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Socioeconomic Attributes in the Topology of the Intercity Road Network in Greece

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Abstract: This paper studies the Greek interregional road network (GRN) using network, statistical, and empirical analysis. The research aims to extract the socioeconomic information embedded in the topology of the GRN and to interpret to what extent this network serves and promotes regional development. The analysis reveals that the topology of the GRN is subject to spatial constraints, relevant to the theoretical model of the lattice network but with some geographically dispersed hub-and-spoke modules. It also reveals that the network structure is described by an adjusted gravitational pattern, with priority given to serving regions according to their population and, secondarily, geographical remoteness, and that its association with regional variables outlines an elementary pattern of "axial development through road connectivity". Interesting contrasts between metropolitan and non-metropolitan (excluding Attica and Thessaloniki) cases emerge from the study. Overall, this paper highlights the effectiveness of complex network analysis in modeling spatial-economic and, in particular, transportation networks and promotes the network paradigm in transportation research.

Keywords: road transport; regional development; complex networks; spatial networks; pattern recognition

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1. Introduction

Road networks are the most widespread and accessible land transport networks, due to the prevalence of the car as a private transport [1,2]. Road networks are a key infrastructure for transporting at all geographical levels, regarding network length, traffic, and number of users [3–5]. Considering that transport is an aspect of human communication subject to unavoidable spatial constraints [2,4,6], the structure and form that land transportation networks take over time reflect the historical and socioeconomic needs of human communication but also depend on the occasional possibilities of society to overcome spatial constraints [7,8]. For example, the structure, geometry, and general form of road networks differ today than in the past, due to the evolution of transport modes, road surfaces, and their respective technologies, as well as to changes in the socioeconomic importance of the cities they connect [2,9].

From the literature [2,3,5,6], we know that roads play a key role in regional and economic development. The study of the individual historical, socioeconomic, and spatial (geographical) conditions surrounding a transport network contributes to a deeper knowledge of its structure and functionality [5], facilitating their modeling process [10]. On the other hand, given that the construction and general creation of transport infrastructure is a time-consuming and costly process [2,5,6,11], it can be argued that the form and topology of transport networks decisively influence the further development of the transport sector, both at national and interregional levels [3,5,12]. That is, in contrast to the case of immaterial (e.g., social) networks [13], transport networks lack the flexibility to timely adapt and restructure their geometry and topology due to their surrounding socioeconomic forces, thus resulting in a slow adaptation to current developments [14].

In economic terms, transport promotes trade, communication, the tourism industry, scientific cooperation, and cultural interaction [2]. From this perspective, the study of road transport networks becomes multivariable [5], as a plethora of variables and parameters are taken into account, covering all aspects of social and economic activity, such as congestion, accessibility, geographical scale, technological progress, sectorial structure, time, utility, and demographics. From an epistemological viewpoint, the study of road networks has attracted the interest of researchers from various disciplines and fields, such as transportation planners, urban planners, economists, regionalists, geographers, architects, environmental engineers, and even physicists and mathematicians [9,15]. This multidisciplinary research further highlights the interdisciplinary nature of the study of transport networks and the need to develop integrative research approaches [9]. From a theoretical perspective, the importance of transport networks in economic development emerges axiomatically [5,11]. Referring to the theories of regional science and economic geography, it can be effortlessly concluded that the ability to overcome spatial constraints is intertwined with transport networks and is a key driver of economic and regional development. For example, in the light of the neoclassical approach, it can be argued that the transport capacity provided by transport networks is the condition for the conduct of international and interregional trade [16], interregional migration, and generally the mobility of the production factor "labor" [17,18], activating in the long run the mechanism of convergence of regional inequalities. On the other hand, agglomeration theories [19,20] and the new economic geography [21,22] attribute to the transport capacity of regions the degree of centripetal or centrifugal forces development and, consequently, the dynamics of the emergence of economies of agglomeration and scale and the development of growth poles, which lead to differential development and the emergence of social and economic inequalities in geographical space. In this context, transport networks are a key pillar of development, and their study contributes to improving the efficiency and safety of transport; the formulation of policies and strategies for spatial planning and economic development; and sustainable development and balanced growth [5,11].

In Greece, land transport is a key component of the national and regional economy and a decisive development factor [11,14,23] due to geomorphological and geopolitical reasons. The country's geopolitical position is decisive for the development of trade and related activities. At the same time, its rich (mountainous and maritime) geomorphology places constraints on the development of land transport, favoring the emergence of alternative, competitive modes of transport. The study of the Greek intercity road network can provide insights into improving infrastructure, increasing accessibility, and enhancing connectivity between different parts of the country. To the extent that accessibility is symbiotically related to regional development [2,3,5,11], the study of Greece's road infrastructure network can contribute to the development of policies aimed at increasing economic activity and facilitating the transport of goods and services, thus reducing regional disparities and strengthening the national and regional economies. Moreover, the case of Greece is of particular interest also from the viewpoint of economies of scale, as the country is subject to a distinct hierarchical structure of population concentrations in the capital city of Athens and the co-capital city of Thessaloniki. These two capital cities are the two largest in Greece, accounting for more than 50% of the country's population (almost 4 and 1.5 million citizens, respectively) and constituting major poles of economic development [11,14,23]. Athens, as the capital, hosts the majority of central administrative services and economic activities [11].

Thessaloniki is also an important economic hub that plays a central role in the northern part of the country [11]. The increased demand for transportation in these two urban mega areas puts the study of their road networks on a different scale, not only because of their importance in the national economy but also because of their significance through their hub participation in international transport axes networks [11,23]. The two cities also face particular spatial and socioeconomic challenges that affect the development and operation of their road networks, both locally and nationally [24]. For example, Athens is the center of a complex and historic web of intermodal (road, coastal, and air) transport infrastructure [11,25,26], facing traffic management and congestion challenges. On the other hand, Thessaloniki is in a strategic geographical position for the Balkan region [27], making it a prominent center for transit trade.

In this context, this paper studies the nationwide intercity road transportation network in Greece, the Greek Road Network (GRN), aiming to extract the socioeconomic information associated with its topology and geometry and to get insights into its dynamics for sustainable regional economic development. Based on the theoretical background of economic geography and network science, this research first argues that transportation networks' connectivity is stimulated by the underlying forces inducing spatial demand, overcoming geomorphological constraints and spatial costs, and driving into economic agglomerations. Also, it conceives network connectivity as a transportation infrastructure capital serving these forces driving regional and economic development. This double reading suggests a "hen-and-egg dilemma" defining the symbiotic relationship between network connectivity and the socioeconomic configuration of the transportation market, on which this paper aims to shed light. To do so, we model the GRN into an undirected and spatially weighted graph using complex network analysis [4,28,29]. This modeling allows the incorporation of structural and functional information within a single quantitative (matrix-based) model. Next, this paper applies statistical techniques and empirical analysis to the topological variables computed on the GRN graph model and to a set of socioeconomic NUTS III variables to detect the level of association between network topology and economic structure and functionality of this road network. The analysis distinguishes the cases of Athens and Thessaloniki by including and excluding their road networks (or merging them into a single node each) from the GRN dataset to capture the level of their contribution in the transportation dynamics of economies of scale. The overall approach aspires to provide methodological guidelines in future transportation research, which faces the challenges of managing economies of scale, economic efficiency, and the adoption of sustainable development imperatives towards addressing spatial asymmetries and promoting regional development.

The remainder of this paper is organized as follows: Section 2 describes the methodological framework of the study, the network modeling, and the analysis methods used. Section 3 presents the results of the analysis; Section 4 provides a discussion in the light of transportation economics, geography, and policy; and, finally, in Section 5, conclusions are given.

2. Methodological Framework

The study of the Greek road transport network (GRN) and its spatial and topological analysis builds on a complex methodological framework, which integrates different methods and tools from complex network analysis and statistical-econometric analysis. The GRN is analyzed using graph modeling, as well as topological and economic indicators, to draw conclusions about the structure and functionality of the road infrastructure network representing the transport market in Greece. The methodological framework in this paper consists of four distinct parts (graph modeling, network analysis, empirical analysis, and discussion and conclusion making) and is illustrated diagrammatically in the flow chart of Figure 1. As it can be observed, the methodological framework consists of four parts. The first one (Figure 1; #1) concerns the modeling part, according to which the real-world transportation road network in Greece is modeled on a graph. For capturing differences in scale due to the participation of the metropolitan regions of Attica and Thessaloniki, in this part, two GRN versions are taken into account; the first includes the total available road network information, whereas the second one excludes the sub-networks of these two metropolitan regions. The second part (Figure 1; #2) of the methodological framework includes a network analysis of the GRN, consisting of the calculation of complex network analysis measures (node degree, edge and path length, network diameter, graph density, clustering coefficient, and modularity) and a pattern recognition approach, building on a combination of pattern recognition methods (such as the examination of the degree distribution, topological layouts, sparsity plots, and the spatial distribution of the GRN). Next, in the third part (Figure 1; #3) of the methodological framework, an empirical analysis applies. The analysis is considered empirical because, beyond the topological variables computed from the GRN graph model, it also applies to a set of socioeconomic variables. The available socioeconomic variables are composed of interregional secondary data capturing transport infrastructure, socioeconomic, and tourism aspects of the GRN transport economy. Technically, the empirical analysis is a correlation-based analysis, as it builds on the correlation matrix, including the Pearson's correlation coefficients computed between all possible pairs of the available NUTS III variables. To detect differences in the network structure due to the economies of scale related to the high urbanization levels of Attica and Thessaloniki, the correlation analysis applies to a double version of the dataset. In the first case, the dataset includes the total of entries corresponding to the NUTS III Greek regions, thus configuring variables of length $n_1 = 51$. In the second case, the entries of Attica and Thessaloniki are removed from the dataset, thus configuring non-metropolitan variables of length $n_2 = 49$. Within this context, the correlation analysis results in the configuration of two versions of 29×29 correlation matrices, the first one computed on the total version ($n_1 = 51$) and the second one on the metropolitan version ($n_2 = 49$) of the 29 available variables. However, beyond the correlation approach, the empirical analysis includes (i) a community detection analysis applied to the graph models associated with the total ($n_1 = 51$) and non-metropolitan ($n_2 = 49$) correlation matrices and (ii) a chi-square test examining the resulting community membership of the total ($n_1 = 51$) and non-metropolitan ($n_2 = 49$) cases. As a correlation matrix converts by default to a complete graph model (where all nodes are mutually connected), to avoid dealing with this trivial topology, the analysis considers only significant ($p \leq 0.10$) correlation coefficients in the computations, and the other cases are set to zero. The community detection analysis that further applies to the correlation graph (see Figure 1) allows grouping the source variables into communities with strongly correlated members within. This process can be seen as a non-parametric econometric approach taking into account structural relevance due to the correlation network's connectivity, namely beyond data variability on which typical non-parametric econometric approaches usually build. Further, the cross-tabulation and chi-square analysis apply to examine the level of association between the variables' membership generated by the community detection applied to the total ($n_1 = 51$) and non-metropolitan ($n_2 = 49$) cases. This approach further examines the structural association of the available empirical variables due to the removal of the metropolitan Greek regions from the interregional transportation market. Finally, the fourth part (Figure 1; #4) of the methodological framework discusses the findings of the research under the transportation research and economics and regional science perspectives.

