Inter-urban Transit Connections: A Network Analysis in an Italian Region

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Abstract. Connectivity between urban centers is a key element for the development of territories. Public transport by road and rail are the two modes of transport most affected by extra-urban connections by land on a regional scale. To analyze these connections, it is interesting to refer to the methods offered by Network Analysis (NA).

In this paper, we want to study the centrality characteristics of interurban transport networks - both bus and train - on a regional scale, taking as a reference the direct connections between cities. This allows us to identify gaps and define hierarchies of network nodes, starting from the movement possibilities present in a node compared to the others.

NA is the methodology used; it allows to obtain synthetic centrality indicators in a network. In this article, two of the main indicators of NA (i.e., Degree Centrality, Strength Centrality) are applied to a test case of regional extension. Methodology used involves evaluation of Degree Centrality in a time-constrained network. Two different networks are considered and compared: the railway and the extra-urban bus transport network. The methodology considered allows to evaluate the centrality of the urban nodes considered with respect to each of the two networks; in this way, it is possible to compare the centrality values on the two networks between them. The case study highlighted is the Sicilian region, in Southern Italy. The analysis involves the study of centrality of the region's main cities. The results highlight asymmetrical differences between the different territories considered and large margins for improvement of the network. Furthermore, among the conclusions, it is interesting to recall the distortions present between the two modes of transport studied.

Keywords: Sustainable mobility · Network Analysis · Extra-urban transportation · Centrality · Accessibility

1 Introduction

The development of an efficient transport system that allows for faster connections and brings territories closer together is an objective consistent with the SDGs of Agenda 2030. In the European Union, connectivity plays a central role. The TEN-T network,

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within its Comprehensive network, aims to make even the most peripheral territories of the Union connected to the network, through the development of key infrastructures [1, 2]. Accessibility to the transport system, and connectivity within it, are central elements in the sustainable development of Agenda 2030. Several objectives are directly linked to the transport system [3]. It is particularly useful to recall three of them. SDG 13 "*Take urgent action to combat climate change and its impacts*" focuses on decarbonisation; with regard to land transport, a modal shift from rubber to rail is essential, in a logic of reducing CO_2 emissions [4]. In light of SDG 9 "*Build resilient infrastructure, promote sustainable industrialization and foster innovation*" it is clear how sustainable infrastructure is at the heart of the Sustainability Agenda: interventions on railways (construction of new lines, electrification of pre-existing lines) fall within this scope. Finally, SDG 11 "*Make cities inclusive, safe, resilient and sustainable*" concerns the transport system, especially in light of Target 11.2 "*By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and older persons*", for the implications of the modal shift from road to rail on road safety and the quality of transport on an urban and extra-urban scale [4].

In this context, the study of the transport infrastructural and services subsystems of the most peripheral and less developed areas of the EU is particularly useful. This paper investigates the centrality of a public transport system on a regional scale, by referring to the EU classification Nomenclature of Territorial Units for Statistics (NUTS), and in particular the NUTS-2 class [5]. In this specific case, the region investigated is Sicily, one of the poorest regions in Italy and in the entire EU [6].

It is of fundamental importance, on a regional scale, to define the aggregate characteristics of the networks for extra-urban transport, considering the environmental needs of a modal shift towards more sustainable modes of transport. Sicily is characterized by an extension of 25,832.4 km^2 [7], the absence of inland waterways and a more concentrated population in coastal areas. For this case study the comparison between transit by road and transit by rail is essential to understand how much the latter can be "dominant" compared to the former and how much, instead, development opportunities are still necessary.

Recent scientific literature proposes a set of methodologies for analysing transport supply systems.

Transport supply models commonly known in literature are part of the broader Transportation System Models (TSM) field of study. They give several methods to analyze and measure structure of existing transportation supply network, allowing ex-ante evaluations of project configurations [8]. Classical TSM methods are used to study problems related to railway transport [9–11]. However, these methodologies often lack the capabilities to produce complete and aggregate indicators of supply structure. Methods from Network Analysis (NA) and classical graph theory may offer synthetic indicators to describe supply network's structure, giving details about operations on transportation network [12, 13].

Through the tools provided by network analysis, the study intends to evaluate two supply subsystems: the railway services subsystem and the extra-urban public transport

services subsystem by road, considering the provincial capitals of the studied region as a reference.

