Drawing indicators of economic performance from network topology: the case of the interregional road transportation in Greece

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INTRODUCTION
Road networks, economy, and space

- Road networks are of major importance for the conduct of worldwide transportation, in terms of network length, traffic, and the number of users.

- Provided that transportation is (by default) subjected to spatial constraints, the structure of transportation networks over time depicts the social ability to overcome at a certain time the spatial constraints, in order the societies to communicate.
The multidisciplinary nature of road transportation research

• In literature, the study of street-networks has been multidisciplinary and has attracted the attention from researchers across many disciplines (transport engineers, urban and regional planners, geographers, architects, environmental scientists, and physicists).

• A major strength of this polyphony is the rich empirical knowledge produced by diverse approaches, whereas the inevitable lack of communication between various disciplines due to their different context of conceptualization becomes a current challenge raising the demand for integration.
The multidisciplinary nature of road transportation research

• The study of the relation between network structure and the socio-economic framework of transportation networks is a complex task subjected to inevitable disciplinary constraints.

• Geographers, urban, and regional planners appear to focus more on the spatial and economic interaction of transportation networks.

• Physicists and computational scientists focused more on network topology.
The multidisciplinary nature of road transportation research

• **Economists** are usually interested in the **underlying living structures** of transport networks and **interpret** them as **markets** consisting of **high sunk costs** and **trade** and **economic interaction**.

• **Geographers** and **regional planners** appear more interested in studying transportation networks **at the regional scale**, 

• **Transport engineers** and **urban planners** usually do research at the **urban scale**.
Introduction

The multidisciplinary nature of road transportation research

• Transport engineers seem to prefer modeling street-networks to axial maps,

• Geographers prefer street-networks modeling to GIS-based physical and metric representations,

• Urban planners prefer street-networks modeling to topological representations,

• Physicists prefer street-networks modeling to topological and metric representations.
Graph modeling as a key for integration

• Graph modeling is a common component in the majority of the multidisciplinary approaches studying transportation networks.

• It builds on the network paradigm to represent communication systems into pair-sets of nodes and links and then to facilitate the study of their structure (called network analysis) in terms of various measurable attributes.

• This modeling is effective in the research of communication systems at every geographical scale.

• Is privileged in including both functional and structural information in a single model.
Graph modeling as a key for integration

• On the other hand, modeling a transport network as a graph is not the prime objective of transportation research but it suggests a powerful tool facilitating the answer to certain research questions.

• Within the context of regional science and transport geography, the importance of transportation networks depends on the underlying living structures facilitating their infrastructures.

• In economic terms, those structures are seen as markets, the dynamics of which are reflected on the topology of transportation networks supporting their needs,

• Vice-versa, structural constraints immanent in transportation networks affect their further developmental dynamics.
Introduction

Graph modeling as a key for integration

- An integrated approach in the study of transportation networks should build on the pillars of the *economy, geography (space)*, and on *graph modeling* (which prevails in empirical research) to provide insights promoting the goals of regional science.
The case study of Greece

- Aiming at serving this demand, the topology of the (nationwide) interregional Road Network in Greece (GRN) is studied in terms of its geographical and socio-economic framework to provide insights into the links between society, economy, and space.
The case study of Greece

- Greece is a coastal country of an area of almost **132,000km²** and it includes more than **14,000km** of coastline and more than **1,350 islands, islets, and rocky islands**, among which over **230** are inhabited.
- In the country, **land transport** is a **key component** for national and regional economic development because it **services** almost **88% of the national population** located in **continental and coastal regions** (covering about **82% of the total land area**).
- The **Greek interregional road network** (GRN) has a length of **35,860km** and it connects **diverse mountainous, land, and coastal places**, which **favor the emergence** of **alternative and competitive** transportation modes.
Introduction

The case study of Greece

• According to the General Framework of Spatial Planning and Sustainable Development of Greece, transportation development is a major strategic goal for the national and regional economic development of the country and the promotion of specialized economic and productivity aspects such as tourism, trade, and communication.
The purpose of this study

- A (geo-referenced) **primary graph** model of the GRN is constructed incorporating **geometric** (geographical) and **topological** (functional) information,

- **Socio-economic** information is extracted from the **regional** (at the NUTS III level) **administrative division** of the country due to data availability and to the governance and policy conceptualization of this division.

- The study **aims** at serving the demand for integration in transportation research by **detecting links between network topology, economy, and space**.
METHODOLOGICAL FRAMEWORK
Methodological framework

The methodological framework

• Conceptualizes the network topology of the GRN as the resultant of various social, economic, spatial, and technological forces that contributed over time to the evolution of the road transportation system in Greece.
Due to the obvious deficiency to monitor the development of the GRN in every time-step of this long growth process, the proposed methodology develops a quantitative framework for the examination of the socioeconomic variables that can better describe the current topological properties of this road transportation network.
The methodological framework

• The overall approach develops links between the network topology and its socioeconomic and geographical framework that can provide insights into this unmonitored diachronically growth process.
The methodological framework

• Is multilevel and consists of five (5) discrete steps
Step#1: Graph modeling

- At the first step, the GRN is modeled into a graph (spatial network)
Step#2: Network analysis