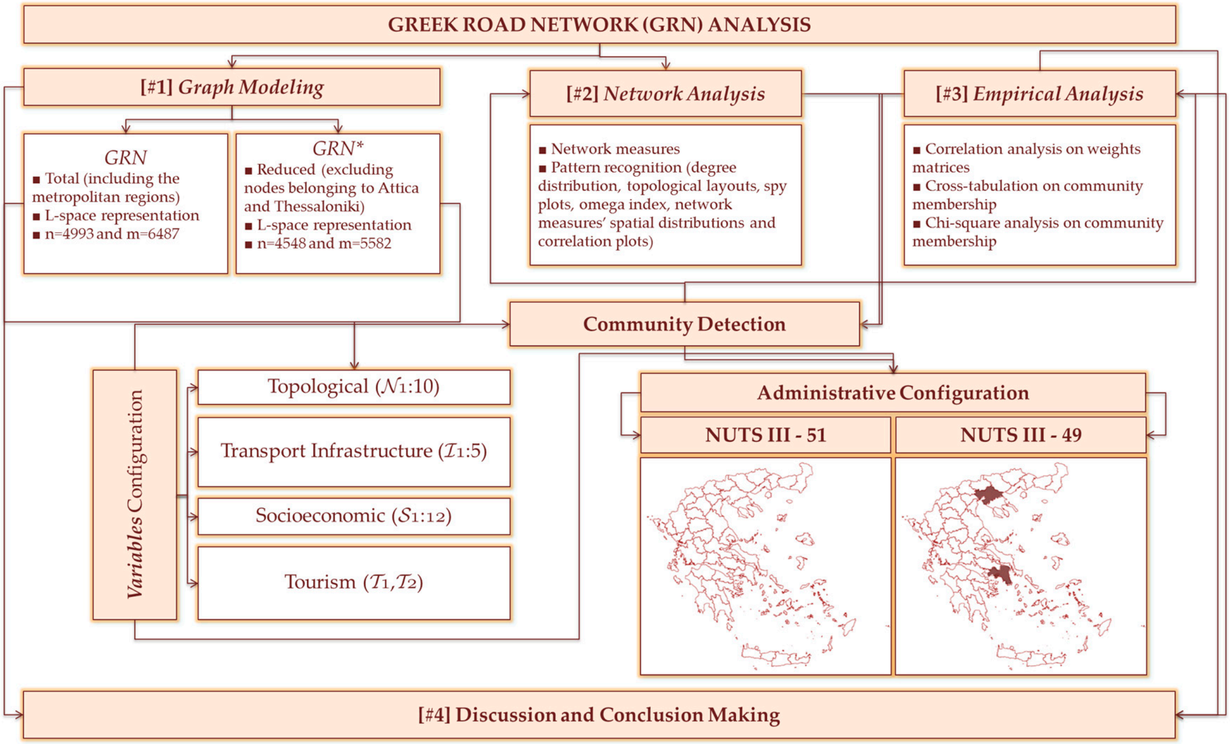


Figure 1. Conceptual diagram of the methodological framework of the study (the * represents the case of excluding nodes belonging to Attica and Thessaloniki).

The following subsections describe the parts composing the methodological framework of this research in more detail.

2.1. Graph Modeling

The GRN is a road network connecting geographical locations, settlements, and cities in Greece. To run the analysis, the GRN is modeled in L-space representation [4] as an undirected graph $G(V,E)$, whose nodes V correspond to road intersections and edges E to unidirectional road routes. In the model, the positions of the nodes correspond to the exact geographical coordinates of the geographical positions of the intersections, but the lengths of the edges are represented as straight segments and not in their natural (to scale) form. This mapping is a common practice in the study of urban road systems [30,31], but is rarely found in the description of cases of national road networks, apparently due to the lack of availability of data for such a level of scale [9]. The data used for the GRN construction refer to the primary, secondary, and tertiary national road network, along with the primary and secondary provincial road networks of Greece, as they are defined in the National Act PD.401/93. The database has been prepared by the Directorate of Road Project Studies (ΔMEO) of the Ministry of Finance and was available in shapefile format by the Hellenic Organization for Cadastral Surveys and Cartography [32]. Within this context, the GRN was constructed as an undirected graph $G(V,E)$, with spatial weights, consisting of n = 4993 nodes (vertices) and m = 6487 edges (links). However, it is a disconnected network [33], having as components the sub-networks of the country's island clusters, together with some cases of isolated road segments located on the mainland. Further, the GRN is a non-directed graph [4,29], where edges represent bidirectional pathways (lanes) of the road network and a spatial network weighted by the information of the physical road segment lengths (measured in km).

2.2. Network Analysis

The GRN network analysis is performed using different measures of network topology and geometry, which provide information on its structural and functional characteristics. The measures chosen in this paper are graph density (ρ); network diameter (dG); node degree (k) and strength (s); closeness centrality (CC); betweenness centrality (CB); local and global clustering coefficient (C); modularity (Q); and average path length ($\langle l \rangle$) and are extracted from the relevant literature [4,29,33,34]. Definitions and details of the network measures used in this paper are shown in Table A1 in the Appendix A. From a methodological viewpoint, graph density [29] is chosen because it provides information about the relative capacity of the network in terms of the number of possible connections in the graph, as it expresses the probability of meeting a connection between two random nodes in the network. Network diameter [29] is chosen because it contains information about the extent and spatial resistance in the network, as it represents the longest and shortest path in the network. Node degree [4,29] is the most popularly used measure in complex network analysis and expresses the average communication potential of the network nodes. Next, spatial strength, or spatially weighted node degree [4] is chosen in this study due to its ability to account for the connectivity and spatial resistance at a network node. Closeness centrality [33], is chosen due to its ability to measure the accessibility of a node based on the average distance from all nodes in the network. Betweenness centrality [33] becomes a particularly useful centrality measure as it captures the degree of mediation of a node in the network, thus highlighting the locations where the network topology submits to the greatest traffic load. The clustering coefficient [29] is chosen because of its ability to capture the degree of "circularity" of traffic flow at a node, namely the degree of integration of connectivity at the neighborhood level or, alternatively, the degree of node regionalization. Finally, the modularity [34,35] underpins much of the analysis in this paper, as it expresses the ability of the network to be divided into communities. This measure is particularly useful because it is able to reveal the community structure and thus the local markets that are formed in the network based on its topology and functionality.

In addition, the analysis is performed using the city organization index (r_n) proposed by [36], as well as the omega index (ω) proposed by [37] for the detection of the small-world property. On the one hand, the city organization index [36] measures the level of city organization based on the concentration of the degree distribution of nodes in the 3–4 degree values.

$$r_n = \frac{n(1) + n(3)}{\sum_{k \neq 2} n(k)} \tag{1}$$

where $n(k)$ expresses the number of nodes that have a degree equal to k. Low scores of this index indicate that an urban road system corresponds to a well-organized pattern, while scores close to one indicate the existence of many dead ends and imperfect intersections, which reflects the lack of planning of the urban transportation system. Although this index is developed and is commonly used for intra-urban analysis, in this paper, we apply it to the interregional GRN aiming to get insights into the level of organization of the road network in terms of square tiling. In terms of interpretation, a well-organized pattern ($r_n \to 0$) in the GRN can provide insights into the existence of perfect competition dynamics in the geographical space resulting in a regular lattice's symmetry. Conversely, an unorganized pattern ($r_n \to 1$) may interpret a lack of planning and induce the existence of spatial inequalities in the network structure.

On the other hand, the omega index [37] is used to detect the small-world property by comparing the average degree of clustering ($\langle c \rangle$) and the average path length ($\langle l \rangle$) of the network with the average path length of an equivalent random graph ($\langle l \rangle_{rand}$) and the average clustering of an equivalent lattice graph of the same degree distribution, according to the relation:

$$\omega = \left(\frac{\langle l \rangle_{rand}}{\langle l \rangle} \right) - \left(\frac{\langle c \rangle}{\langle c \rangle_{latt}} \right) \quad (2)$$

Values of the ω-index close to zero illustrate the small-world property; positive values indicate characteristics of a random-like network, while negative values indicate characteristics of a lattice-like one. The computations of the null models are performed using the randomization algorithm of [38] and the latticization algorithm of [39]. Although, theoretically, the small-world property is tested on an available graph family, when it is detected that it does not grow faster than logarithmically as the number of nodes tends to infinity [40], in an empirical context (where no family of graphs associated with an empirical network is usually available), the ω-index computation provides a satisfactory approximation. Overall, the analysis of [37] for small-world property detection is chosen in this paper because of the theoretical importance of the random, lattice, and small-world network topologies from both a traffic engineering and spatial planning perspective. In particular, randomness in transport systems expresses an absence of transport planning that can lead to congestion phenomena and generally increased entropy that implies operational costs and the need to redefine the network topology with large-scale transport projects [2,8,23]. Further, the small-world property witnesses the existence of targeted shortcuts development, expressing trends of causality in a network structure. On the other hand, a lattice model expresses the existence of fully equivalent relationships in geographical space, in terms of location attractiveness and spatial demand [2,8], associated with a centrifugal mechanism for regional markets' development, as described in [22] new economic geography.

2.3. Empirical Analysis

This part of the analysis aims to detect the level of association between the topological attributes of the GRN and some of its major socioeconomic characteristics. To do so, this paper applies a correlation analysis to a set of road network infrastructure, economic, and tourism variables, which are geographically defined on the NUTS III scale. The conversion of the topological information at the regional (NUTS III) level was necessary, as no secondary socioeconomic information is available at the physical reference scale (infrastructure intersections) of the GRN to serve the scope of this research. The variables participating in the correlation analysis are shown in Table A2 in the Appendix A.

In particular, the variables participating in the analysis are divided into four main categories: (1) road network topology variables (*N*), (2) transport infrastructure variables (*I*), (3) socioeconomic variables (*S*), and (4) tourism variables (*T*). The road network topology variables (*N*) are considered critical to understanding the structure and functionality of the GRN. The number of nodes (N_1) in each regional sub-network lists the important intersections, and the number of edges (N_2) lists the road segments connecting them. The average node degree (N_3) expresses the density of node connections in each regional sub-network, where higher values indicate higher spatial concentrations following agglomeration theories [19,20,41], while the average spatial strength (N_4) combines distances with connectivity, thus providing a more complete picture of the value of each connection in terms of its dispersion in geographic space. The network diameter (N_5), which represents the largest shortest distance between two nodes, provides information about the overall network dimension, while the graph density (N_6) indicates the capacity of network connections. Modularity (N_7) analyzes the tendency of each regional sub-network to be divided into communities and can provide structural information about the configuration of GRN's regional markets in the context of the new economic geography [22]. On the other hand, the number of connected components (N_8) lists the disconnected transportation markets in the GRN regional sub-networks. Here, island counties are by default at a disadvantage compared to the others, as the development of road connections is generally a matter of the islands' land areas. Finally, the average clustering coefficient (N_9) reveals the flow circulation tendency on the regional sub-networks, while the average path length (N_{10}) provides insights into the overall accessibility of each regional sub-network, expressing the average spatial impedance to transport on the regional intercity system.

On the other hand, the transport infrastructure variables (*I*) focus on the geometrical and logistical aspects of the GRN at the regional level. The total road network length in each region (I_1) expresses the road network's area and coverage in a region, and in economic terms, represents the amount of sunk costs of road infrastructure [8] per region. Complementarily, road network density (I_2) expresses the degree of coverage of the region's road network per geographical area unit, providing an indication of the efficiency of the region's road network in terms of its geographical area (I_3), which in theoretical terms corresponds to the physical capital (as a productivity coefficient) available to the region [23]. The number of ports (I_4) and airports (I_5) in each region provides intermodal information, which is critical for the intensity of transport economic activity and the supply chain and can be interpreted in accordance with the complementarity or competitiveness (substitution) approach of transport [2,5] within a region.