The study is primarily oriented towards planners, managers of infrastructure companies and public administrators, due to the implications offered by the synthetic nature of the indicators proposed for the analysis of complex networks.

The work is structured as follows. Section 2 recalls the main literature references of the considered field. Section 3 describes the methodological tools of network analysis adopted. Section 4 describes the case study and presents the results obtained. Finally, Sect. 5 discusses the results, and the main conclusions.

2 Background

The analysis of the centrality of a network focuses on the classification of the analysed network nodes according to synthetic and analytical criteria. NA allows the importance of a node within a network to be defined [14]. NA can be used in those contexts in which a system can be represented as a network of point elements and their relationships. The applications in the literature are diverse: geopolitical studies, economic [15, 16], and social network analysis [17, 18].

In the transport sector, it has found wide application in public transport [19, 20] as well as in maritime and air transport [21, 22].

In this sense, transport networks are analysed through the representation of relationships between nodes and the estimation of centrality.

In transport networks, centrality measures are useful to obtain synthetic information on the topology and organisations of the network, with reference to both infrastructure and services. NA indicators determine the level of importance of transport nodes, their centrality in the network and the characteristics of their interactions. These elements are useful for identifying any criticalities in existing networks and then designing interventions to overcome them.

Various applications are present in the railway case and have been applied to networks in Asian [23–25] and European countries [26]. The proposed analyses have made it possible to analyse large-scale railway networks and to assess their connectivity and centrality characteristics.

In the study under examination, a central element is the study of the relationships between cities and the possibilities of movement that the supply system offers to users. In this sense, the research is directed towards the study of service networks and not towards the network of infrastructures.

In the following, for the treatment of network analysis in the railway sector, reference is made to the following treatment reported in the literature. Referring to [27], there are two main methods for representing a network of railway relations:

- The first method models the network as a bipartite graph, where nodes are divided into two distinct sets: a set S representing stations and a set T representing train services. A link between a station $s \in S$ and a train service $t \in T$ exists only if train t stops at station s;
- The second method constructs a graph in which the nodes directly represent the stations of the railway network. Two stations, i and j, belonging to set S, are connected

to each other if there is at least one railway service that stops at both of them. The network obtained in this way is called a *weighted station-station network*. This approach is widely used in railway network modelling, as it offers a more immediate representation of the structure of the connections between the stations.

In the following sections, the second method for representing the railway network will be considered, and the same criterion is adopted for the extra-urban public transport network.

3 Methodology

The main element of the study is the characterization of the centrality of the network nodes. Network analysis allows, as defined in Sect. 2, to quantitatively characterize and classify the nodes of a network. The proposed study for the application of network analysis to the two transport systems is divided into three sequential moments: data acquisition, data preparation, network analysis indicators.

The "data acquisition" is necessary to define the criteria of the study and the acquisition of data useful for the analysis of the transport system considered. In the case in question, two public transport systems are to be studied: the railway service network and the extra-urban road public transport service network. The elements to be defined and the data to be acquired are the following:

- The geographical area of reference (nation, region, city);
- The geographic aggregation needed. Depending on the nature of the study, it may be useful to provide a different degree of aggregation or to analyze the system in a completely disaggregated way;
- Time interval t;
- Public transport operators;
- The timetable of services operating within the reference area in the time period considered;
- The criterion for defining the existence of a relationship between two nodes of the network.

First two points define the nodes of the network. The remaining ones characterize the arcs of the network. Last point is linked to the type of territorial aggregation considered. In this study, all provincial capitals are considered, and the single node is expressed by the generic provincial capital of the study area defined in the first point. There is a relationship with the transport mode m between two provincial capitals i, j if there is, at time t, a direct service managed by the operator k $r_{ij,m,k}(t)$ that links having origin in node i and destination in node j, or a service $r_{ji,m,k}(t)$ having origin in node j an destination in node i. The analyzed services, both railway and road transport, are generally balanced; it is possible to assume that there are as many inbound as outbound services. As a consequence, we will work on undirected graphs.

