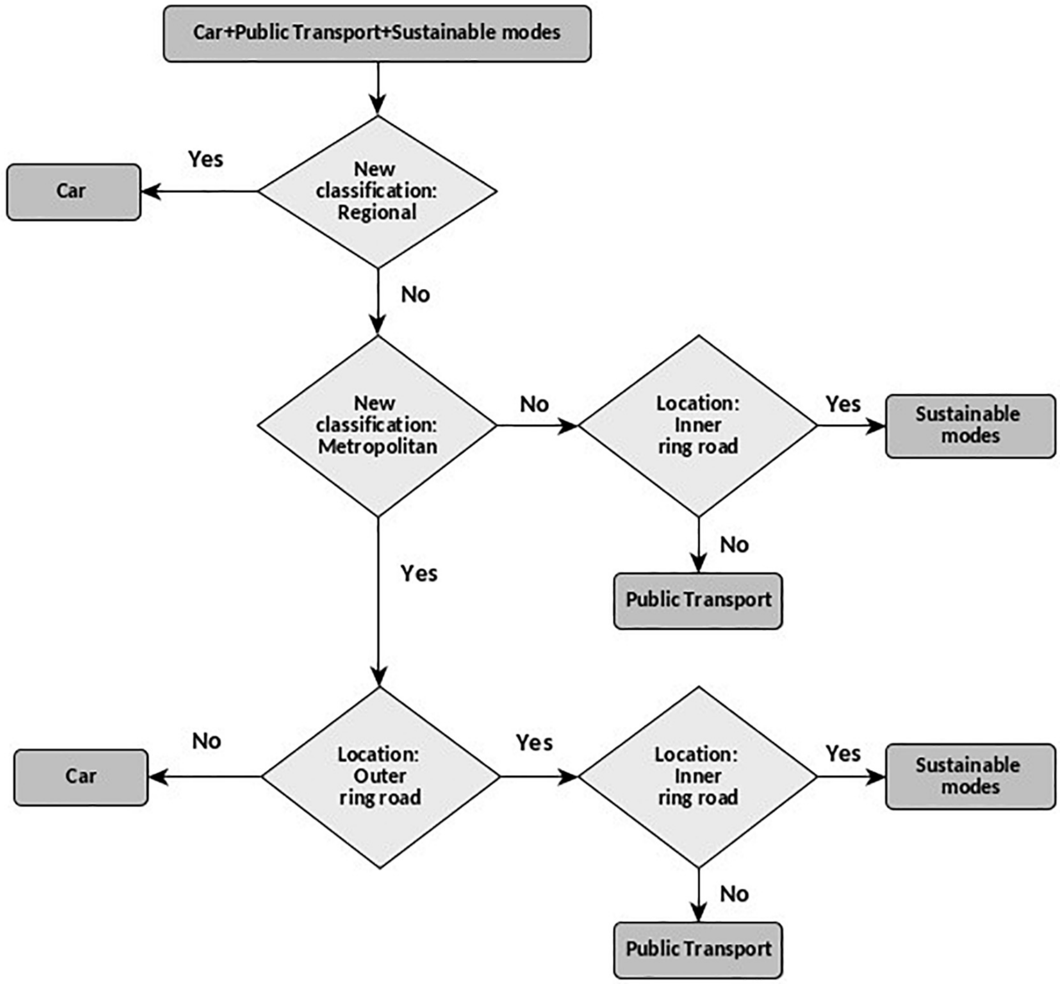


**Fig. 3.** Process for modes' prioritization (Part II).

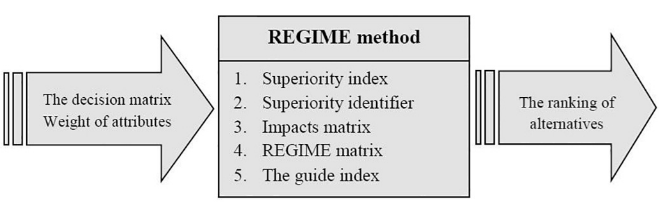


**Fig. 4.** Methodological flow of REGIME method [68].

to create streets for people and not for vehicle. This criterion is calculated via the length of corridors prioritizing sustainable modes.