Socioeconomic variables (*S*) are drawn from the wider literature on transport infrastructure, economics, and spatial development [2,5,6,10,42] to provide as complete a socioeconomic status of each region as possible. In this context, the region's population (S_1), on which a number of gravity and non-gravity models have been developed through time [2,20,23], is a key gravity variable of spatial economic systems and a key indicator for understanding the scale of economic activities in the region. On the other hand, the degree of urbanization (S_2) measures the intensity of concentration and urbanization economies [11,42] in a region, while the indirect (S_3) and direct (S_4) population potential measure access to economic activities and economic growth within and outside a region by population and spatial distances [23]. Then, regional GDP (S_5) and the share of primary (S_6), secondary (S_7), and tertiary (S_8) sectors provide information on the size of output by region and the sectorial structure of the regional economy [6,23], being predominantly a factor of the attractiveness of population concentrations and transport infrastructure development in the geographical space [2,14]. Further, drawing on the regional development theories of sectorial structure, regional dualism, endogenous growth, and knowledge economy [6,20,23], the variables: agribusiness investments (S_9); regional productivity dynamism (S_{10}); welfare index (S_{11}); and education level (S_{12}) are used to capture more specific information about the forms of productivity (e.g., partially inelastic, related to the agricultural sector; labor intensive, related to human capital and welfare; or knowledge intensive, related to the education level) and the life quality productivity offers to a region's social structure. Next, although they belong to the group of socioeconomic variables, this paper examines tourism variables (*T*) separately, focusing on the impact of tourism on the regional economies, due to the importance of tourism in the national economy of Greece [8,23]. The share of tourism in regional GDP (T_1) is considered to provide information on the contribution of the tourism industry to the local economy, and the tourism life cycle (TALC) coefficient to provide information on the regions' tourism carrying capacity and saturation, in the context of the symbiotic relationship between transport infrastructure and tourism demand in Greece [14,23].

This paper does not incorporate geomorphological variables in the analysis. To the extent that the relationship between geographical space and economic activities is symbiotic [43], this research argues that geomorphological constraints are interrelated to spatial demand emerging in geographical space, and thus it should not be conceived separately from socioeconomic variables. That is, to the extent that geomorphological variables either stimulate or constrain the emergence of urban and economic agglomerations, this paper assumes that geomorphological frictions are inherent in nearly all the socioeconomic variables included in the analysis. Consequently, since the incorporation of additional geomorphological information is considered unnecessary for this study, the empirical findings of the analysis are dependent on this underlying assumption. Studying this perspective in more detail may suggest avenues for further research. Further, in the configuration of the empirical variables, no traffic and road capacity (lanes per route) information is included due to data availability constraints. If this kind of information were available, then the graph model would be more representative of the GRN transportation market in terms of functionality, and further variables of node strength could be included in the analysis. This lack of data availability suggests an empirical constraint in the GRN analysis due to model specialization, as is also the case in the construction of every econometric model. However, this limitation does not affect the structural and topological aspects of the analysis, as the functional and capacity aspects of the GRN are taken into account in certain weighted network measures, which can be studied individually. As the only weighted aspect considered in this study is the kilometric distance of network edges, the GRN graph model should be interpreted as only including structural information, and its functional aspects would be detected through correlation analysis to the available (non-topological) socioeconomic attributes of the transportation market. In this context, correlation analysis is applied to the available variables, which are shown in detail in the Appendix A (Table A2), followed by community detection and a chi-square test of independence. In terms of mathematical notation, the empirical analysis can be expressed as follows:

$$CM|n_{i=1,2} = \{r_{xy}\} = \left\{ \frac{Cov(x,y)}{\sqrt{Var(x)} \cdot \sqrt{Var(y)}} \right\} = \left\{ \frac{Cov(x,y)}{\sigma_x \cdot \sigma_y} \right\} \quad (3)$$

where $CM|n_{i=1,2}$ is the correlation matrix produced by all pairs of variables x and y in Table A2; cov(x,y) is the covariance; and var(x), var(y) stand for the respective variances of variables x and y. Pearson's bivariate correlation analysis [44,45] is used to understand linear relationships between pairs of variables, which are collectively assigned in a 29×29 correlation matrix format. The analysis is performed in two phases: with ($CM_{n1=51}$) and without ($CM_{n1=49}$) the major economic centers in the regions of Attica and Thessaloniki. The purpose of this double approach is to identify differences in correlations that may arise due to the economies of scale of these two highly urbanized regions. In terms of variable length, the calculations are conducted at the NUTS III regional scale with $n_1 = 51$ and $n_2 = 49$ items. In the correlation analysis, the exclusion of these two metropolitan Greek regions from the GRN dataset cannot be considered an interfering (in structure) factor, as the non-metropolitan dataset ($n_2 = 49$) was created by removing the corresponding rows from the complete dataset ($n_1 = 51$), where all measures were computed without removing any network nodes. As long as the matrices of statistically significant ($p \leq 0.10$) correlations are considered adjacency matrices of graphs, it is possible to apply a community detection (meta)analysis to identify immanent correlation structures between the correlated variables. In mathematical terms, we can express the conversion of the correlation matrices to graph models as follows:

$$G(CM|n_{i=1,2}) = G(\{r_{\mathbf{xy}}\}) = G(V_i, E_i) \equiv CG(V_i, E_i) \quad (4)$$

where $G(V,E)$ is a graph model composed of the node set V and the edge set E; and the symbol CG stands for a correlation graph. In this context, the community detection of the CG can be expressed as a mathematical transformation of the form:

$$\begin{gathered}\mathbf{g}|\,n_{i=1,2} : CG(V_i, E_i) \to RG \subset \mathbb{R}^{1\times n_i} \\ \mathbf{g} = \{g_i\}\ s.t.\ \max\left\{ Q = \frac{\sum_{i,j}[A_{ij}-P_{ij}]\cdot\delta(g_i,g_j)}{2m} \right\}\end{gathered} \tag{5}$$

where $\mathbf{g}\,|\,n_{i=1,2}$ is the vector of community membership for the total (n_1 = 51) and non-metropolitan (n_2 = 49) cases; CG is the correlation graph; RG is the range set of $\mathbf{g}$; and Q is the modularity function (defined in Table A2). In practice, the resulting communities represent thematically homogeneous and strongly interrelated variables. The detection of communities is not influenced by the thematic classification of the available variables into the N, I, S, and T groups, as the correlation network is constructed from the correlation matrix produced by all possible pairs of variables (both within and between communities) in Table A2. Thus, the thematic classification serves primarily for conceptualization, organization, and perhaps improved interpretation, without compromising the generality of this process. In terms of execution, the optimization algorithm of [35] is used for community analysis, which is a greedy algorithm aiming to maximize the internal connectivity of communities while minimizing the between connectivity [34]. The analysis is applied to two different correlation matrices, one including the road infrastructure of the whole country and another one without the regions of Attica and Thessaloniki.

Finally, the results of the community detection are compared to assess the impact of metropolitan regions on the configuration of the Greek transport infrastructure market (and the consequent understanding of its underlying network structures) and to explore the similarity between variables. The comparison is conducted through the chi-square test of independence [46,47], which assesses whether there is a statistically significant relationship between two categorical variables. In addition, the symmetric Phi and Cramer's V measures [44] are computed, which assess the strength of the relationship between the variables, similar to Pearson's correlation coefficient for scalar cases. The results of the community detection with the statistical tests are evaluated in common to provide a comprehensive picture of the relationships between the variables and the importance of the topology and topology of transport infrastructure for regional and economic development.

3. Results

3.1. Network Measures

The analysis of the GRN network measures yields the results in Table 1, from which some interesting observations can be made. First, in terms of network structure and composition, although it does not include isolated nodes, the GRN is composed of (a=) 156 components. To the extent that the mainland road network in Greece composes one giant connected component, the remaining 155 components correspond to local road networks of Greek islands that were taken into account in the GRN modeling. This state of disconnectedness due to insular morphology provides avenues for further research into examining intermodal ways of connections to improve transport connectivity in Greece at the national scale. The maximum degree of node connectivity is (k_{max}=) 8, which is significantly lower compared to the corresponding level of 20 road connections in urban networks [4,30]. This result indicates that the regional network has fewer central nodes compared to urban networks, suggesting a less concentrated structure in the regional versus urban area.

Table 1. Results of the calculation of network measures for GRN.

Metric/Size	Symbol	Unit	Value				
			Total Network	Non-Metropolitan [(a)]	Change (%)	Non-Metropolitan [(b)]	Change (%)
Nodes	n	# [(c)]	4993	4548	−8.91%	4550	−8.87%
Edges	m	#	6487	5528	−14.78%	5575	−14.06%
Self-connections	$n(e_{ii} \in E)$	#	0	0	-	0	-
Isolated nodes	$n(k = 0)$	#	0	4	-	4	-
Connected components	α	#	156	164	5.13%	160	2.56%
Max node degree	$k_{\max}$	#	8	8	0.00%	33	312.50%
Min node degree	$k_{\min}$	#	1	0	−100.00%	0	−100.00%
Average node degree (binary)	$\langle k \rangle$	#	2.60	2.43	−6.54%	2.451	−5.73%
Average node degree (weighted)	$\langle k_w \rangle$	km	14.11	13.92	−1.35%	14.135	0.18%
Average edge length (weighted)	$\langle d(e_{ij}) \rangle$	km	5.39	5.73	6.31%	n/a	n/a [(d)]
Total edge length (weighted)	$\sum_{ij} d(e_{ij})$	km	35,860	31,708	−11.58%	n/a	n/a
Average path length (binary)	$\langle l \rangle$	#	46.75	36.59	−21.73%	41.638	−10.93%
Average path length weighted	$d(\langle l \rangle)$	km	247.52	210.05	−15.14%	n/a	n/a
Network diameter (binary)	$d_{\text{bin}}(\text{G})$	#	144	136	−5.56%	127	−11.81%
Network diameter (weighted)	$d_{\text{w}}(\text{G})$	km	993	782	−21.25%	n/a	n/a
Graph density (planar)	ρ_1	net [(e)]	0.433	0.401	−7.39%	0.409	−5.63%
Graph density (non-planar)	ρ_2	net	0.001	0.001	0.00%	0.001	0.00%
Clustering coefficient	C	net	0.042	0.045	7.14%	0.046	9.52%
Average clustering coefficient	$\langle C \rangle$	net	0.114	0.069	−39.47%	0.071	−37.72%
Modularity	Q	net	0.946	0.965	2.01%	0.962	1.69%

a. Excluding nodes belonging to Attica and Thessaloniki. b. Merging nodes belonging to Attica and Thessaloniki. c. Number of items. d. Not available. e. Dimensionless number.

In terms of connectivity, the average score of the node degree in the GRN is ($\langle k \rangle$=) 2.60, appearing similar to the corresponding level of 2.5 connections for urban networks [4,30]. This result describes a balance in the connectivity of road networks in urban and peri-urban areas, indicating that the GRN provides an adequate degree of connectivity, although its structure is less concentrated. The planar graph density of the GRN (ρ_1 = 0.433) indicates that the network occupies a significant proportion of its total planar capacity. However, in a non-planar context, the respective density is very low (ρ_2 = 0.001), indicating the potential of expanding it and increasing the GRN's carrying capacity.

In terms of connections' length and distance, the average strength ($\langle k_w \rangle$ = 14.11 km); average edge ($\langle d(e_{ij}) \rangle$ = 5.39 km) and path length ($\langle l \rangle$ = 46.75; $d(\langle l \rangle)$ = 247.52 km); total length ($\sum_{ij} d(e_{ij})$ = 35,860 km); and diameter ($d_{\text{bin}}(\text{G})$ = 144; $d_{\text{w}}(\text{G})$ = 993 km) provide information of the complex spatial impedance [8] to which movements within the GRN are subjected at different scales. In terms of clustering, the clustering coefficient (C) of the GRN is significantly higher than the corresponding level of a random network $1/n = 2{\cdot}10^{-4}$ [4], indicating that the network's growth mechanism is not subject to randomness but to causal magnification. The joint picture obtained from the distance and clustering measures is that the GRN is far from being considered a random network and appears more akin to a lattice-like network; as it is subject to network planarity constraints but is clearly differentiated from the pure theoretical lattice model [4], which would have an average path length of $\langle l \rangle_{\text{latt}}$ = 70.66 edges. Finally, GRN's modularity describes a high tendency of the network to divide into communities, suggesting that it follows a dispersed and separable traffic service pattern. Overall, the analysis provides evidence that the GRN is a regional network with fewer central nodes than urban networks, is described by a balanced degree of connectivity, has room for growth, and presents a diversified, non-centralized, structure that allows for the creation of regional communities.