The "data preparation" defines, for each mode of transport considered, the adjacency matrix $A_{ij,m}(t)$ and their generic element $a_{ij,m}(t)$ defined as:

$$a_{ij,m}(t) = \begin{cases} 1, \text{ if } \exists r_{ij,m,k}(t) \mathrm{V} r_{ji,m,k}(t), i \neq j \\ 0, \qquad\qquad otherwise \end{cases} \tag{1}$$

The relationship analytically represents the transport network of mode m, and the existence of direct services enabled by the available services in the time t. The definition provided for the adjacency matrix allows to evaluate, with the same criterion, both the public transport network on the road and the railway transport network. In this work, the focus is on the possibilities of movement, from city to city, through direct connections. Therefore, between the two structures typically present in the literature of network analysis, L-space and P-space, the latter is used, because of its capability to represent relations between nodes [28, 29]. The definition provided for $a_{ij,m}(t)$ allows to define the graph in P-space from the presence of at least one direct connection. Once the adjacency matrix has been defined, it is then possible to describe the graph $G = (V, E)$, with V set of nodes and E set of edges, that characterizes the network for transport mode m. Let N be the number of nodes in the graph. Considering the direct connections between nodes i and j, it is also possible to define the value of $f_{ij,m}(t)$, frequency of service of mode m, expressed as the sum, extended to all operators k of mode m, of the existing services.

The third step is the application of network analysis indicators. In the study in question, three indicators are proposed: Degree Centrality, Strength Centrality and Constrained Degree Centrality.

The Degree Centrality (DC) is expressed as

$$c_{i,m}(t) = \frac{\sum_j a_{ij,m}(t)}{N - 1} \tag{2}$$

DC defines the ratio between the sum of the connections of node i with the other nodes of the network compared to the total potential connections (N-1), referred to the mode m. The DC evaluates the degree of connection of each node of the network. A high DC value, close to 1, indicates that the generic node has many connections; a low value indicates that the node has few connections. It is also possible to evaluate the distribution of the degree centrality among the different nodes, evaluating the percentage of nodes that have a certain degree value. The reconstruction of the distribution of the DC allows to obtain overall information on the degree of interconnection of the network.

The limit of Degree Centrality is that it only provides a condition of existence for the connection between two nodes, without defining its entity.

Since it has been specified that the graphs considered for the study are undirected, it is necessary to specify a quantitative measure to define the Strength Centrality that takes into account both the path from i to j and the opposite path. In this work the formulation of Strength Centrality (SC) proposed is

$$s_{i,m}(t) = \sum_j f_{ij,m}(t) + \sum_j f_{ji,m}(t) \tag{3}$$

SC evaluates the centrality of the generic node i considering the sum of the frequencies entering and exiting node i. SC therefore allows to correct the distortion induced by DC, whereby two nodes could share the value of connections even though they have completely different frequencies by orders of magnitude.

The third proposed indicator, the Constrained Degree Centrality (CDC), allows to provide an aggregate quantitative value on the connections in a specific Δ. Given $\tau_{ij,m}$, the time considered as a reference for the service with mode m to connect nodes i and

j, it is possible to define the generic $a_{ij,m}(t)^{\Delta}$; Its value is 1 if $\tau_{ij,m} < \Delta$, 0 otherwise. In this way, it is possible to define the indicator as:

$$cc_{i,m}(t)^{\Delta} = \frac{\sum_j a_{ij,m}(t)^{\Delta}}{N-1} \tag{4}$$

The cc indicator measures the number of direct connections that respects a specific time constraint. The proposed formulation takes up the one expressed in Eq. (2) adapting it to the case of a temporal cutoff Δ.

The paper studies the characteristics of the direct connections between the nodes of the considered network. Therefore, the methodology described is focused on the two indicators that allow to provide synthetic measures of the direct connec-tions of a node on a network represented in P-space. Other indicators commonly used within the NA (Closeness, Betweenness, Eigenvector Centrality) refer to the study of paths that, in a railway network, represent interchanges and transfers, outside the scope of the research.

4 Results

This Section presents the results of the analysis. Section 4.1 describes the case study; Sect. 4.2 presents the obtained results by applying the formulations presented in Sect. 3.

4.1 Case Study

The analysis focuses on the study of extra-urban connections by train and bus between the nine former provincial capitals of the Sicilian Region. Sicily is the fifth Italian region by population, with 4,797,359 inhabitants [30]; with around 40% of its inhabitants at risk of poverty, it is among the poorest regions in Europe [31]. It has a motorway network of approximately 400 km managed by ANAS [32] and approximately 320 km managed by CAS [33] and a railway network of 1,370 km managed by Rete Ferroviaria Italiana (RFI) and 110 km managed by Ferrovia Circumetnea (FCE) [34, 35] (Fig. 1).