### *3.3.2. Assigning priorities to criteria*

The next step of the multicriteria process is to assign priorities to the 4 groups of criteria that we presented in the previous step. Priorities should reflect the preferences of society and relevant authorities [67], therefore this task was carried out via short interviews with diverse

**Table 1**
List of criteria.

| Group | Criteria | Description/Calculation | Values | Direction |
|---|---|---|---|---|
| Network Structure | Readability | Number of categories | Plain | Negative |
| | Simplicity | Absolute value of reduction rate of existing strategic network | % | Positive |
| Socio-economic | Feasibility | Qualitative evaluation of the estimated feasibility (cost) | Low, Moderate, High | Positive |
| | Traffic safety | Percentage of car-oriented streets' length reduction | % | Positive |
| Sustainability | New mobility culture | Existence of categories promoting public transport or sustainable modes | Binary | Positive |
| | Multimodality | Entropy index of categories prioritizing different modes | Plain | Positive |
| | Impact to environment | Qualitative evaluation of expected environmental impacts (congestion, GHG emissions, noise pollution, etc.) | Low, Moderate, High | Negative |
| Urban | Central areas' protection | Absolute value of reduction rate of central areas where link and place functions conflict | % | Positive |
| | Unification of urban fabric | Length (km) of traffic barriers (arterials) which are eliminated due to the new classification | km | Positive |
| | Vitality enhancement | Sustainable modes corridors | km | Positive |

stakeholders. Specifically, these stakeholders deal with urban and transport issues concerning metropolitan areas and namely they were public transport operators, municipalities and regional administrations, ministries, NGOs and scientific associations. The sample consisted of 10 people that were representing each one of the abovementioned organizations. The interviews were made either in person or via Skype and they were not recorded. The evaluators were provided with the 4 groups along with a brief description of each one, and we requested them to rank these categories, according to their significance. At the end of each interview, all evaluators were asked if they agreed with the notes made, in order to validate the results. After the interviews we set values to the ranking of the evaluators (4-Very high significance, 3- High significance, 2-Low significance and 1-Very low significance). As a result, we were able to calculate the mean value of every group, and therefore calculate its final ranking. The final results indicate the following order: 1) Sustainability, 2) Socio-Economic, 3) Network Structure. and 4) Urban.

### 3.4. Selection and description of best alternative

The next step is the selection of the most efficient alternative for our study area. The REGIME method is applied two times in the DEFINITE software in order to integrate different perspectives, thus producing diverse and more reliable results. In the first application, the criteria are treated as equal, while in the rest applications they gain weights according to the priorities set. It should be mentioned that this specific alternative is chosen based on a combinatorial view on the results. The best alternative will be the one that occurs as preferred in the majority of the applications. However, in the case where each application of REGIME method picks up a different alternative, then the best alternative will be the one that occurred from the second application, because it prioritizes the sustainability dimension.

After the selection of the most efficient alternative, we proceed to the final step which contains a more detailed description, thus revealing briefly how this particular alternative will be implemented. In this context, we propose some desirable planning and design characteristics as well as some indicative cross-sections which refer to each category proposed. It should be acknowledged that these design characteristics ensure accessibility for all street users, thus improving quality of life of vulnerable groups and achieving community integration [74].

## 4. Application to the metropolitan area of Athens and results

### 4.1. Study area

The method is applied to the mainland part of Attica Region in Greece. The study area is composed by 58 municipalities, containing the metropolitan centers of Athens and Piraeus. It covers an area of approximately 2.836 km$^2$ (77% of the entire Attica region) and according to the last census in 2011, it has 3.714.500 residents, thus representing the 33% of the entire country's population. The study area is a region with diverse characteristics (urban, transport, social, etc.). It has also serious urban sprawl but at the same time strong metropolitan centers. According to the Regional Plan of Attica [75], major central areas are divided into two categories (metropolitan and intermunicipal) (Fig. 5). Furthermore, the compact urban area encompasses 38 municipalities.

In general, the existing strategic network of the study area is car-oriented, thus allowing the penetration of the compact urban core by primary arterials and urban motorways. As a result, intensive traffic flow is passing through the intermunicipal and metropolitan centers as well as through numerous neighborhoods, shaping unfavorable conditions concerning pedestrians, cyclists and vulnerable social groups. This condition is mainly due to the absence of coherent and efficient ring road zones. Noteworthy, the only existing ring road protects the basic central area of the city, but its configuration lacks considerably of readability. Furthermore, the complex form of the strategic road network is not cohesive and intelligible and additionally it creates serious severances to the urban fabric (Fig. 5). At the same time, the current classification system undermines the role of sustainable transport modes such as walking, cycling and public transport, since none of the categories of the strategic road network, give priority to any of these modes. The percentage of the strategic network in the entire road network of the city is around 9,80% (motorways are 22,0% and primary arterials are 78,0%), meaning that a substantial number of roads are devoted in facilitating the movement motor vehicles.

As a result, major adjustments are needed to improve the inadequate condition of the current strategic network, which is incapable of promoting sustainable mobility. In the next steps, we will attempt to find the best alternative aspect of the proposed method in order to increase the efficiency of the classification system.

### 4.2. Application of the method and results

Taking into consideration the suggested method, we developed a new strategic road network of metropolitan Athens. We conducted a thorough evaluation of every road segment in the existing strategic network in order to determine its significance and the modes that should be prioritized. As we described in the previous section, we formulated 3 classification alternatives, which represent a different vision about the study area (car-oriented, public transport-oriented and sustainable-greener modes-oriented). In the current section, we present the results of each application and the final classification systems that occurs.