Regarding the impact of metropolitan regions on the aforementioned analysis, the last four columns of Table 1 provide information on the variation of network measures resulting from the removal and merging (into a single node each) of the sub-networks of Attica and Thessaloniki. As can be observed, in all cases of the network measures except for the connecting components (+2.56%; +5.13%), average road segments kilometric distance (+6.31%), global clustering coefficient (+7.14%; +9.52%), and modularity (+1.69%; +2.01%); removing the effect of the two metropolitan regions on the country's road transport network leads to a loss of topological value of the order of (on average) 20% (from 0 to 100%). This reading leads to the conclusion that, for the most part, the effect of the two metropolitan regions causes "contraction trends" in the topological characteristics of the GRN. However, when interpreting the exceptions, we can observe that, with the removal of Attica and Thessaloniki, the GRN emerges more disconnected, remote, regionalized, and separable. Especially regarding connectedness, this is particularly evident in the "false" increase in the GRN's maximum degree (over 3×) due to the merging of the metropolitan sub-networks into a single node. Through these exceptions, it is possible to see that the two metropolitan regions in Greece function in a proportion of (on average) 5% as a 'link' in the national long-distance transport system of the country.

3.2. Pattern Recognition

As the analysis of the network measures reveals so far a perplexing topological and spatial structure of the Greek road network, this section proceeds to study the topological and spatial patterns that can be detected in the GRN. Starting from the study of the degree distribution shown in Figure 2, we observe that the GRN does not strictly follow the scale-free pattern, as its degree distribution fits only in an amount of 59.6% (based on the value R^2 = 0.569) to a power-law curve [4,28] with an exponent γ = 2.8. This result suggests that, while the GRN exhibits some characteristics of hierarchical organization, its actual structure is more limited and significantly influenced by geographical features.

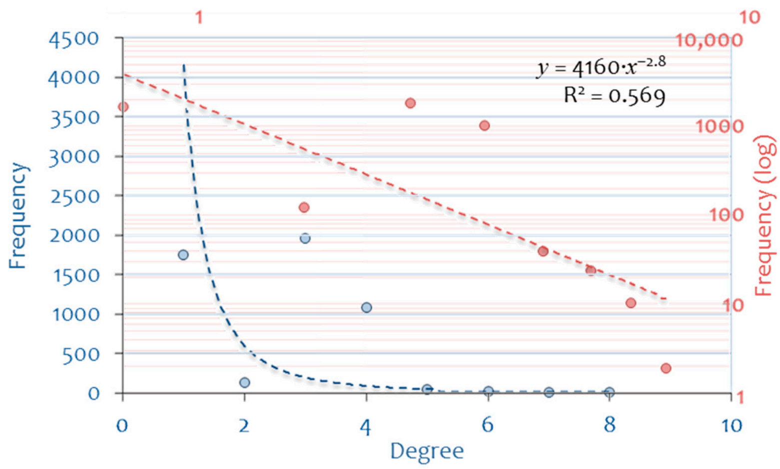


Figure 2. The GRN's degree distribution, left in metric and right in logarithmic scale.

The observation of the effects of spatial constraints in the GRN topology is also supported by the spy plot results, compared to equivalent (degree-distribution-equivalent random-like and lattice-like; node-equivalent small-world and scale-free) null models. As shown in Figure 3, the sparsity pattern of the GRN exhibits concentration around the main diagonal, indicating limited distant connections due to the spatial barriers implied by the distant locations (nodes are labeled by their geographical relevance) in the adjacency matrix. The similarities with the lattice-like and small-world null models support the view that the GRN combines elements of these two types of networks, adopting characteristics of homogeneity and, at the same time, causality to the extent that it supports spatial demand of intercity transport. This picture is further supported by the analysis of the city organization index ($r_{n,GRN}$ = 0.762), which suggests that the GRN does not approach an ideal Hippodamian urban organization plan [11] of regularity 4 (square lattice) but shows significant variations that express lags in spatial organization, according to [36].

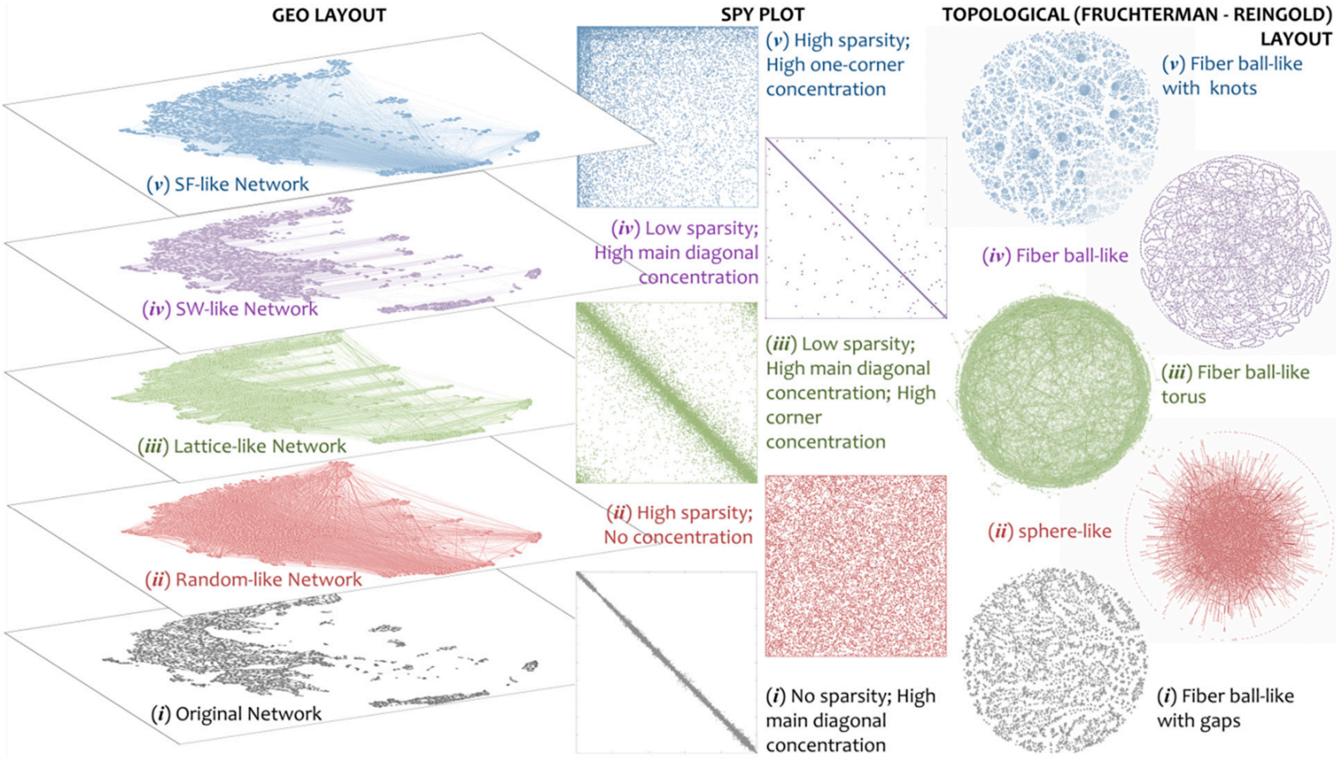


Figure 3. Spy plots of the adjacency matrices of (**i**) the GRN and (**ii**) a degree-distribution-equivalent random-like model; (**iii**) a degree-distribution-equivalent lattice-like model; (**iv**) a node-equivalent small-world (*SW*) model; and (**v**) a node-equivalent scale-free model.

Further, the spatial distributions of degree, betweenness, and closeness centrality, clustering coefficient, and spatial strength in Figure 4 reveal that the central areas in degree and betweenness centrality are typically either population or geographically significant or are associated with key national roadways. This observation confirms the influence of the main road infrastructure on the regional development of Greece, which follows a linear S-type pattern along the length of the eastern coastal national front [14]. In terms of node degree, we can observe that its spatial distribution (Figure 4i) appears quite asymmetric. However, the hub areas in the regions of Attica, Thessaloniki (central-north), and Achaea (west), which are the three most populated in Greece [23], appear quite distinct. Further, we can observe some hubs, located in the regions of Xanthi and Rhodope (north-east), Arta (central-west), and Euboea and Corinth (both near Attica), are not highly populated areas. Their privilege in degree is a result either of proximity to growth poles (as Athens and Thessaloniki are) or of location serving peripheral connectivity. In contrast to the degree, the spatial distribution of betweenness follows a more distinguishable pattern. As shown in Figure 4ii, central values in terms of betweenness are linearly distributed along the S-type motif, extending from the region of Corinth to Kavala that coincides with the major national road axis called PATHE (Patras–Athens–Thessaloniki–Evzonoi). This S-type configuration [14] defines a pattern of regional development based on linear sprawl driven by proximity to a high volume of transportation flows.

Next, the spatial distribution of closeness centrality (Figure 4iii) shows a strong correlation between geographic centrality and closeness, which has important implications for transport policy, as it suggests the influence of transport costs as a determinant of the emergence of spatial patterns, in line with the theoretical mechanisms described in previous sections [19,20,22,41]. Subsequently, clustering coefficient distribution, although asymmetric, reinforces the picture that areas with high clustering are usually associated with economic activities or growth points, as central clustering nodes are neighbors to the GRN (degree) hubs (see Figure 4iv). To the extent that clustering in graphs expresses the level of flow circulation [8], the high values may reveal regional markets and areas with significant economic or related activity. In GRN, such markets are composed of the regions Achaea–Elis–Arcadia; Attica–Boeotia–Euboea; Central Macedonia; and Thesprotia–Ioannina. This approach can provide further insights into whether it can be examined jointly with the method proposed by [24] for the detection of dipoles and polycentric functional areas, addressing avenues for further research. Relevant urban development theories [11,42] describe axial urban sprawl along intercity transportation corridors, which may stimulate the emergence of megalopolises (such as the case of the east coastal forehead of the USA). Loosely speaking, clustering layouts similar to those of Figure 4iv may provide useful insights into forecasting the dynamics of urban sprawl and thus are proposed as a topic of further research. Finally, the spatial distribution of spatial strength (Figure 4v) follows a complex pattern suggesting that central nodes are important for connectivity in both nearby and distant areas, which is consistent with the theories of [19,21,41] on the process of self-sustained spatial development of places and their transformation to growth poles. This part of the network analysis examining the spatial distributions of network topology measures may also generate variables to be included in a multi-objective optimization [48,49] analysis. In particular, each spatial distribution considered in Figure 4 illustrates the (numeric) distribution of a network variable (node degree, strength, clustering, betweenness, and closeness) in the geographical space, at the node scale. Within this context, any filtering of the values in each variable (for instance, one common filtering may regard the dichotomy into low/high values compared to the mean) can drive into a hierarchical classification of the network nodes and thus can discriminate nodes (and, successively, regions) in terms of importance to be further included in multi-objective optimization problem solving. This perspective, along with the potential to produce a joint hierarchical classification for the total network variable, suggests avenues of further research.

Finally, the modularity classification (the numeric community labels of network nodes) spatial distribution layout is shown in Figure 5. As it can be observed, community membership is mainly driven by geographical forces, namely members within a community are relevant in terms of proximity. This outcome is in line with empirical research describing that community structure in spatial networks is generally geographically defined [4,50,51], and cases of interest emerge when this rule breaks or there is a mismatch with physical or arbitrary barriers. To this extent, by overlaying the community structure of GRN with the NUTS II administrative division of Greece, we can observe a considerable coincidence between these two types of spatial clustering and organization. In this context, cases of interregional communities may provide insights into the detection of spatial partnerships for the development of dipoles or polycentric markets [24].