• Major measures of topology and geometry are computed to provide insights into the structure and functionality of the GRN.
Step#3: Empirical analysis

- A set of network and socioeconomic (SE) variables are configured at the regional scale and are further included in an empirical analysis consisting of correlations and principal component analysis (PCA).
Step#4: Tabulation

• The results of the empirical analysis are tabulated to detect relevance between network and SE variables.
Step#5: Conclusion making

- **Conclusions** about the socioeconomic performance of the topological aspects of GRN are formulated.
**Step#1: Graph modeling**

- The GRN is modeled to an undirected **geo-referenced primal graph** consisting of \( n=4,993 \) nodes and \( m=6,487 \) links.
- **Nodes**: road route intersections (change of routes)
- **Links**: intermediate road-paths of successive nodes
Step#1: Graph modeling

- Ferry connections operating as *bridges* were *not included* in the model.
- Edge weights express the *kilometric* real-network *distance* between successive nodes.
Step#1: Graph modeling

- The **primal** representation is **largely geometric** and is preferable for the study of GRN because of the **interregional scale** of the analysis.

- **Cities** and other **urban units** are **dimensionless** (appear as points) in a **regional map** and thus the **interregional** underlying living **structures** are more **driven** by **geographical** (geometric) **forces** rather than by the **functionality needs** of their societies.
Step#1: Graph modeling

• The empirical analysis is applied to NUTS III (prefectural) administrative division (where plenty of socio-economic data and indicators are available), which produces sub-graphs incorporating governance and policy information about the underlying living structures of the interregional transportation in Greece.

• Within this framework, the representation of GRN into a (geo-referenced) primal graph can be more directly related to this administrative conceptualization and to the underlying economies that the prefectures represent.
Step#1: Graph modeling

• GRN is not a connective graph, but an aggregate network including 156 components.

• The biggest component includes the major road network of the mainland country, whereas the others include the local road networks of the biggest Greek islands (only those including asphalt parts are included).

• Insufficient connectivity was managed by the local restriction method (LRM), where local measures (i.e. computed within connected components) are converted to global (aggregate) without any modification.

• GRN is geo-referenced, namely network nodes are located at the geographical coordinates of their corresponding road intersections in the real-network and links are configured by the linear segments between nodes instead of by the curved-shaped real routes that they represent.
Methodological framework

Step#2: Network analysis

- is implemented on a set of measures of network topology

<table>
<thead>
<tr>
<th>Measure</th>
<th>Symbol</th>
<th>Description</th>
<th>Math Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graph density</td>
<td>$\rho$</td>
<td>The fraction of the existing connections of the graph to the number of the possible connections. It expresses the probability to meet in the GMN a connected pair of nodes.</td>
<td>$\rho = m/\left(\begin{smallmatrix} n \ 2 \end{smallmatrix}\right) = \frac{2m}{n \cdot (n-1)}$</td>
</tr>
<tr>
<td>Node Degree</td>
<td>$k$</td>
<td>The number of the edges adjacent to a given node, expressing the node’s communication potential.</td>
<td>$k_i = k(i) = \sum_{j \in V(G)} \delta_{ij}$, where $\delta_{ij} = \begin{cases} 1, &amp; \text{if } e_{ij} \in E(G) \ 0, &amp; \text{otherwise} \end{cases}$</td>
</tr>
<tr>
<td>Node (spatial) strength</td>
<td>$s$</td>
<td>The sum of edge distances being adjacent to a given node.</td>
<td>$s_i = s(i) = \sum_{j \in V(G)} \delta_{ij} \cdot d_{ij}$, where $d_{ij} = w(e_{ij})$ in km</td>
</tr>
<tr>
<td>Average Path Length</td>
<td>$\langle l \rangle$</td>
<td>Average length $d(i,j)$ of the total of network shortest paths.</td>
<td>$\langle l \rangle = \frac{\sum_{v \in V} d(v_i,v_j)}{n \cdot (n-1)}$</td>
</tr>
</tbody>
</table>
Step#2: Network analysis

- is implemented on a set of measures of network topology

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<tr>
<td>Clustering Coefficient</td>
<td>$C(i)$</td>
<td>Probability of meeting linked neighbors around a node, which is equivalent to the number of the node’s connected neighbors $E(i)$ (i.e. the number of triangles), divided by the number of the total triplets shaped by this node, which equals to $k_i(k_i-1)$.</td>
<td>$C(i) = \frac{E(i)}{k_i \cdot (k_i - 1)}$</td>
</tr>
<tr>
<td>Modularity</td>
<td>$Q$</td>
<td>Objective function expressing the potential of a network to be subdivided into communities. In its mathematical formula, $g_i$ is the community of node $i \in V(G)$, $[A_{ij} - P_{ij}]$ is the difference of the actual minus the expected number of edges falling between a particular pair of vertices $i,j \in V(G)$, and $\delta(g_i,g_j)$ is an indicator function returning 1 when $g_i=g_j$.</td>
<td>$Q = \frac{\sum_{i,j}[A_{ij} - P_{ij}] \cdot \delta(g_i,g_j)}{2m}$</td>
</tr>
</tbody>
</table>
Step#2: Network analysis