#### 4.2.1. Alternative I - "a city based on cars"

The first alternative develops a car-oriented vision that maintains the existing rationale. The $SPI_1$ in this case is calculated by the following formula, considering only total width and public transport existence for every segment:

$$SPI_1 = TW + PT \quad (2)$$

Furthermore, as it only prioritizes car-movement, the classification matrix is $1 \times 3$ (Table 2) and therefore the final categories in this classification system are three. Namely, Car Regional, Car Metropolitan and Car Citywide.

The results concerning the first alternative (A1-Conservative) are the following: 27% of the new strategic network has regional significance, 65% metropolitan and 8% citywide. In addition, the whole strategic network prioritizes car circulation and therefore car-oriented streets have not been notably reduced.

#### 4.2.2. Alternative II - "public transport to stimulate urban mobility"

The second alternative shapes a public transport-oriented vision that changes slightly the existing rationale. The $SPI_2$ in this case is calculated by the following formula, considering total width, public transport existence and metropolitan cycling routes for every segment:

$$SPI_2 = TW + PT + CL \quad (3)$$

According to the classification procedure, the classification matrix is 2*3 (Table 3). However, some categories are considered risky, therefore the strategic road network consists of 4 categories, which are the following: Regional Car, Metropolitan Car, Metropolitan Public Transport and Citywide Public Transport.

The results regarding the second alternative (A2-Moderate) are the following: 27% of the new strategic network has regional significance, 63% metropolitan and 10% citywide. In each category separately we should mention the subsequent: a) the entire regional network gives priority to car circulation, b) 32% provides priority to public transport and 68% prioritizes car circulation and c) the citywide network is characterized by a public transport prioritization condition.