Overall, the GRN analysis highlights the importance of the impact of spatial constraints on the organizational structure and morphology of the network. The GRN exhibits characteristics that suggest limited application of scale-free and small-world patterns, with a stronger influence on local geography and lattice-like features. These results provide valuable information for understanding, modeling, designing, and improving the road network and may provide a basis for the formulation of development and transport policies.

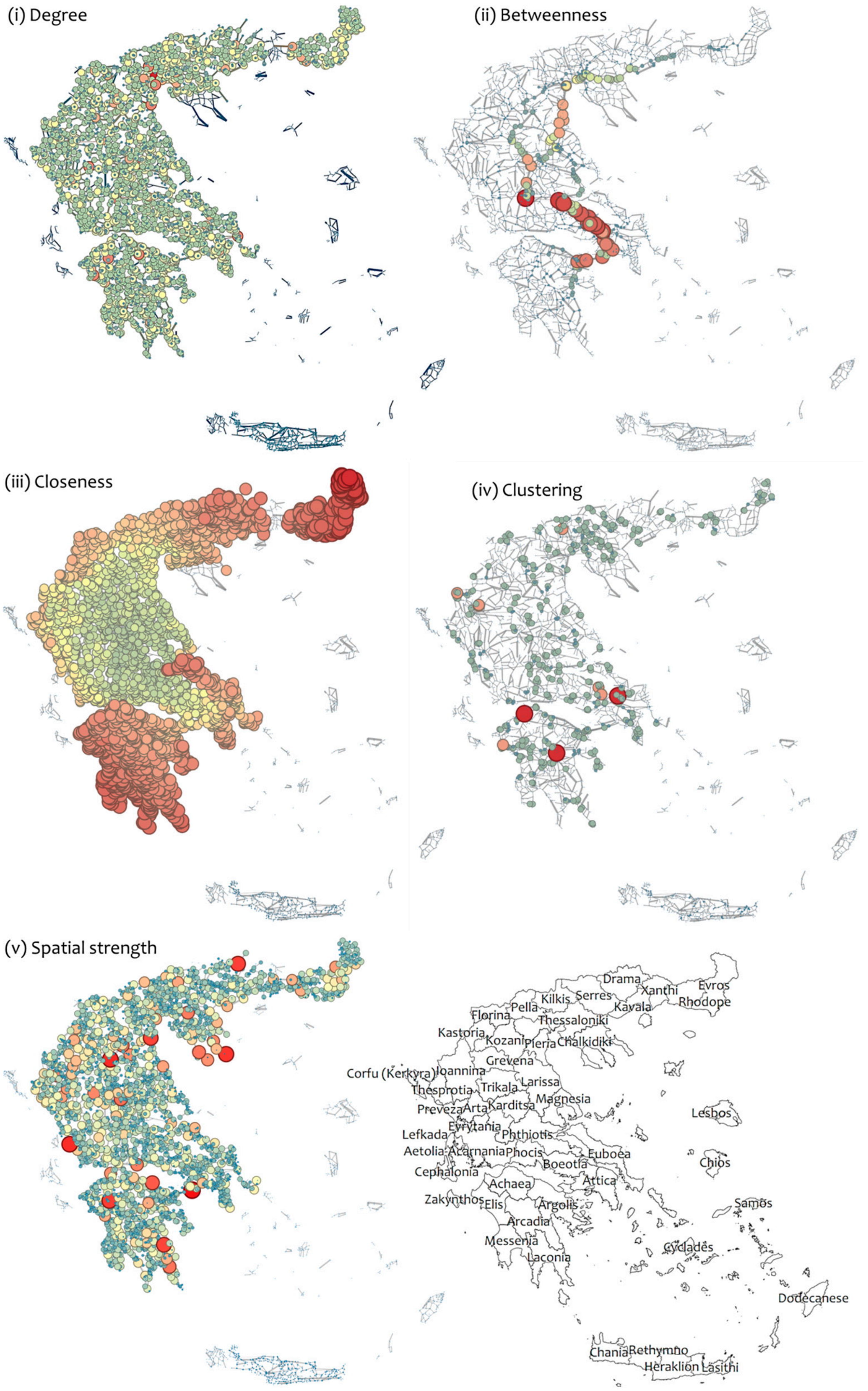


Figure 4. Spatial distribution of GRN's node: (**i**) degree; (**ii**) betweenness; (**iii**) closeness; (**iv**) clustering; and (**v**) spatial strength (for all cases except closeness, high scores are shown bigger and in red color, while low scores smaller and in blue; for closeness the color palette and node size is inversed).

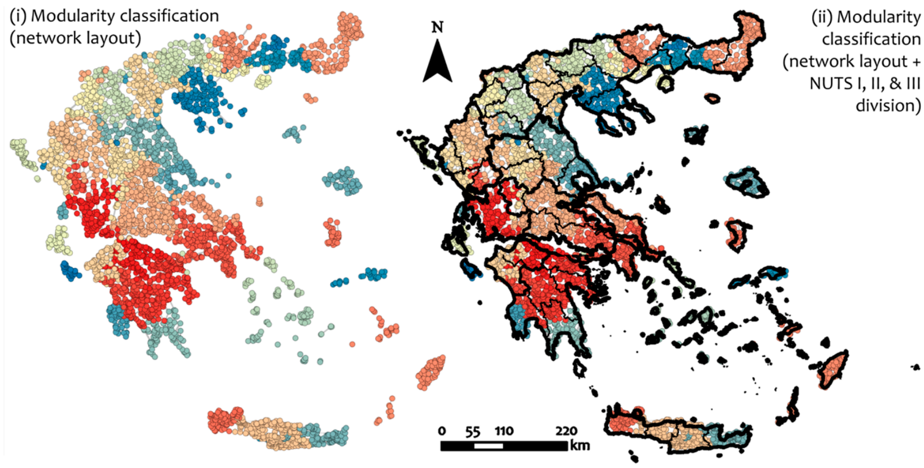


Figure 5. Spatial distribution of GRN's modularity classification into 199 communities (color similarity denotes membership in the same community).

3.3. Empirical Analysis

In the empirical analysis, the correlation matrices calculated on the variables in Table A2 for the cases of n_1 = 51 (including the metropolitan Attica and Thessaloniki) and n_2 = 49 NUTS III (excluding the metropolitan cases) are initially considered as weighted graphs, for each of which the community configuration is calculated, as shown in Figure 6. As it can be observed, the first modularity community (G_1) includes variables related to topological characteristics (size, connectivity, divisibility, and efficiency) of the road network, secondarily to road infrastructure characteristics (length and geographical area), and lastly to socioeconomic characteristics (primary sector's share in regional GDP) of the Greek transportation market. It is noteworthy that all variables in this community remain fixed both in the analysis with and without metropolitan regions. This stability suggests that the correlations between these variables are not significantly affected by the presence of the two urbanized regions in the Greek intercity transportation market. This observation allows us to define a core set of relationships between the topological, geographical, and socioeconomic characteristics of the GRN, which seems to be governed by the economic demand related to the primary sector, as the only socioeconomic variable involved is S_6. To the extent that demand due to primary sector activities is the "oldest" form of spatial demand [6,11,23], this result interprets that most topological characteristics of the road network have been shaped by primary developmental spatial dynamics. This finding is consistent with the findings in the preceding network analysis in this paper, which describe the prevalence of classical development patterns in shaping the GRN.

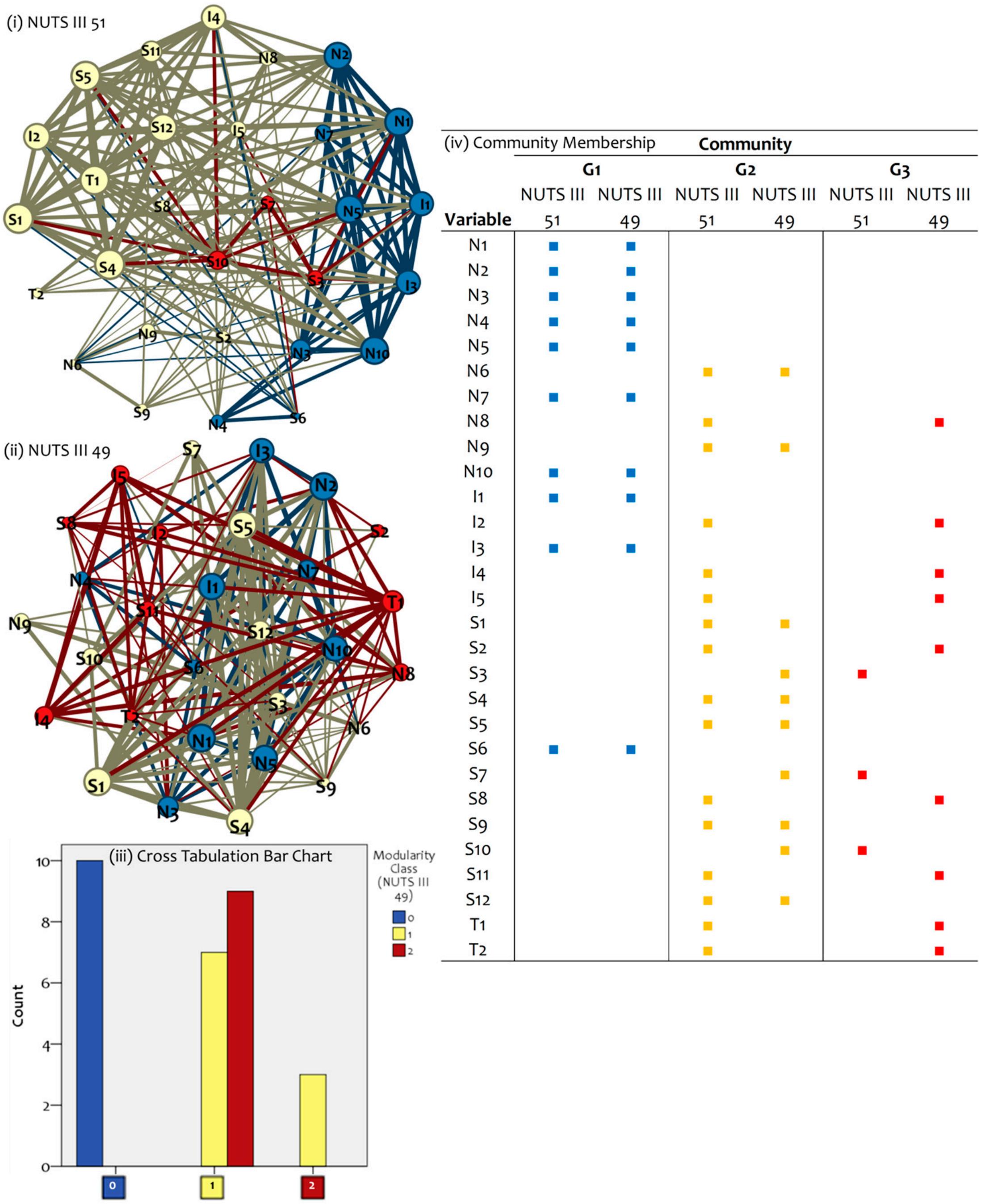
The second community includes variables related mainly to the socioeconomic characteristics of road infrastructure and secondarily to its geometric infrastructure and topological characteristics. Variables such as N_6 (graph density), N_9 (average clustering coefficient), S_1 (population), S_4 (direct population potential), S_5 (regional GDP), S_8 (tertiary sector share), S_9 (agro-industrial investments), and S_{12} (educational level) remain in the same community (G_2) in both analyses, developing a kernel of stable relationships between network density and clustering, on the one hand, and gravitational modulation, tertiary aggregation, investment expenditure in the primary sector, education level, and welfare, on the other. This stable presence consequently illustrates the stability of the relationships between these variables in terms of Attica's and Thessaloniki's contribution. Here, the presence of variables S_1 and S_4 in the core of the stable (fixed) relationships emerges as particularly interesting, as it expresses a deeper pattern of gravitational configuration of the density and clustering of the road network in Greece, which overcomes the demand for road transport due to the hub role of the metropolitan centers of Attica and Thessaloniki. However, some variables change community when Attica and Thessaloniki are excluded. For example, the variable I_2 "moves" from community G_2 to G_3, whereas S_7 "moves" from G_3 to G_2. These changes imply that road density and the secondary sector share are related to the geographical and economic specificities of Attica and Thessaloniki, where population density and industrial activities are higher compared to other regions [11,26]. Further, the changes in community membership captured for the variables N_8 (connected components), I_4 (number of ports), and I_5 (number of airports), which "move" from community G_2 to G_3, may be similarly insightful over the gravitational forces applied to the GRN. In particular, these changes may imply that maritime and air transport infrastructures relate to the demand for land connectivity through scale effects, a fact that can be theoretically interpreted in the context of their functionality as gateways. Finally, the third community includes variables mainly related to socioeconomic and infrastructure characteristics of the GRN, but in this community, no core of stable relationships between the analysis with 51 and 49 regions can be detected. This finding illustrates the turbulent role that Attica and Thessaloniki play in the equilibrium of the relationships of the variables involved in the third group of variables. For example, variables I_2 (road density); S_8 (tertiary sector share); and S_{11} (level of welfare) move from community G_2 to G_3. These movements illustrate that these variables are influenced by the presence of Attica and Thessaloniki, where the tertiary sector (services) and social structures are more developed [11,26] compared to other regions.