- is implemented on a set of measures of network topology

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</tr>
</thead>
<tbody>
<tr>
<td>Closeness</td>
<td>CC</td>
<td>The total binary distance ( d(i,j) ) computed on the shortest paths originating from a given node ( i \in V(G) ) with destinations all the other nodes ( j \in V(G) ) in the network. This measure expresses the node’s reachability in terms of steps of separation.</td>
<td>[ CC(i) = \frac{1}{n-1} \sum_{j=1, i \neq j}^{n} d_{ij} = \bar{d}_i ]</td>
</tr>
<tr>
<td>Betweenness</td>
<td>CB</td>
<td>The proportion of the (( \sigma )) shortest paths in the network that pass through a given node ( i ).</td>
<td>[ CB(i) = \sigma(i)/\sigma ]</td>
</tr>
</tbody>
</table>
Step#3: Empirical analysis

- To implement the analysis, several vector variables are constructed, referring to the network topology, network infrastructures, economic and productivity framework, and the socio-demographic profile of the GRN.

- These variables were extracted from the relevant literature about regional development in Greece, based on data availability and the theoretical conceptualization of road transportation networks, within the framework of transport geography.

- Obviously, the available variables participating in the analysis are representative and cannot be exhaustive in the description of the relevant theoretical framework.
Step#3: Empirical analysis

- For the construction of the network-topology variables, the graph-model of the GRN was further divided into 51 groups, (sub-graphs) including the regional road networks of the (51) prefectures in Greece.
## Methodological framework

### Step #3: Empirical analysis

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>NODES</td>
<td>Network nodes</td>
<td>The number of nodes included in each regional group (sub-graph).</td>
</tr>
<tr>
<td>EDGES</td>
<td>Network edges</td>
<td>The number of edges included in each regional sub-graph.</td>
</tr>
<tr>
<td>ADEG</td>
<td>Average degree</td>
<td>The average degree of the nodes included in each regional sub-graph.</td>
</tr>
<tr>
<td>DIAM</td>
<td>Network diameter</td>
<td>Network diameter of each regional sub-graph.</td>
</tr>
<tr>
<td>MOD</td>
<td>Modularity</td>
<td>The value of modularity-function for each regional sub-graph.</td>
</tr>
<tr>
<td>AC</td>
<td>Average clustering coefficient</td>
<td>The average clustering coefficient of the nodes included in each regional sub-graph.</td>
</tr>
<tr>
<td>APL</td>
<td>Average path length</td>
<td>The average path length of each regional sub-graph.</td>
</tr>
<tr>
<td>ACC</td>
<td>Average closeness centrality</td>
<td>The average closeness centrality of the nodes included in each regional sub-graph.</td>
</tr>
<tr>
<td>ACB</td>
<td>Average betweenness centrality</td>
<td>The average betweenness centrality of the nodes included in each regional sub-graph.</td>
</tr>
</tbody>
</table>
**Step#3: Empirical analysis**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDL</td>
<td>Road length</td>
<td>Total road length included in each prefecture (m).</td>
</tr>
<tr>
<td>AREA</td>
<td>Regional area</td>
<td>Total area of each prefecture (m²).</td>
</tr>
<tr>
<td>RDD</td>
<td>Road density</td>
<td>Defined by the fraction RDL/AREA.</td>
</tr>
<tr>
<td>PRT</td>
<td>Ports</td>
<td>The number of ports included in each prefecture.</td>
</tr>
<tr>
<td>APRT</td>
<td>Airports</td>
<td>The number of airports included in each prefecture.</td>
</tr>
</tbody>
</table>

**Network infrastructure variables**

- **URB**: Level of urbanization. Is defined by the percentage of the capital city's population to the regional population.

**Network topology variables**

- **NODES**: Network nodes. The number of nodes included in each regional group (sub-graph).
- **B**: Average degree. The value of the average degree of the nodes included in each regional sub-graph.
- **ADEG**: Average degree. The average degree of the nodes included in each regional sub-graph.
- **EDGES**: Network edges. The number of edges included in each regional sub-graph.
- **MOD**: Modularity. The value of modularity for each regional sub-graph.
- **DIA**: Network diameter. The network diameter of each regional sub-graph.
- **CN**: Average closeness centrality. The average closeness centrality of the nodes included in each regional sub-graph.
- **BC**: Average betweenness centrality. The average betweenness centrality of the nodes included in each regional sub-graph.
- **PATH**: Average path length. The average path length of each node in each regional sub-graph.
- **CL**: Average clustering coefficient. The average clustering coefficient of the nodes included in each regional sub-graph.
- **POPC**: Regional population dynamism. Defined by the percentage of the capital city's population to the regional population.
- **SOC**: Regional productive dynamism. Defined by the fraction RDL/AREA.
- **PRT**: Regional primary product. The regional product in the primary sector to the regional GDP.
- **SEC**: Regional complex product. The regional product in the secondary sector to the tertiary sector.
- **PP**: Primary specialization. The primary specialization of each prefecture in the primary sector.
- **TP**: Tertiary specialization. The tertiary specialization of each prefecture in the tertiary sector.
- **SP**: Secondary specialization. The secondary specialization of each prefecture in the secondary sector.
- **AP**: Airports. The number of airports included in each prefecture.
- **PORT**: Ports. The number of ports included in each prefecture.
### Step#3: Empirical analysis