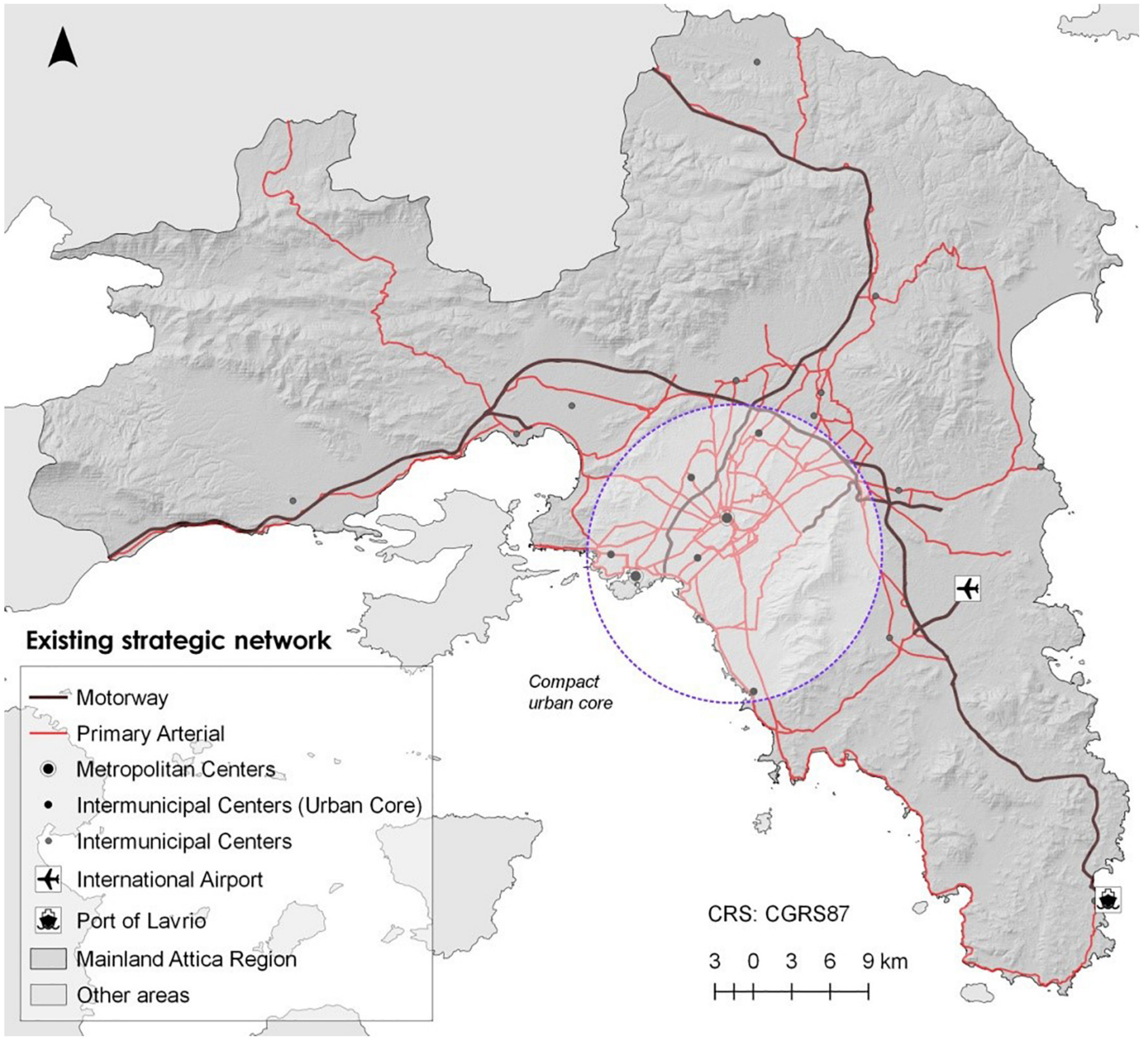


**Fig. 5.** Existing strategic network, compact urban core and main urban centers.

**Table 2**
Categories of alternative A-1.

| Mode\Significance | Regional | Metropolitan | Citywide |
|---|---|---|---|
| Car | RC | MC | CC |

**Table 3**
Categories of alternative A-2.

| Mode\Significance | Regional | Metropolitan | Citywide |
|---|---|---|---|
| Car | RC | MC | Risky |
| Public transport | Risky | MPT | CPT |

**Table 4**
Categories of alternative A-3.

| Mode\Significance | Regional | Metropolitan | Citywide |
|---|---|---|---|
| Car | RC | MC | Risky |
| Public transport | Risky | MPT | CPT |
| Sustainable modes | Risky | MSM | CSM |

*4.2.3. Alternative III - "bringing sustainable modes to the forefront"*

The final alternative shapes a vision fostering sustainable/greener modes that transforms the existing rationale radically. The $SPI_3$ in this case is calculated by the following formula, considering all possible features for every segment:

$$SPI_3 = UI + TW + PT + CL \quad (4)$$

According to the classification procedure, the classification matrix is 3*3 (Table 4). However, some categories are considered risky, therefore the strategic road network consists of 6 categories, which are the following: Regional Car, Metropolitan Car, Metropolitan Public Transport, Metropolitan Sustainable Modes, Citywide Public Transport and Citywide Public Transport. Focusing on each category separately we should note the following: a) the entire regional network gives priority to car circulation, b) 1,3% of the metropolitan network favors sustainable modes, 30,2% provides priority to public transport and 68,5% prioritizes mainly car movement (the last percentage refers to routes outside the main urban core) and c) 9,3% the citywide network turns into sustainable modes and the rest 90,7% favors public transport movement.

The results concerning the third alternative (A3-Innovative) are the following: 28% of the new strategic network has regional significance, 61% metropolitan and 11% citywide.

**Table 5**
Impact matrix of REGIME (criteria values).

| Group | Criteria | Values | | |
|---|---|---|---|---|
| | | A1 | A2 | A3 |
| Network Structure | Readability | 3 | 4 | 6 |
| | Reduction of strategic network | 12,48% | 11,22% | 9,50% |
| Socio-economic | Feasibility | High | Moderate | Low |
| | Traffic safety | 12,48% | 38,3% | 38,3% |
| Sustainability | New mobility culture | no | yes | yes |
| | Multimodality | 0 | 0,61 | 0,70 |
| | Impact to environment | High | Moderate | Low |
| Urban | Central areas protection | 33% | 90,48% | 90,48% |
| | Unification of urban fabric | 0 | 223,5 | 237,73 |
| | Vitality enhancement | 0 | 0 | 14,3 |

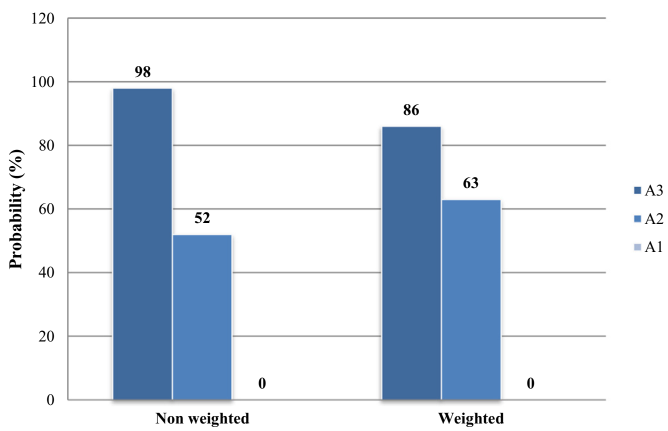


**Fig. 6.** Results of multicriteria analysis.

### 4.3. Application of multicriteria analysis and selection of the best alternative

After the formulation of the 3 different classification alternatives, we proceed to the implementation of the multicriteria analysis. A fundamental step is the construction of the impact matrix (See Table 5). This matrix is composed by the values of each criterion (quantitative or qualitative) in every alternative.