In an attempt to comprehensively quantify the effect of Attica and Thessaloniki on the structural relationship of the variables in Table A2, we calculate (i) the correlation coefficient between the correlation tables with 51 and 49 prefectures and (ii) the level of association between the composition of modularity communities with 51 and 49 prefectures. The results of the analysis are shown in Table 2. First, from the results of the chi-square test, we can observe that there is a statistically significant correlation between community membership calculated with 51 and 49 regions. This significant association is the result of the "stable cores" (members who do not change community), as previously described.

Table 2. Results of the empirical (correlation and chi-square test) analysis.

i. Pearson's Correlation r_{XY} [a]			
Metric		**Value**	**Sig.**
Pearson's rho		0.811	0.000
N		29	
ii. Chi-Square Test of Association [b]			
Metric	**Value**	**df**	**Asymp. Sig. (2-Sided)**
Pearson chi-square	33.894 [c]	4	0.000
Likelihood ratio	41.720	4	0.000
Linear-by-linear association	12.431	1	0.000
No of valid cases	29		
iii. Symmetric Measures [b,d,e]			
Metric		**Value**	**Approx. Sig.**
Nominal by nominal	Phi	1.081	0.000
	Cramer's V	0.764	0.000
N of Valid Cases		29	

a. X = the 29 × 29 Table 2's correlation matrix, computed on N = 51 NUTS III regions; Y = the 29 × 29 Table 2's correlation matrix, computed on N = 49 NUTS III regions (excluding Attica and Thessaloniki). b. X = the modularity classification of Table 2's correlation matrix, computed on N = 51 NUTS III regions; Y = the modularity classification of Table 2's correlation matrix, computed on N = 49 NUTS III regions (excluding Attica and Thessaloniki). c. Seven cells (77.8%) have an expected count of less than 5. The minimum expected count is 0.93. d. Not assuming the null hypothesis. e. Using the asymptotic standard error assuming the null hypothesis.



Variable	G1 NUTS III 51	G1 NUTS III 49	G2 NUTS III 51	G2 NUTS III 49	G3 NUTS III 51	G3 NUTS III 49
N1	■	■				
N2	■	■				
N3	■	■				
N4	■	■				
N5	■	■				
N6			■	■		
N7	■	■				
N8			■			■
N9			■	■		
N10	■	■				
I1	■	■				
I2			■			■
I3	■	■				
I4			■			■
I5			■			■
S1			■	■		
S2			■			■
S3				■	■	
S4			■	■		
S5			■	■		
S6	■	■				
S7				■	■	
S8			■			■
S9			■	■		
S10				■	■	
S11			■			■
S12			■	■		
T1			■			■
T2			■			■

Figure 6. The correlation network of Table A2 variables computed for (**i**) the n_1 = 51 NUTS III regions; (**ii**) the n_2 = 49 NUTS III (excluding the metropolitan Athens and Thessaloniki) regions; community membership is shown at different colors and correlation strength proportionally to node sizes; (**iii**) cross tabulation bar chart for the community membership between n_1 = 51 and the n_2 = 49 NUTS III regions; (**iv**) the community membership breakdown.

Next, the results of the correlation analysis illustrate that the invariant correlations between the variables in Table A2 (due to the removal of the prefectures of Attica and Thessaloniki from the sample) amount to 0.811·100 = 81.1%; or, conversely, that the effect of Attica and Thessaloniki on the strength of the correlations between the topological, infrastructure, and socioeconomic characteristics of the GRN is of 20% magnitude. Similarly, the effect of the two metropolitan prefectures on the community configuration is estimated at 25% magnitude. In conclusion, we find that the influence of the prefectures of Attica and Thessaloniki on the relationship between the topological, infrastructural, and socioeconomic characteristics of the GRN can be estimated in the range of 20–25%. Given that the population coverage of metropolitan prefectures exceeds 50% of the country's population [11,14,23], this mismatch (20–25% vs. 50%) can be attributed to the demand for transport road infrastructure created by the need to connect regional and border regions with the centers; as well as to the country's broader pursuit of regional development. This finding highlights a secondary regional development pattern of the GRN, beyond the gravitational one, which concerns connectivity to remote and peripheral places, thus promoting regional development [14]. According to the previous analysis, this pattern is restricted to spatial constraints and seems to follow lattice-like dynamics and a linear pattern described by "axial development through road connectivity".

4. Discussion

The previous analysis revealed that the GRN topology is determined by spatial constraints, as evidenced by the sharp patterns (deviating from a power-law curve) in the degree distribution; the significant values concentration around the main diagonal in the spy plots of the adjacency matrices; the results of the ω-index, which is negative approximating lattice-like characteristics; the spatial distributions of major network measures (degree, betweenness, closeness, clustering, spatial strength, and modularity classification), which provided insights into conceiving network centrality in terms of geographical proximity, population agglomerations, and intensity of economic activities; the community structure of the network into communities of geographical proximity; and the power-law-like patterns describing the correlations (k, CB), (k, s) and (k, C). Overall, the topology of the GRN appeared more relevant to the theoretical (null) model of the lattice network, which is developed under a competitive spatial pattern ruled by spatial constraints. In an economic geography context, the lattice-like topology illustrates an underlying growth mechanism of centrifugal forces in the network's geographical space, favoring the development of peripheral markets. This interpretation reveals a mismatch between the country's gravitational configuration (which is described by two major urban concentrations, of over 50% of the national population, in the metropolitan regions of Attica and Thessaloniki) and the endogenous structure of the transportation market (to the extent it is captured by network topology).

Given the country's gravitational configuration, described by the existence of two major urban development poles concentrating more than 50% of the country's population, this research focused on assessing the impact of Attica and Thessaloniki in shaping the relationship between topological characteristics, transport infrastructure characteristics, and socioeconomic attributes. In particular, the analysis showed that Attica and Thessaloniki have a particular influence on the variables related to network density (I_2), the existence of ports and airports (I_4, I_5), the secondary and tertiary sector specialization (S_7, S_8), and welfare (S_{11}). In contrast, the community configuration relationships of most of the road network topology variables (N_1, N_2, N_3, N_4, N_5, N_7, N_{10}), population (S_1), and productivity and education variables (S_4, S_5, S_6, S_{12}) appear indifferent to the effect of these metropolitan areas. Overall, this analysis provided a framework for examining regional differences and the influence that specific regions may have on the interregional socioeconomic equilibrium. Except in the highly urbanized regions of Attica and Thessaloniki, it is possible to obtain a clearer picture of the regional characteristics of the rest of the country, revealing the dynamics of the correlations of the (topological, infrastructural, and socioeconomic) determinants of the country's road network, free from economies of scale and agglomeration (which govern Attica and Thessaloniki and highlight the complexity of Greece's spatial development at the national intercity level). This approach led to the conclusion that even with the removal of the effect of these two highly urbanized regions, the spatial pattern of transport development in Greece remains gravity driven; namely, it is heading towards the emergence of further development poles. That is, it appears that the development of transport infrastructure in Greece is mainly driven by a self-sustained mechanism of growth poles, following the economic geography's theoretical models of [19,41], but also the mechanism of preferential attachment (see [4,8] described by network science). In a spatial planning and transportation planning context, this finding suggests following a planning model targeting the promotion of polycentric development in Greece. For instance, some policy measures and good practices that can apply in this direction regard providing incentives for developing special economic zones (SEZs) [52,53], attracting investments at these secondary growth poles, stimulating their regional development; transport infrastructures, through the public investment program to enhance mobility and economic agglomeration at these secondary growth poles; and other critical infrastructures (such as tourism, educational, and public health) to either enhance or reform the economic basis of these secondary growth poles and promote their regional development.

Second, it became apparent that the mechanism that led to the formation of the complex topological and socioeconomic relations of the GRN is not singularly gravitational. It is also governed by characteristics that serve the imperative of regional development and strengthening of remote and peripheral areas. The imprint of this mechanism is evident in the lattice-like characteristics detected by the network analysis conducted in the first section of this research. From a theoretical viewpoint, this mechanism is twofold and indirectly gravitational, as; on the one hand, it is triggered by the demand for transport links to and from urban poles that characterizes regional locations, as described as spread and backwash effects in the related approaches to [19] theory; on the other hand, the spatial costs involved in covering center-periphery distances, as described in the new economic geography of [22], leading to the emergence of centrifugal forces in geographic space that favor the emergence of regional markets and, consequently, to the deviation from the strictly gravity-based pattern detected in the results of the empirical analysis of Table 2.

The methodological approach followed in this paper provides insights into transportation and regional policy and spatial planning. First, the proposed method of capturing the major growth poles' contribution to the GRN (by excluding their sub-networks from the global network structure) can become a useful tool in transportation planning, both for modeling and evaluation purposes. As far as modeling is concerned, it can drive the construction of a map delineating the structural (topological) importance of sub-networks (due to their removal) in an intercity transportation system. This can be done by repeatedly applying the proposed removal method to all critical growth poles' areas in the network and afterward mapping the levels of their topological change. Collectively, projecting all these results on a map can serve the discrimination between the developed and laggard regions and can therefore facilitate the configuration of priority zones for government support (e.g., public investments, transportation budget allocation, etc.), which is a major concern in spatial economic policy. In terms of evaluation, by constructing a map of topological importance prior to and after the application of a developmental act (policy, law, etc.), the proposed method can measure the medium-term effects of this act on the topology of a transportation network. Further, the proposed method of detecting communities in the correlation network constructed by the available topological and socioeconomic variables can provide a supportive tool for econometric modeling. Provided that a major concern in econometrics is model specialization, the community correlation method can be informative for the construction of nested econometric models based on variables' relevance. In the context of the GRN, this approach allowed capturing the thematic influence that the Attica and Thessaloniki regions have on the GRN, focusing on certain variables. This finding, along with the other empirical results of this research, can be used to develop more tailored policies. For instance, the need to upgrade the road infrastructure network in areas outside the major urban centers of the GRN is apparent, which can be realized through investments in regional ports and airports, raising the mechanism of Keynesian regional multipliers induced by the autonomous increase in investment expenditure. Towards this direction, policy measures and good practices promoting regional and economic development can apply, such as the development of SEZs, transport, and other critical infrastructures; the provision of incentives (subsidizations, subventions, tax discounts, etc.) to attract private investments; and the strengthening of economic interaction between interregional neighbor cities to promote the development of dipole (polycentric) structures.