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDP</td>
<td>Gross domestic product</td>
<td>The GDP that is produced by each prefecture.</td>
</tr>
<tr>
<td>$A_{SEC}$</td>
<td>Primary specialization</td>
<td>The specialization of each prefecture in the primary (agriculture) sector. Defined by the percentage of the regional product in the primary sector to the regional GDP.</td>
</tr>
<tr>
<td>$B_{SEC}$</td>
<td>Secondary specialization</td>
<td>The specialization of each prefecture in the secondary (industries) sector. Defined by the percentage of the regional product in the secondary sector to the regional GDP.</td>
</tr>
<tr>
<td>$C_{SEC}$</td>
<td>Tertiary specialization</td>
<td>The specialization of each prefecture in the secondary (services) sector. Defined by the percentage of the regional product in the tertiary sector to the regional GDP.</td>
</tr>
<tr>
<td>$T_{GDP}$</td>
<td>Tourism specialization</td>
<td>The specialization of each prefecture in tourism. Defined by the percentage of the regional product in tourism to the regional GDP.</td>
</tr>
<tr>
<td>RPD</td>
<td>Regional productive dynamism</td>
<td>A complex indicator measuring employment levels, productivity structures, and productivity levels in local economies.</td>
</tr>
</tbody>
</table>
### Step #3: Empirical analysis

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>POP</td>
<td>Regional population</td>
<td>The population of each prefecture (according to the 2011 national census).</td>
</tr>
<tr>
<td>URB</td>
<td>Level of urbanization</td>
<td>Is defined by the percentage of the capital city’s population to the regional population.</td>
</tr>
</tbody>
</table>

**Socio-demographic variables**

**Network topology variables**

- NODES: Network nodes
  - Description: The number of nodes included in each regional group (sub-graph).
- URB: Level of urbanization
  - Description: Is defined by the percentage of the capital city’s population to the regional population.
Step#3: Empirical analysis

- The empirical analysis of the GRN builds on correlation and the principal component analysis (PCA).

- **Pearson’s bivariate coefficients of correlation** are computed pair-wise, on the set of available variables.

- For a pair of variables X,Y, the Pearson’s correlation coefficient $r_{XY}$ is calculated by the fraction of the covariance of X,Y to the product of their respective sample standard deviations.

- The coefficient ranges within the interval [-1,1] and detects linearity between X,Y when it is equal to one.
Step#3: Empirical analysis

- PCA is used to **reduce the dimension** of a set of possibly correlated (source) n variables, by **converting them** into a set of **linearly p uncorrelated ones**, the principal components.

- Applies an **orthogonal transformation** to them, which can be considered as **fitting a p-dimensional ellipsoid** \((p \leq n)\) to the data.
RESULTS AND DISCUSSION
Results and Discussion

Network analysis (network measures)

- The max degree of GRN is $k_{GRN,max} = 8$ and it is almost half than the average max degree of urban road networks.
- The average degree of the interregional road network is $≈ 2.598$, which is similar to the average degree ($≈ 2.5$) of urban road networks.
- This result illustrates a balance between the T-shaped and X-shaped intersections in the topology of GRN.
Results and Discussion

Network analysis (network measures)

- The binary average path length is considerably smaller than the expected average path length of an equivalent lattice with the same number of nodes (≈70),
- This result implies that the topology of GRN is less costly than a regular network submitted to spatial constraints (lattice network)
Results and Discussion

• The graph density expresses that the GRN possesses 43.3% of the possible connections that can be developed in the 2d-space and it can be used as an indicator of the spatial coverage (efficiency) of the network’s connectivity.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Symbol</th>
<th>Unit</th>
<th>GRN Aggregate</th>
<th>Sub-networks (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network nodes</td>
<td>n</td>
<td>#(b)</td>
<td>4,993</td>
<td>82.04 – 107.14</td>
</tr>
<tr>
<td>Network edges</td>
<td>m</td>
<td>#</td>
<td>6,487</td>
<td>100.12 – 133.84</td>
</tr>
<tr>
<td>Self-loops</td>
<td>n(e_i ∈ E)</td>
<td>#</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Isolated nodes</td>
<td>n(k=0)</td>
<td>#</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Network components</td>
<td>α</td>
<td>#</td>
<td>156</td>
<td>2.568 – 3.34</td>
</tr>
<tr>
<td>Graph density (planar)</td>
<td>ρ_1</td>
<td>net (c)</td>
<td>0.433</td>
<td>0.45 – 0.461</td>
</tr>
<tr>
<td>Graph density (non-planar)</td>
<td>ρ_2</td>
<td>net</td>
<td>0.001</td>
<td>0.047 – 0.006</td>
</tr>
<tr>
<td>Maximum degree</td>
<td>k_max</td>
<td>#</td>
<td>8</td>
<td>3.58 – 3.91</td>
</tr>
<tr>
<td>Minimum degree</td>
<td>k_min</td>
<td>#</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Average degree</td>
<td>⟨k⟩</td>
<td>#</td>
<td>2.598</td>
<td>1.18 – 1.24</td>
</tr>
<tr>
<td>Average strength</td>
<td>⟨s⟩</td>
<td>km</td>
<td>14.108</td>
<td>6.41 – 6.734</td>
</tr>
<tr>
<td>Average edge length</td>
<td>⟨d(e_i)⟩</td>
<td>km</td>
<td>5.388</td>
<td>2.438 – 2.583</td>
</tr>
<tr>
<td>Total edge length</td>
<td>∑_y d(e_y)</td>
<td>km</td>
<td>35,860</td>
<td>488.5 – 659.514</td>
</tr>
<tr>
<td>Average path length (binary)</td>
<td>⟨l⟩</td>
<td>#</td>
<td>46.794</td>
<td>6.067 – 7.682</td>
</tr>
<tr>
<td>Average path length (weighted)</td>
<td>d(⟨l⟩)</td>
<td>km</td>
<td>247.52</td>
<td>32.57 – 41.49</td>
</tr>
<tr>
<td>Network diameter (binary)</td>
<td>d_hom(G)</td>
<td>#</td>
<td>144</td>
<td>16.12 – 20.43</td>
</tr>
<tr>
<td>Network diameter (weighted)</td>
<td>d_w(G)</td>
<td>km</td>
<td>993</td>
<td>111.16 – 140.882</td>
</tr>
<tr>
<td>Clustering coefficient (network)</td>
<td>C</td>
<td>net</td>
<td>0.042</td>
<td>0.022 – 0.029</td>
</tr>
<tr>
<td>Average clustering coefficient</td>
<td>⟨C⟩</td>
<td>net</td>
<td>0.07</td>
<td>0.036 – 0.048</td>
</tr>
<tr>
<td>Network modularity</td>
<td>Q</td>
<td>net</td>
<td>(0.683)</td>
<td>0.715 – 0.798</td>
</tr>
</tbody>
</table>