As we can see, the values concerning the different criteria are considerably different between the 3 alternatives. This condition signifies that the results, regardless of the weights, will be discrete and clear. A relevant figure presents the results that occurred from the two REGIME applications (Fig. 6). It should be noted that the overall score of each alternative, is calculated by the average of the relative success indices. The relative success index represents the probability of a certain alternative to prevail over another [67].

It is evident that the third alternative, which is the entitled as "Sustainable modes-oriented", is at the top of the ranking, with great difference from the rest alternatives, in both applications. Precisely, it has over 85% probability of being selected in each case, while the rest have 50–60% or 0%. Therefore, the results are the following:

- MCA 1: Alternative 3-"Sustainable modes-oriented"
- MCA 2: Alternative 3-"Sustainable modes-oriented"

According to the results, it is rather obvious that the most efficient alternative is the third one, which contains a radical approach regarding the strategic network of Athens. At next, we proceed to the presentation of the characteristics of this selected alternative.

### 4.4. Best alternative presentation. Describing planning and design issues

The configuration of the new strategic network illustrates that car-oriented streets have been reduced by 38,3%. In general terms, the new strategic network has been decreased by approx. 9,5%, thus

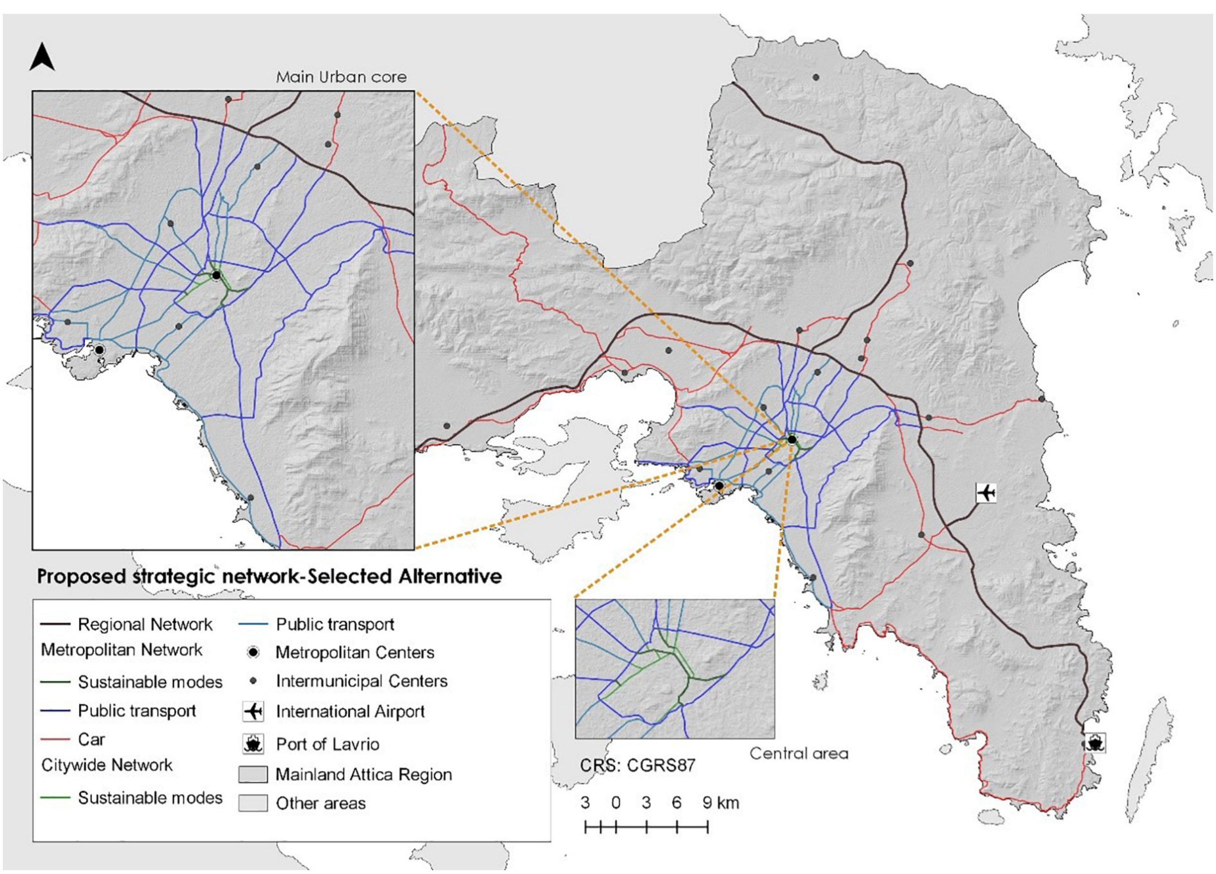


**Fig. 7.** Proposed strategic network-Selected alternative.

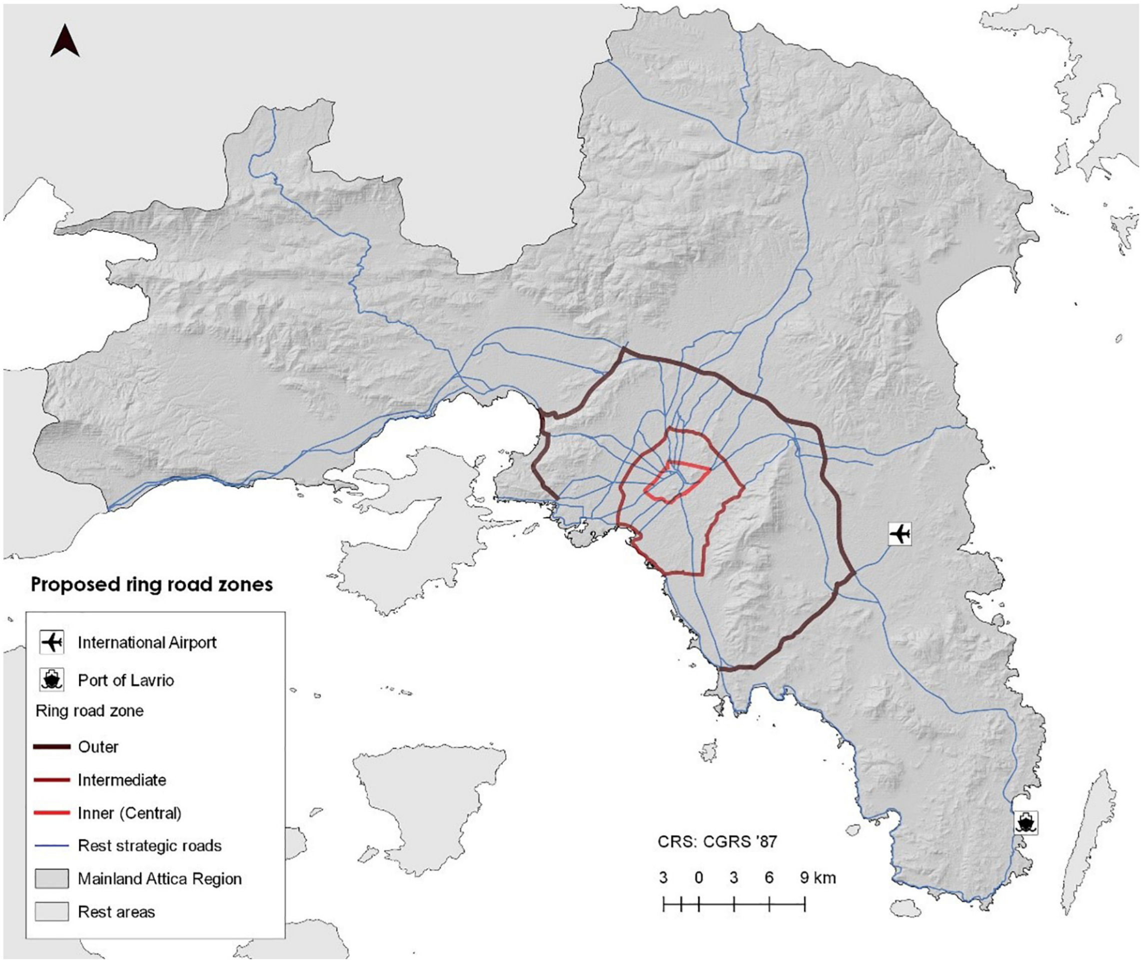