In this direction, the strengthening of secondary urban centers (such as Patras, Larissa, and Heraklion) that claim a gravity role by removing Attica and Thessaloniki from the gravity map can contribute to the diffusion of economic activity and the reduction of over-concentration on the Athens–Thessaloniki road axis. Of course, the quantification of such policy measures necessitates a separate study providing avenues of further research, as many issues related to the sectorial structure of the involved economies, timeframe and scale, the specific policy goals, type and level of investments, and potential economic, social, and environmental effects of such policy measures should be taken into account in detail and in a measurable context. Regardless of this requirement for further analysis, this study contributes to this debate by providing insights into mapping the landscape of demand for further growth pole development. As regards the share of further development of their road infrastructure (which Attica and Thessaloniki claim), this analysis suggests that further development of the transport infrastructure of these metropolitan areas should be conducted towards improving the clustering coefficient of their road connections (namely the mutual connections of these major urban development poles). This targeting has the potential to activate urban sprawl forces that may expand urban space through a decentralization mechanism producing polycentric structures.

Considering the central role of metropolitan regions in the country's intermodal connectivity (which, beyond the empirical documentation, is institutionally defined in the national General Framework for Spatial Planning and Sustainable Development), the creation of new or upgrading of intermodal (road, rail, maritime, and air) connections is expected to enhance the overall efficiency of the national transport network and raise the mechanism for polycentric urban and regional development based on Taaffe's and growth poles (see [2] models). Of course, as this research does not study intermodal connectivity in a quantitative context, this direction suggests an avenue for further research building on the methodological contribution of this paper. That is, to the extent that network efficiency is conceived by the literature in terms of average path length and connectedness (connected components), reproducing the analysis in this paper for a multilayer and multimodal transportation graph model by considering scenarios of including new multimodal connections in the network gateways may provide insights into the overall transportation network's efficiency. By considering the scenario of excluding the metropolitan regions of Attica and Thessaloniki, this paper configures a methodological framework for doing so. Furthermore, the unstable community membership (due to their dependence on the intermodal transport infrastructure of the two metropolitan regions) of the tourism variables (T_1, T_2), revealed by the analysis, provides directions for the upgrade of alternative road network routes serving the country's tourist destinations. Here, the strengthening of secondary urban centers (Patras, Larissa, Heraklion) as gateways for tourist arrivals can be decisive in the direction of decentralized and regional development. This can be done through the development of infrastructures for increasing the airports' capacity in such urban centers and rescheduling a number of transit flights to apply to the airports located there. However, similarly to a previous discussion, the quantification of such policy measures provides avenues for further research. Finally, the stability shown by the education level variable (S_{12}) in the analysis of Figure 6 provides directions for the adoption of regional development policies based on the knowledge economy and endogenous growth mechanism, following the models of refs. [54,55], according to which the economic growth mechanism emerges feedback due to the increased returns to scale brought about by knowledge as a productive factor. Finally, the analysis also highlighted the importance of enhancing rural and agro-tourism development as a structural pillar of stability in a country's economic and transport development, as the S_6 variable emerged stable to the effect of metropolitan forces and at the same time highly correlated with the topological characteristics of the GRN.

5. Conclusions

According to Sisyphus' analogy in transportation economics, the effort to address the traffic or transportation problem through single transport infrastructures' upgrading proportionally to their load may be fruitless and lead to a vicious cycle due to the circular relationship describing the increase of transport capacity and the derived demand for transportation. This analogy highlights the need for transportation and spatial planning to overcome traditional methods and practices submitted to disciplinary constraints and shift to more integrated models incorporating multidisciplinary socioeconomic, structural, and environmental considerations that satisfy the sustainability requirement. To serve this demand for integration, this paper developed a multidisciplinary approach combining graph modeling, complex network analysis, and statistical and empirical techniques to study the topological and geometric characteristics of the nationwide intercity road transportation network in Greece (GRN), in association with its socioeconomic information. The methodological approach aimed at mapping the topological characteristics of the GRN and capturing the level to which network structure is related to its socioeconomic framework, getting insights into its dynamics for sustainable regional economic development. The application of this methodological approach in the field of transport research can be particularly effective, both in empirical terms and in terms of transportation planning and regional development.

The empirical analysis was conducted under data availability constraints that did not allow the formulation of variables related to network geomorphology, road capacity, and cross-section geometry. With the awareness of these limitations, this study did not focus on the relationships' precise quantification and the construction of specialized econometric models but on the identification of structural relationships through meta-analysis based on the community detection in the correlation matrices of available variables. Within this context, the analysis revealed a major gravity pattern describing the structure and functionality of the Greek Road Network (GRN), with the main priority being the service of areas according to their population and, secondarily, the model of "axial development through road connectivity", stimulating linear spatial development and sprawl. Regions privileged in topological and structural road network characteristics also appear to enjoy benefits in terms of agricultural specialization, while those that are privileged in structural road network attributes also appear to enjoy benefits in terms of population density, economic development, level of education, tourism demand, and other socioeconomic characteristics. To the extent that the phenomenon of transportation emerges from differential spatial demand between places, this paper first provided insights into considering the collective concept of network topology as a family of variables associated with spatial demand. In the context of Sisyphus' paradigm, network topology and, more broadly, structure (or topology) are symbiotic to transportation, as they simultaneously suggest the cause and the result of transport flows; therefore, network topology should be taken into account and incorporated in the protocols and processes of transportation and spatial planning.

This paper proposed methods and suggested ways for doing so, examining the scenario of measuring the contribution of the two metropolitan regions in Greece, both in the GRN's topology and its level of association with its socioeconomic environment.

By revealing both the development potentials and the asymmetry in the distribution of road connections in the GRN, this paper highlights the need, on the one hand, to promote regional development mechanisms in places lacking adequate road infrastructure and, on the other hand, to manage the bottleneck effects detected at network locations with heterogeneous connectivity. The analysis has shown that the topology of the GRN has been shaped on the basis of the lattice (mesh-like) topology, due to the effect of spatial constraints, with distinctive correlations between geographical proximity, population concentration, and intensity of economic activities. However, spatial demand driven by population and economic concentrations within the geographical area appears to generate a gravity configuration reflected in the development of population and economic centers within the GRN transport market. While the removal of nodes (which are integral structural components of the real-world system) may invite criticism concerning realism and impose unavoidable conceptual limitations in this study, this node-removal approach has remained consistent with the gravity configuration identified for the entire GRN. This finding implies that the spatial development of the GRN occurs through successive autonomous processes of "growth poles" and their associated preferential attachment, highlighting the requirement for targeted policy interventions aimed at reducing regional disparities, sustainable transport, and balanced regional development.

From a methodological perspective, the analysis in this paper proposes a method for identifying and measuring the growth poles' quantitative contribution to transportation networks and can serve as a tool for evaluating scenarios on their structure and functionality. In terms of implementation, some proper actions towards improving network functionality, transport efficiency, and sustainable development may include a mix of policies aiming at the development of special economic zones (SEZs); may regard the provision of incentives for investments promoting the comparative advantages of the regions; can contribute to improving accessibility and road and multimodal infrastructure; enhance inter-county interaction and the mobility of productive sectors; and improve the quality of transport services.

Against this background, this article can serve as a reference for the formulation of policies that will improve transportation network functionality and enhance the balanced regional development of Greece. Overall, the analysis provides useful tools for spatial planning, transport management, and regional development in Greece, enhancing the understanding of the relationships between network topology and transport infrastructure and their socioeconomic properties, as well as the impact of large urban centers on this complex map of spatial, transport, and economic relations. The overall approach followed in this paper can provide a methodological framework for analyzing long-distance transport infrastructure at both national and other spatial levels, proposing strategies for improving infrastructure, enhancing regional development, and promoting socioeconomic equity and convergence.

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Appendix A

Table A1. Topological network measures used in the GRN analysis.

Measure	Description	Math Formula
Graph	A pair set G(V,E) of nodes (V) and edges (E), where *n* is the number of nodes and *m* the number of links.	G(V,E)
Graph density (ρ)	The share of graph connections (m) to the possible connections; expressing the chance of meeting an edge between two randomly chosen network nodes.	$\rho = m/\binom{n}{2} = \frac{2m}{n\cdot(n-1)}$
Network diameter (*dG*)	The longest shortest path *p*(*i*,*j*) that can be found in a network.	$d(G) = \max\{\, p(i,j) \mid i,j \in V\}$
Node degree (*k*)	The number of connections that a given node *i* has.	$k_i = m(i) = m_i = \sum_{j\in V(G)} \delta_{ij} = \sum_{j\in V(G)} \delta_{ij}$, where $\delta_{ij} = \begin{cases} 1, \text{ if } e_{ij} \in E(G) \\ 0, \text{ otherwise} \end{cases}$
Node strength or weighted degree (*s*)	The total weight (w_{ij}) volume of node *i*; δ_{ij} is the Kronecker's delta function for the detection of a network edge (e_{ij}).	$s_i = s(i) = \sum_{j\in V(G)} \delta_{ij} \cdot d_{ij}$, where $d_{ij} = w(e_{ij})$ in km
Closeness centrality (CC)	An accessibility metric, measuring the average network distance *d*(*i*,*j*) from node *i*.	$CC(i) = \frac{1}{n-1} \cdot \sum_{j=1,i\neq j}^{n} d_{ij} = \overline{d}_i$
Betweenness centrality (CB)	The share of shortest-paths $\sigma(i)$ crossing node *i*, measuring the node's importance in terms of intermediacy.	$CB(i) = \sigma(i)/\sigma$
Local clustering coefficient (*C*)	The share of mutual connections *E*(*i*) of node *i* with its neighbors; $k_i(k_i - 1)$ is the number of triplets configured by this node. When computed over all network nodes defines the global clustering coefficient.	$C(i) = \frac{E(i)}{k_i\cdot(k_i-1)}$
Modularity (*Q*)	An objective function measuring a network's divisibility; g_i is the community of node *i*, $[A_{ij} - P_{ij}]$ is the difference between actual and expected links for a pair of nodes *i*,*j*, and $\delta(g_i,g_j)$ is the Kronecker's delta function for the detection of group membership ($g_i = g_j$).	$Q = \frac{\sum_{i,j}[A_{ij}-P_{ij}]\cdot\delta(g_i,g_j)}{2m}$
Average path length $\langle l \rangle$	The average of the network path-lengths *d*[*p*(*i*,*j*)], expressing the network's impedance to communication.	$\langle l \rangle = \frac{\sum_{v\in V} d(p(i,j))}{n\cdot(n-1)}$

Sources: Koschutzki et al. (2005) [33]; Newman (2010) [29]; Fortunato (2010) [34]; Barthelemy (2011) [4].

Table A2. Variables participating in the GRN's correlation analysis.

Symbol	Description
	Road Network Topology Variables
N_1	The number of nodes of each GRN's regional (*) sub-network.
N_2	The number of edges of each GRN's regional sub-network.
N_3	The average degree of each GRN's regional sub-network.
N_4	The average distance-weighted degree (spatial strength) of each GRN's regional sub-network.
N_5	The value of network diameter for each GRN's regional sub-network.
N_6	The score of graph density for each GRN's regional sub-network.
N_7	The score of modularity for each GRN's regional sub-network.
N_8	The connected components of each GRN's regional sub-network.
N_9	The value of average clustering coefficient for each GRN's regional sub-network.
N_{10}	The value of average path length for each GRN's regional sub-network.
	Transport Infrastructure Variables
I_1	The total length of the GRN is included in each region.
I_2	The GRN's network density by region. It is defined as the total length of the road network included in each region to its surface area.
I_3	The regional area of the GRN (in m^2).
I_4	The number of GRN's ports per region.
I_5	The number of GRN's ports per region.