a. 95% confidence interval for the mean (computed for the sub-networks)

b. Number of elements

c. Dimensionless number

d. Proportionally adjusted to the number of communities (i.e. divided by the number of communities/components)
Results and Discussion

Network analysis (network measures)

- The clustering coefficient is $C_{GRN} = 0.042$ and the average clustering coefficient is $= 0.114$, which is considerably different from the expected value ($\sim 1/n = 2 \cdot 10^{-4}$) of an ER random network, implying causality (non-randomness) in the configuration of the road network in Greece.

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</tr>
<tr>
<td>Network components</td>
<td>$\alpha$</td>
<td>#</td>
<td>156</td>
<td>2.568 – 3.34</td>
</tr>
<tr>
<td>Graph density (planar)</td>
<td>$\rho_1$</td>
<td>net</td>
<td>0.433</td>
<td>0.45 – 0.461</td>
</tr>
<tr>
<td>Graph density (non-planar)</td>
<td>$\rho_2$</td>
<td>net</td>
<td>0.001</td>
<td>0.047 – 0.006</td>
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<tr>
<td>Maximum degree</td>
<td>$k_{\text{max}}$</td>
<td>#</td>
<td>8</td>
<td>3.58 – 3.91</td>
</tr>
<tr>
<td>Minimum degree</td>
<td>$k_{\text{min}}$</td>
<td>#</td>
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<td>1</td>
</tr>
<tr>
<td>Average degree</td>
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<td>#</td>
<td>2.598</td>
<td>1.18 – 1.24</td>
</tr>
<tr>
<td>Average strength</td>
<td>$\langle s \rangle$</td>
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<td>14.108</td>
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</tr>
<tr>
<td>Average edge length</td>
<td>$\langle d(e) \rangle$</td>
<td>km</td>
<td>5.388</td>
<td>2.438 – 2.583</td>
</tr>
<tr>
<td>Total edge length</td>
<td>$\sum d(e)$</td>
<td>km</td>
<td>35,860</td>
<td>488.5 – 659.514</td>
</tr>
<tr>
<td>Average path length (binary)</td>
<td>$\langle l \rangle$</td>
<td>#</td>
<td>46.794</td>
<td>6.067 – 7.682</td>
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<tr>
<td>Average path length (weighted)</td>
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<td>km</td>
<td>247.52</td>
<td>32.57 – 41.49</td>
</tr>
<tr>
<td>Network diameter (binary)</td>
<td>$d_{\text{bin}}(G)$</td>
<td>#</td>
<td>144</td>
<td>16.12 – 20.43</td>
</tr>
<tr>
<td>Network diameter (weighted)</td>
<td>$d_{\text{w}}(G)$</td>
<td>km</td>
<td>993</td>
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</tr>
<tr>
<td>Clustering coefficient (network)</td>
<td>$C$</td>
<td>net</td>
<td>0.042</td>
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</tr>
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<td>0.036 – 0.048</td>
</tr>
<tr>
<td>Network modularity</td>
<td>$Q$</td>
<td>net</td>
<td>0.946</td>
<td>(0.683)^d</td>
</tr>
</tbody>
</table>

^d Proportionally adjusted to the number of communities (i.e. divided by the number of communities/components)
Results and Discussion

Network analysis (network measures)

• The modularity has a score of $Q_{GRN} = 0.946$, which expresses a strong capability to be divided into communities.