**Fig. 8.** Proposed ring road zones.

contributing slightly to efficient network management and better readability. Furthermore, as we described in the third section, the new strategic network forms 3 main ring road zones (inner, intermediate and outer) that coordinate the flow of traffic properly and protect the compact urban core from through traffic (Fig. 8). Such areas occupy a total of 15,1% of the entire mainland region of Attica, setting the conditions for fostering sustainable mobility. Additionally, the ratio of beltness [76] is equal to 56%, reflecting a balanced condition between the radial and circumferential arterial routes. What is more, the new strategic network indicates the introduction of 237,7 km of routes devoted to sustainable mobility either walking and cycling or public transport, whereas the existing classification system does not have a specific regulation. Finally, the selected alternative increases the protection of central areas from thoroughfares by approx. 90%.

The best alternative proposes 6 categories which define street significance and mode priority (See Fig. 7). In this context, we prepared Table 6, in order to illustrate the proposed relation between the modes, and some desirable characteristics regarding each category. These characteristics are the following: i) type of junctions (elevated, signalized, etc.), ii) existence of left turns, iii) maximum allowed speed, iv) on-street parking existence, v) public transport (Tram, BRT, LRT, Bus, etc.), vi) cycling routes (separate or roadway infrastructure), vii) pedestrian accommodation (sidewalks, crosswalks, etc.) and viii) land uses and urban identity.