Table A2. *Cont.*

Symbol	Description
	Socioeconomic Variables
S_1	The population of the region (2021 census).
S_2	The level of urbanization per region, defined by population share of its capital city.
S_3	Indirect population potential; a regional indicator measuring the volume of economic activities to which a region *i* has access. It is defined by the sums of ratios between destinations' populations P_j divided by squared distances d_{ij}^2 ($IPP_i = \sum_j \frac{P_j}{d_{ij}^2}$).
S_4	Direct population potential; a regional indicator measuring the volume of economic activities developed within a region. It is defined proportionally to the region's population P_i and inversely to the squared diameter of the region's area d_i ($DPP_i = \frac{P_i}{d_i^2}$).
S_5	The regional gross domestic product, expressed by the regional share to the country's GDP.
S_6	The regional primary sector's specialization, expressed by the share of the primary sector to the regional GDP.
S_7	The regional secondary sector's specialization, expressed by the share of the secondary sector to the regional GDP.
S_8	The regional tertiary sector's specialization, expressed by the share of the tertiary sector to the regional GDP.
S_9	The level of agribusiness investments, expressed by the per capita amount invested in the creation of new agro-industrial enterprises.
S_{10}	Regional productivity dynamism; a composite indicator defined by the average of the normalized (i.e., lying in the interval) employment and unemployment rates, change in gross value added (GVA), and per labor GVA in the regional economy.
S_{11}	Welfare index; a composite indicator defined by the average of the normalized housing area, bank deposits, energy consumption, and private car ownership in a region.
S_{12}	Education level; a composite indicator defined by the sum of population shares per educational level (1–7) in a region.
	Tourism Variables
T_1	Tourism Share. The share of tourism to the regional GDP.
T_2	Tourism Area Life Cycle (TALC) Coefficient. Expresses the level of saturation of the county in terms of overnight stays per visitor.

*. All regions are defined in the NUTS III level. Data sources: Polyzos (2019) [23]; Tsiotas (2021) [8]; Tsiotas and Polyzos (2024) [14].

References

1. Kurant, M.; Thiran, P. Extraction and analysis of traffic and topologies of transportation networks. *Phys. Rev. E* **2006**, *74*, 036114. [CrossRef] [PubMed]
2. Rodrigue, J.P.; Comtois, C.; Slack, B. *The Geography of Transport Systems*; Routledge Publications: New York, NY, USA, 2013.
3. Gauthier, H.L. Geography, transportation, and regional development. *Econ. Geogr.* **1970**, *46*, 612–619. [CrossRef]
4. Barthelemy, M. Spatial networks. *Phys. Rep.* **2011**, *499*, 1–101. [CrossRef]
5. Polyzos, S.; Tsiotas, D. The contribution of transport infrastructures to the economic and regional development: A review of the conceptual framework. *Theor. Empir. Res. Urban Manag.* **2020**, *15*, 5–23.
6. Capello, R. *Regional Economics*; Routledge: New York, NY, USA, 2016.
7. Blumenfeld-Lieberthal, E. The topology of transportation networks. *Netw. Spat. Econ.* **2008**, *9*, 427–458. [CrossRef]
8. Tsiotas, D. Drawing indicators of economic performance from network topology: The case of the interregional road transportation in Greece. *Res. Transp. Econ.* **2021**, *90*, 101004. [CrossRef]
9. Marshall, S.; Gil, J.; Kropf, K.; Tomko, M.; Figueiredo, L. Street network studies: From networks to models and their representations. *Netw. Spat. Econ.* **2018**, *18*, 735–749. [CrossRef]
10. Nijkamp, P.; Reggiani, A.; Tsang, W.F. Comparative modeling of interregional transport flows: Applications to multimodal European freight transport. *Eur. J. Oper. Res.* **2004**, *155*, 584–602. [CrossRef]
11. Polyzos, S. *Urban Development*, 2nd ed.; Kritiki Publications: Athens, Greece, 2023. (In Greek)
12. Herzog, I. National transportation networks, market access, and regional economic growth. *J. Urban Econ.* **2021**, *122*, 103316. [CrossRef]
13. Sgroi, D. Social network theory, broadband and the future of the World Wide Web. *Telecommun. Policy* **2008**, *32*, 62–84. [CrossRef]
14. Tsiotas, D.; Polyzos, S. Transportation Networks and Regional Development: The Conceptual and Empirical Framework in Greece. *Sustain. Reg. Dev. Sci. J.* **2024**, *1*, 15–39.
15. Ducruet, C.; Beauguitte, L. Spatial science and network science: Review and outcomes of a complex relationship. *Netw. Spat. Econ.* **2014**, *14*, 297–316. [CrossRef]
16. Hewings, G.J.; Oosterhaven, J. Interregional trade: Models and analyses. In *Handbook of Regional Science*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 373–395.
17. Harris, J.R.; Todaro, M.P. Migration, unemployment and development: A two-sector analysis. *Am. Econ. Rev.* **1970**, *60*, 126–142.
18. Faggian, A.; Rajbhandari, I.; Dotzel, K.R. The interregional migration of human capital and its regional consequences: A review. In *Transitions in Regional Economic Development*; Routledge Publications: New York, NY, USA, 2018; pp. 227–256.
19. Myrdal, G. *Economic Theory and Under-Developed Regions*; Duckworth: London, UK, 1957.

20. McCann, P.; Van Oort, F. Theories of agglomeration and regional economic growth: A historical review. In *Handbook of Regional Growth and Development Theories*; Edward Elgar Publishing: Cheltenham, UK, 2019; pp. 6–23.
21. Krugman, P. Increasing returns and economic geography. *J. Political Econ.* **1991**, *99*, 483–499. [CrossRef]
22. Fujita, M.; Krugman, P. The new economic geography: Past, present and the future. In *Fifty Years of Regional Science*; Springer: Berlin/Heidelberg, Germany, 2004; pp. 139–164.
23. Polyzos, S. *Regional Development*, 2nd ed.; Kritiki Publications: Athens, Greece, 2019. (In Greek)
24. Tsiotas, D.; Axelis, N.; Polyzos, S. A methodological framework for defining city dipoles in urban systems based on a functional attribute. *Cities* **2021**, *119*, 103387. [CrossRef]
25. Chorianopoulos, I.; Pagonis, T.; Koukoulas, S.; Drymoniti, S. Planning, competitiveness and sprawl in the Mediterranean city: The case of Athens. *Cities* **2010**, *27*, 249–259. [CrossRef]
26. Salvati, L. Neither ordinary nor global: A reflection on the 'extra-ordinary' expansion of Athens. *Urban Plan. Transp. Res.* **2014**, *2*, 49–56. [CrossRef]
27. Christofakis, M.; Papadaskalopoulos, A. The Growth Poles Strategy in regional planning: The recent experience of Greece. *Theor. Empir. Res. Urban Manag.* **2011**, *6*, 5–20.
28. Albert, R.; Barabasi, A.-L. Statistical mechanics of complex networks. *Rev. Mod. Phys.* **2002**, *74*, 47–97. [CrossRef]
29. Newman, M.E.J. *Networks: An Introduction*; Oxford University Press: Oxford, UK, 2010.
30. Buhl, J.; Gautrais, J.; Reeves, N.; Solé, R.; Valverde, S.; Kuntz, P.; Theraulaz, G. Topological patterns in street networks of self-organized urban settlements. *Eur. Phys. J. B* **2006**, *49*, 513–522. [CrossRef]
31. Cardillo, A.; Scellato, S.; Latora, V.; Porta, S. Structural properties of planar graphs of urban street patterns. *Phys. Rev. E* **2006**, *73*, 066107. [CrossRef] [PubMed]
32. Hellenic Organization for Cadastral Surveys and Cartography-HOCSC Road Network DRPS (Department of Road Project Studies). 2005. Available online: http://geodata.gov.gr/dataset (accessed on 3 July 2015).
33. Koschutzki, D.; Lehmann, K.; Peeters, L.; Richter, S. Centrality Indices. In *Network Analysis*; Brandes, U., Erlebach, T., Eds.; Springer: Berlin/Heidelberg, Germany, 2005; pp. 16–61.
34. Fortunato, S. Community detection in graphs. *Phys. Rep.* **2010**, *486*, 75–174. [CrossRef]
35. Blondel, V.D.; Guillaume, J.-L.; Lambiotte, R.; Lefebvre, E. Fast unfolding of communities in large networks. *J. Stat. Mech.* **2008**, *2008*, P10008. [CrossRef]
36. Courtat, T.; Gloaguen, C.; Douady, S. Mathematics and morphogenesis of the city: A geometric approach. *Phys. Rev. E* **2010**, *83*, 036106. [CrossRef]
37. Telesford, Q.; Joyce, K.; Hayasaka, S.; Burdette, J.; Laurienti, P. The Ubiquity of Small-World Networks. *Brain Connect.* **2011**, *1*, 367–375. [CrossRef]
38. Maslov, S.; Sneppen, K. Specificity and stability in topology of protein networks. *Science* **2002**, *296*, 910–913. [CrossRef]
39. Sporns, O.; Kotter, R. Motifs in brain networks. *PLoS Biol.* **2004**, *2*, e369. [CrossRef]
40. Porter, M.A. Small-world network. *Scholarpedia* **2012**, *7*, 1739. [CrossRef]
41. Perroux, F. Economic space: Theory and applications. *Q. J. Econ.* **1950**, *64*, 89–104. [CrossRef]
42. O'Sullivan, A. *Urban Economics*, 7th ed.; McGraw-Hill/Irwin Publications: Portland, OR, USA, 2007.
43. Fratesi, U.; Elhorst, P.; Abreu, M.; Amaral, P.; Bond-Smith, S.; Corrado, L.; Ditzen, J.; Felsenstein, D.; Franklin, R.S.; Fuerst, F.; et al. The inextricable nature of space and economy. *Spat. Econ. Anal.* **2024**, *19*, 107–114. [CrossRef]
44. Norusis, M. *IBM SPSS Statistics 19.0 Guide to Data Analysis*; Prentice Hall: Upper Saddle River, NJ, USA, 2011.
45. Walpole, R.E.; Myers, R.H.; Myers, S.L.; Ye, K. *Probability & Statistics for Engineers & Scientists*, 9th ed.; Prentice Hall Publications: New York, NY, USA, 2012.
46. McHugh, M.L. The Chi-square test of independence. *Biochem. Medica* **2013**, *23*, 143–149. [CrossRef] [PubMed]
47. Sharpe, D. Chi-Square Test is Statistically Significant: Now What? *Pract. Assess. Res. Eval.* **2015**, *20*, 8. [CrossRef]
48. Miandoabchi, E.; Daneshzand, F.; Szeto, W.Y.; Farahani, R.Z. Multi-objective discrete urban road network design. *Comput. Oper. Res.* **2013**, *40*, 2429–2449. [CrossRef]
49. Arbex, R.O.; da Cunha, C.B. Efficient transit network design and frequencies setting multi-objective optimization by alternating objective genetic algorithm. *Transp. Res. Part B Methodol.* **2015**, *81*, 355–376. [CrossRef]
50. Guimera, R.; Mossa, S.; Turtschi, A. The worldwide air transportation network: Anomalous centrality, community structure, and cities' global roles. *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 7794–7799. [CrossRef]
51. Kaluza, P.; Koelzsch, A.; Gastner, M.T.; Blasius, B. The complex network of global cargo ship movements. *J. R. Soc. Interface* **2010**, *7*, 1093–1103. [CrossRef]
52. Farole, T.; Akinci, G. (Eds.) *Special Economic Zones: Progress, Emerging Challenges, and Future Directions*; World Bank Publications: Washington, DC, USA, 2011.
53. Wang, J. The economic impact of special economic zones: Evidence from Chinese municipalities. *J. Dev. Econ.* **2013**, *101*, 133–147. [CrossRef]

54. Lucas, R.E., Jr. On the mechanics of economic development. *J. Monet. Econ.* **1988**, *22*, 3–42. [CrossRef]
55. Romer, P.M. The origins of endogenous growth. *J. Econ. Perspect.* **1994**, *8*, 3–22. [CrossRef]