• An adjusted modularity score to the number of communities (due to disconnectedness) can result as $Q_{GRN} = 0.946/(216/156) = 0.683$, which describes the high capability of GRN to be divided into communities.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Symbol</th>
<th>Unit</th>
<th>Aggregate</th>
<th>Sub-networks$^{(a)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network nodes</td>
<td>$n$</td>
<td>#</td>
<td>4,993</td>
<td>82.04 – 107.14</td>
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<tr>
<td>Network edges</td>
<td>$m$</td>
<td>#</td>
<td>6,487</td>
<td>100.12 – 133.84</td>
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<tr>
<td>Self-loops</td>
<td>$n(e_i \in E)$</td>
<td>#</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Isolated nodes</td>
<td>$n(k=0)$</td>
<td>#</td>
<td>0</td>
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<td></td>
<td>(0.683)$^{d}$</td>
<td>0.715 – 0.798</td>
</tr>
</tbody>
</table>
Results and Discussion

Network analysis (spy plot)

• The spy plot illustrates a linear pattern of connectivity, along the main-diagonal of the adjacency.
• This linear pattern illustrates the development of links (connections) mostly between successive (neighbor) nodes in the network.
• The arrangement implies a lattice-like topology for the GRN, where the existence of spatial constraints is considerable.
Results and Discussion

Network analysis (spatial distributions)

• The degree shows that GRN has a mesh (lattice-like) topology, where the degree-hubs are scattered along the mainland, without being connected.

• This observation implies the existence of spatial constraints in the topology of the GRN, which is incapable to develop direct links (connectivity) between the hubs and thus is incapable to develop a more complex structure of hierarchy.
Results and Discussion

Network analysis (spatial distributions)

- The modularity classification configures a map where network communities show strong geographical dependence.
- This observation indicates the existence of spatial constraints and complies with other literature findings.
Results and Discussion

Network analysis (spatial distributions)

• The distribution of betweenness-hubs undertaking the major traffic-load of GRN, configures an “S”-shaped pattern along the eastern coastal line of the country.

• This pattern complies with the “S”-shaped pattern of Greek regional development.
Network analysis (spatial distributions)

- The distribution the map of **closeness centrality** shows that nodes located at **central** geographical places enjoy **higher scores** of closeness centrality, whereas nodes located at the **periphery do not**.

- The **bridge connection** of the regions of Attiki (6) and Korinthia (29) also enjoys high scores of closeness centrality, although it is not located at the geographical core in the mainland.

- Highest scores for the island components is a result of insufficient connectivity.
Results and Discussion

Correlation analysis

- The **majority** of network variables (NODES, EDGES, ADEG, DIAM, MOD, APL, ACC) **include** (either high or moderate) **information** about the network infrastructure.

- This implies that **network variables** are related to **structural aspects** of the road transportation network, which is somewhat expected to the extent that network topology and geometry are interacting concepts in spatial networks.
Correlation analysis

• Network variables NODES, EDGES, DIAM, and APL are positively correlated with GDP, $T_{\text{GDP}}$, and POP, implying that the size-defined and path-defined network variables also include demographic and economic and productivity information.

• This suggests a first indication of interpreting the size and path-defined aspects of the GRN’s network topology as a socio-economic indicator.
Results and Discussion

Correlation analysis

- The **negative correlation** between **modularity (MOD)** and **urbanization (URB)** describes that road networks with high capability to be divided into communities are more likely to meet in less urbanized regions.

- This implies that **high levels of urbanization compete to community development** and thus to regional polycentrism.

- **Modularity** may operate as an indicator of **polycentrism and monocentrism** in the regional structures where these road networks are developed.
Correlation analysis

- Negative correlations between the centrality variables (ACC, ACB) and the network infrastructure-variables of complementary (to land) transportation modes (PRT, APRT) as well as to the tertiary sector specialization ($C_{SEC}$).
- Greek regions with road transportation networks of high centrality are less likely to be supported with highly developed facilities of port and airport infrastructures.
- They are also less likely to have high tertiary sector specialization.
Correlation analysis

- These results imply the **competing roles** between network centrality and the level of investments in port and air transportation modes as well as the specialization in the tertiary sector.

- This analysis of GRN provides **insights** into considering these centrality-based measures as indicators of infrastructure development of complementary to land transport modes and the tertiary sector development.
Principal component analysis

- 6 principal components explain an amount of ~81% of the total variance
- Figures c and d filter the max and min values of the PCA coefficients
- Each component appears to have a different semiology composed by the physical meanings of the network and socio-economic variables being projected to each one
## Principal component analysis

<table>
<thead>
<tr>
<th>Principal Component</th>
<th>POSITIVE</th>
<th>NEGATIVE</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC#1</td>
<td>Size and geometry of network infrastructures; Population size; Size of productivity.</td>
<td>Level of urbanization.</td>
</tr>
<tr>
<td>PC#2</td>
<td>Road density; Development of complementary (to land) transportation modes; Tertiary sector specialization.</td>
<td>Network geometry, Primary sector specialization.</td>
</tr>
<tr>
<td>PC#3</td>
<td>Intermediacy and industrialization.</td>
<td>Network size; Tertiary sector specialization.</td>
</tr>
<tr>
<td>PC#4</td>
<td>-</td>
<td>Development of complementary (to land) transportation modes; Secondary sector specialization; Regional productivity dynamism.</td>
</tr>
<tr>
<td>PC#5</td>
<td>Builds on the notions of road network clustering and urbanization.</td>
<td>Regional polycentrism; Accessibility; Major regional productivity.</td>
</tr>
<tr>
<td>PC#6</td>
<td>Builds on the concepts of accessibility and productivity in the primary sector and negatively on the concepts of network clustering and road density.</td>
<td>Network clustering; Road density.</td>
</tr>
</tbody>
</table>
Principal component analysis