Apart from the detailed table (Table 6), we created some example cross-sections, which illustrate a desirable designation for each strategic network category (See Figs 9-14). These cross-sections are aimed at accommodating every possible transport mode according to the category they belong to. It is clear that the level of modes' mix intensifies when we shift from automobile to sustainable modes priority. Finally, we should note that the widths of each feature are correspondent to Greek Planning Guidelines [28].

## 5. Discussion-conclusions

This paper suggests an integrated method for re-defining the strategic road network of a metropolitan region through using a data-driven approach. This method concerns mainly large metropolitan cities with population above 3 million residents and size greater than 2.000 $km^2$. It should be mentioned that the main point of the research is the adequate integration of greener modes such as walking, cycling and collective transport in the transport system. We should highlight that these modes are the stimulus for conducting this study.

We adopt a unified and alternative approach which considers both the transport and the urban dimension of the study area by creating a two-dimensional classification that encompasses link significance and mode priority. Furthermore, this research utilizes Multicriteria Analysis (MCA) and especially the REGIME method in order to, primarily, evaluate the various alternatives proposed and secondly, to choose the best alternative for the classification system of the study area. The criteria used in MCA cover a wide range of issues such as urban characteristics, socio-economic factors, network properties and sustainability features. MCA is an integral part of the methodological approach as it contributes to the highlighting of benefits and drawbacks of each alternative, thus pointing out the most efficient strategic road network classification. However, this research limits the alternatives to 3 in order to be

**Table 6**
Proposed characteristics of each category

| Code | Proposed characteristics |
|---|---|
| RC | ♦ Car movement: elevated or signalized junctions, no left turns<br>♦ Speed: up to 100-120km/h<br>♦ On-street parking: prohibited<br>♦ Public transport: regional bus<br>♦ Cycling infrastructure: absent<br>♦ Pedestrian infrastructure: minimum or absent design<br>♦ Land uses: Vehicle-oriented |
| MC | ♦ Car movement: Elevated or signalized junctions, no left turns<br>♦ Speed: up to 80-90km/h<br>♦ On-street parking: prohibited<br>♦ Public transport: regional bus or Tram or BRT<br>♦ Cycling infrastructure: minimum or absent design<br>♦ Pedestrian infrastructure: minimum design<br>♦ Land uses: Mainly Vehicle-oriented |
| MPT | ♦ Car movement: signalized junctions<br>♦ Speed: up to 60-70km/h<br>♦ On-street parking: prohibited<br>♦ Public transport: tram or BRT<br>♦ Cycling infrastructure: separate infrastructure<br>♦ Pedestrian infrastructure: moderate design<br>♦ Land uses: Mainly human-oriented |
| MSM | ♦ Car movement: Signalized or marked junctions<br>♦ Speed: up to 40km/h<br>♦ On-street parking: under specific circumstances<br>♦ Public transport: Tram or BRT<br>♦ Cycling infrastructure: Separate or roadway infrastructure<br>♦ Pedestrian infrastructure: Enhanced design<br>♦ Land uses: Human-oriented |
| CPT | ♦ Car movement: signalized junctions<br>♦ Speed: up to 50km/h<br>♦ On-street parking: mainly prohibited<br>♦ Public transport: tram or BRT or simple bus<br>♦ Cycling infrastructure: separate or roadway infrastructure<br>♦ Pedestrian infrastructure: moderate or enhanced design<br>♦ Land uses: Mainly human-oriented |
| CSM | ♦ Car movement: signalized or marked junctions<br>♦ Speed: up to 30-40km/h<br>♦ On-street parking: under specific circumstances<br>♦ Public transport: tram or BRT or simple bus<br>♦ Cycling infrastructure: separate or roadway infrastructure<br>♦ Pedestrian infrastructure: enhanced design<br>♦ Land uses: human-oriented |

addressed properly in the specific extent of the paper. Of course, there could be more alternatives in future studies.

As we described the existing literature seems to have dealt with various cases of MCA concerning transport and urban planning issues. However, there is no relevant literature about the use of MCA in the determination of road hierarchy or street classification. Therefore, this very research attempts to fill in this gap, by introducing a case study in the metropolitan area of Athens. It is essential to spread the use of MCA in transport studies, because it contributes significantly to the evaluation of the proposals, thus increasing their efficiency and feasibility. A strategic road network which has been evaluated and chosen among different formulation alternatives can be more cohesive and distinct. Of course, we should note that the current research does not address new approaches on MCA, but instead it focuses on the use of existing methods, in order to boost the existing planning practice, which mainly in Greece, is based on conventional and one-fold solutions.