• The first principal component (PC#1) is positively related to network size (NODES, EDGES), connectivity (ADEG), network path (DIAM, APL), modularity (MOD), network infrastructure (RDL, AREA), the gravitational-productivity configuration (POP, GDP), and tourism specialization ($T_{GDP}$).

• Although seems complex, its semiology highlights the conceptual conjunction between network size and length, network infrastructure, population, and the major productivity configuration of Greece.

• This semiology was also observed at the previous correlation analysis, where size and path-defined aspects of the GRN’s network topology were found to be correlated with variables GDP, $T_{GDP}$, and POP.

• The negative relation of this component with the variable of regional urbanization (URB) complies with another previous finding of the correlation analysis about the negative correlation captured between modularity (MOD) and urbanization (URB).
Principal component analysis

• The **second** principal component (PC#2) is **positively related** to the regional **density** of the **road network** (RDD), **port** and **airport infrastructures** (PRT, APRT), and the **specialization** in the **tertiary sector** ($C_{SEC}$).

• Is **negatively related** to **network connectivity** (ADEG), network **path-length** (DIAM, APL), network **infrastructure** (RDL, AREA), and the **primary sector specialization** ($A_{SEC}$).

• The semiology of this component overall regards the **relevance** of **road density** with the **tertiary sector** and with the **complementary** (to land) transportation modes, implying generally that the **density** of regional **road networks operates** in the service of the **tertiary sector** and it also **facilitates** the **development** of complementary transportation modes.

• This observation refers to the theories of **economies of scale** and the **emergence** of **gateways** and one of its aspects is also evident by the negative correlations captured between the **closeness centrality variable** ($ACC$) and the variables PRT, APRT, and $C_{SEC}$. 
Results and Discussion

Principal component analysis

- The third principal component (PC#3) is positively related to the betweenness centrality of GRN (ACB), the specialization in the secondary sector (BSEC), and the regional productivity dynamism,

- Is negatively related to network size (NODES, EDGES) and the tertiary sector specialization (CSEC).

- This observation is supported by the negative correlations captured between the betweenness centrality (ACB) and the variables PRT, APRT, and CSEC.

- The semiology of this component builds on the concepts of intermediacy and industrialization and inversely on the concepts of network size and regional specialization in services.

- Regions with networks of high intermediacy (betweenness centrality) facilitate the development of the secondary sector and compete with the functionality of the tertiary sector. This interpretation verifies the established theoretical approaches regarding the interrelation between accessibility and industrial location.
Principal component analysis

• The fourth principal component (PC#4) is **negatively related** to the complementary (to land) transportation modes (PRT, APRT), the secondary sector specialization ($B_{SEC}$), and the **regional productivity dynamism** and it appears to have an almost inverse semiology with the positive configuration of the principal components 2 and 3.

• Conceptually, component 4 highlights the **relevance between port and airport infrastructures** and the **development of regional productivity**, and particularly of the **secondary sector**.

• The semiology of this principal component may be related to the **theories of transportation of freight** and the **development of gateways in logistics networks**.
Principal component analysis

- The **fifth** principal component (PC#5) is **positively related** to the average **clustering** coefficient (AC) and the level of regional **urbanization** (URB),

- Is **negatively** related to the **network modularity** (MOD), network **accessibility** (ACC), and major aspects of **regional productivity** (POP, GDP, \( T_{GDP} \)).

- Conceptually, this component builds on the notions of road network **clustering** and **urbanization**, referring to the theories of **connectivity** and **polycentric urban development**, and **negatively** on the notions of **community partition**, **accessibility**, and **gravitational regional productivity**, referring to the theories related to **economies of agglomeration**.
Principal component analysis

- The sixth principal component (PC#6) is positively related to the closeness centrality of GRN (ACC) and the specialization in the primary sector ($A_{sec}$), whereas it is negatively related to network clustering (AC) and the road density (RDD).

- The semiology of the sixth component builds on the concepts of accessibility and productivity in the primary sector and negatively on the concepts of network clustering and road density, implying that accessibility is a major factor in the development of the primary sector to which network clustering and density compete.

- This conceptualization is related to the major need for space for the development of agricultural productivity.
# RESULTS AND DISCUSSION

## Tabulation

<table>
<thead>
<tr>
<th>Network measure</th>
<th>SE-performance Indicator</th>
<th>POSITIVE LINKAGE</th>
<th>NEGATIVE LINKAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NODES</td>
<td></td>
<td>Network infrastructure density and size; Demographic size; Economic size; Productivity size.</td>
<td>Intermediacy and industrialization.</td>
</tr>
<tr>
<td>EDGES</td>
<td></td>
<td>Network infrastructure density and size; Demographic size; Economic size; Productivity size.</td>
<td>Intermediacy and industrialization.</td>
</tr>
<tr>
<td>ADEG</td>
<td></td>
<td>Network infrastructure density and size.</td>
<td>Development of complementary transport modes.</td>
</tr>
<tr>
<td>DIAM</td>
<td></td>
<td>Network infrastructure density and size; Demographic size; Economic size; Productivity size.</td>
<td>Development of complementary transport modes.</td>
</tr>
<tr>
<td>MOD</td>
<td></td>
<td>Network infrastructure density and size; Development of regional polycentrism.</td>
<td>Urbanization.</td>
</tr>
<tr>
<td>AC</td>
<td></td>
<td>Regional urbanization.</td>
<td>Development of regional polycentrism.</td>
</tr>
<tr>
<td>APL</td>
<td></td>
<td>Network infrastructure density and size; Demographic size; Economic size; Productivity size.</td>
<td>Development of complementary transport modes.</td>
</tr>
<tr>
<td>ACC</td>
<td></td>
<td>Network infrastructure density and size; Development of the primary sector.</td>
<td>Development of complementary transport modes; Development of the tertiary sector.</td>
</tr>
<tr>
<td>ACB</td>
<td></td>
<td>Development of the secondary sector.</td>
<td>Development of complementary transport modes; Development of the tertiary sector.</td>
</tr>
</tbody>
</table>
Results and Discussion

Tabulation

• The number of nodes (NODES), the number of links (EDGES), the diameter (DIAM), and the average path length (APL) of GRN can be related to infrastructure, demographic, economic, and productivity’s information of the region including the network.

• The average degree (ADEC) appears more specialized and can be related just to infrastructure information (network infrastructure density and size).

• Except for infrastructure information, the modularity (MOD) can be related to the urbanization level and the polycentric structure of the regions.
Tabulation

• The **average clustering coefficient** (AC) can also be related to regional urbanization,

• The **average closeness** (ACC) and **betweenness** (ACB) centrality, except **infrastructural information**, may provide insights into the level of **development** of **complementary** transport modes, and of the **productivity sectors** (primary, secondary, and tertiary)
Results and Discussion

Tabulation

• Based on the exploratory nature of the research and the certain geographical scale of this case study, the correspondences cannot lead to a universal semiology (i.e. free of geographical scale and the peculiarities of the case study) of the topological measures they involve.

• This is because, first, the network modeling parameters (e.g. the choice of primal representation, the repairing method of insufficient connectivity, the edge-weights selection, the regional configuration of the sub-networks, etc.) are each time reflected on the topological features of the network-model and, secondly, the underlying living structure of a network refers to a certain market or an economic system.

• However, within the empirical context of this research, the overall approach succeeded to highlight the relation between network topology and the socio-economic information of its (real-world) underlying living structure and therefore it provided universal methodological evidence and specialized insights based on the case study to support the linkage between these two concepts.
Conclusions

• This paper modeled the interregional road transportation network in Greece (GRN) into a geo-referenced primal graph and it discussed its geographical and topological features under the regional economics’ perspective.

• The study aimed at serving the demand for integration in transportation research by detecting links between network topology, economy, and space.

• The analysis showed that the GRN is a network submitted to spatial constraints highlighting that road networks are majorly configured by geographical forces.
Conclusions

• The lattice-like configuration of this road network and its incapability to develop links between the hubs implies the restriction of GRN to develop more effective network topologies, such as a scale-free or a rich-club topology, and thus to improve its structural efficiency in terms of hierarchy.

• This restriction seems to be related to the developmental constraints due to the network’s geographical framework, which is reflected in the uneven traffic dynamics of the eastern and western parts of the country.
Conclusions

• The analysis also provided insights into considering some aspects of network topology as indicators of economic performance.

• In particular, the network size (number of nodes, number of edges) and network length (network diameter, average path length) appeared to be related to population and productivity-controlled variables, such as the regional GDP and regional specialization in tourism (which is a major economic sector in Greece).

• The modularity expressing the network’s potential to be divided into communities appeared to be related to regional urbanization and thus capable to operate as an indicator of polycentrism and mono-centrism in the regional structures.
Conclusions

• Centrality-based measures of the GRN, such as the **closeness** and **betweenness** centrality, showed **relevance** with aspects of **productivity** and of the **development** of **complementary transportation modes**.

• The **closeness centrality** appeared to be **positively related** to the regional specialization in the **primary sector** and **negatively** to the regional specialization in the **tertiary sector** and the **development** of **port and airport infrastructures** in the region.
Conclusions

• The betweenness centrality appeared to be positively related to the regional specialization in the secondary sector and negatively to the regional specialization in the tertiary sector and the development of airport infrastructures in the region.

• The overall approach highlighted the effectiveness of complex network analysis in spatial planning and regional economic analysis and it showed that graph modeling of road networks suffices to provide insights into the socio-economic, geographical, spatial, and developmental framework of these transportation systems.


• Hellenic Statistical Service – ELSTAT (2011) “Results of the census of population-Habitat 2011 referring to the permanent population of Greece”, *Newspaper of the (Greek) Government (ΓΕΚ)*, Second Issue (T-B), Number 3465, 28-12-12.


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