Regarding the methodological process for the construction of the strategic road network, it should be mentioned that two key aspects are utilized; a) connectivity, which implies the network edges' property for linking major central areas and b) continuity among all strategic routes, not addressed only to motor vehicles but to all modes (e.g. walking, cycling, micromobility and public transport). Additionally, the proposed process, determines multiple ring road zones that have the potential to decrease car penetration and at the same time to facilitate the prioritization of sustainable modes. Moreover, the methodological framework demonstrates key characteristics concerning each road network category that are able to connect planning and implementation procedures.

As applied in the case of Athens, the proposed method is expected to result in a comprehensive and readable strategic network, an increase of sustainable modes of transport such as walking, cycling and public transport, environmental protection through the reduction of GHG emissions, air pollutants and energy consumption as well as enhancement of urban vitality and a better level of accessibility for all. Furthermore, it is striking that the proposed network has the potential to achieve significant reductions in traffic congestion. Of course, all of the above should be tested carefully in future studies.

Moreover, this research is definitely associated with traffic safety issues, since it deals with the organization of the road network. Tellingly, the paper contributes significantly to the improvement of traffic safety level in the study area. First of all, the creation of ring road zones reduces through movements, thus decreasing the exposure in the city centers. Moreover, the regeneration and redesign of arterials through a) construction of roundabouts in case of serious movement conflicts, b) widening of sidewalks or other pedestrian oriented interventions, c) construction of cycle tracks, when the coexistence with cars in cycle lanes seems dangerous, d) signaling and e) public transport exclusive lanes (tram or buses) is expected to reduce accidents' risk i.e. probability of traffic accident occurrence. Furthermore, the reduction of speed limits will deal effectively with the severity of the accidents.

This research has significant value for urban and transportation planning since it deals with the fundamental issue of street classification. We developed a structured and coherent method which could serve as a decision support tool for policymakers and planners. It could be easily replicated to other cities with similar characteristics as

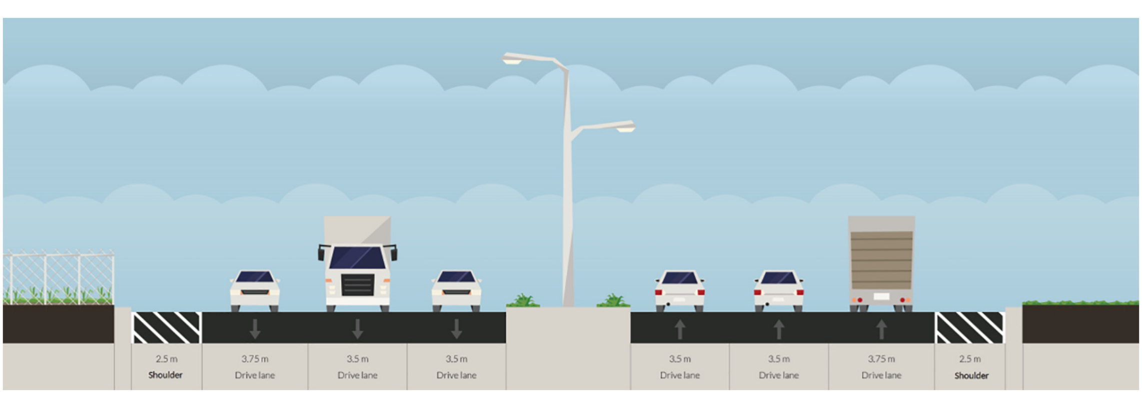


**Fig. 9.** Type: RC (Width: 32 m).


**Fig. 10.** Type: MC (Width: 30 m).


**Fig. 11.** Type: MPT (Width: 32 m).


**Fig. 12.** Type: MSM (Width: 30 m).


**Fig. 13.** Type: CPT (Width: 25 m).


**Fig. 14.** Type: CSM (Width: 24 m).

well, especially with radial-centric road network. In addition, the approach adopted could affect the existing formal/institutionalised urban and transport planning practices.

Road network hierarchy is a broad issue that cannot be entirely discussed in this research. This certain paper concentrates its research interest on the metropolitan scale, thus exploring ways to determine the strategic network of the city. The method proposed does not deal with streets belonging to categories with municipal or local importance since they demand different and more specific approaches. For this reason, a crucial step that can extend this research, is the conceptualization and development of a method addressing local spatial level e.g. municipality or neighborhoods clusters. Such a research would formulate a classification strategy determining collectors or urban boulevards, traffic calmed streets, pedestrian routes, etc. Another path could be to create an evaluation framework for assessing the quality and the exact impacts of the proposed classification. Furthermore, one more essential advance of the method proposed would be the integration of further transport modes (i.e. metro or suburban rail system). Future research could also address the construction of new road segments in order to compose the new strategic network of a city. In addition, new scientific attempts could utilize different methods of evaluating the various classification alternatives, in order to produce better results. What is more, the use of more data-driven and innovative tools and methods has the potential to advance even more the proposed method. Finally, the utilization of a wide spectrum of new data sources (e.g. crowdsensing, questionnaire surveys, secondary mobility and activity data, etc.) would also be a substantial contribution.

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