The transport operators consulted for the analysis of the problem are reported in Table 1. The other railway company operating in Sicily, FCE, is not present in the study because the line on which it operates does not connect different provincial capitals. The road transport companies considered in the study are all those that have at least one direct connection between two provincial capitals.

The criterion for defining a connection between two capitals, given the two modes of transport considered (train and bus) is the existence of a direct connection between the two corresponding nodes. As a case study, the services present on a generic winter weekday were considered.

Data were provided by the operators reported in Table 1; the timetables used as a reference are freely available on the respective sites. The study considers daily intervals. The services considered are all those with a departure time within the date considered. The choice of the weekday allows to study the case in which there are the greatest number of services.

Only direct services were indicated on all the relations considered.

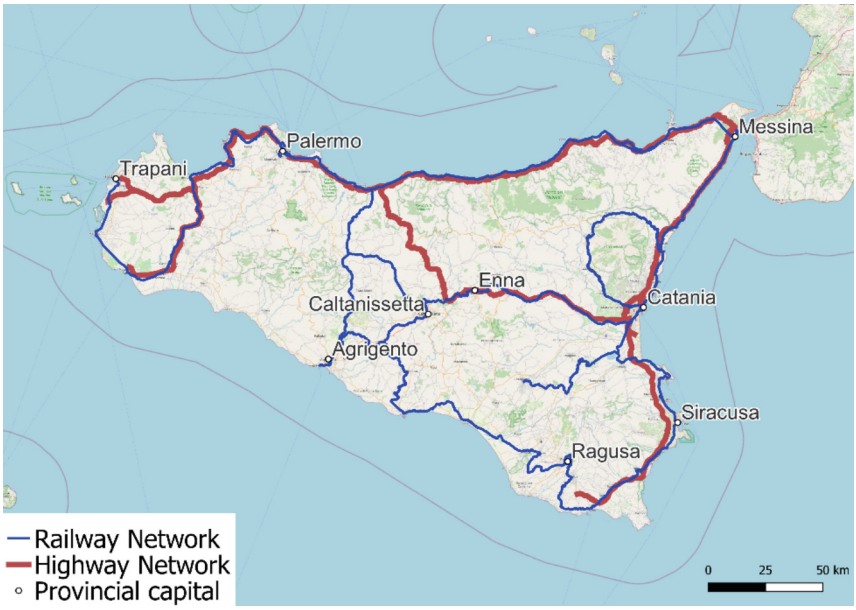


Fig. 1. Railway and Highway Network of Sicily. Source: Openstreetmap; QGIS [36, 37].

As of 2025, there are two lines with suspended circulation (Trapani-Palermo and Gela-Caltagirone) not shown in the image. Furthermore, on the stretch between Catania and Enna, circulation is temporarily suspended due to work on the doubling of the line [36–40].

Due to the temporary interruption on the Palermo-Catania railway line, for the connections from Catania to Enna, Caltanissetta and Palermo, the services that include a replacement bus from the Trenitalia company were considered.

Table 1. Transportation companies considered in the study.

Company	Train/Bus	Area	Reference
AST	Bus	Catania-Siracusa, Siracusa-Ragusa, Palermo-Ragusa	[41]
Astra autolinee	Bus	Caltanissetta-Enna	[42]
Autolinee lumia	Bus	Trapani-Agrigento	[43]
Autoservizi Cuffaro	Bus	Palermo-Agrigento	[44]
Camilleri Argento & Lattuca	Bus	Palermo-Agrigento	[45]
Etna trasporti	Bus	Catania-Ragusa	[46]
Flixbus	Bus	Regional scale	[47]
Interbus	Bus	Siracusa-Enna, Siracusa-Catania	[48]

(*continued*)

Table 1. (*continued*)

Company	Train/Bus	Area	Reference
SAIS	Bus	Regional scale	[49, 50]
SAL Autolinee	Bus	Agrigento-Palermo	[51]
Segesta autolinee	Bus	Palermo-Trapani	[52]
Trenitalia	Train	Regional scale	[53]

4.2 Analysis

Considering the timetable of the companies considered in Table 1, the two graphs are shown in Fig. 2.

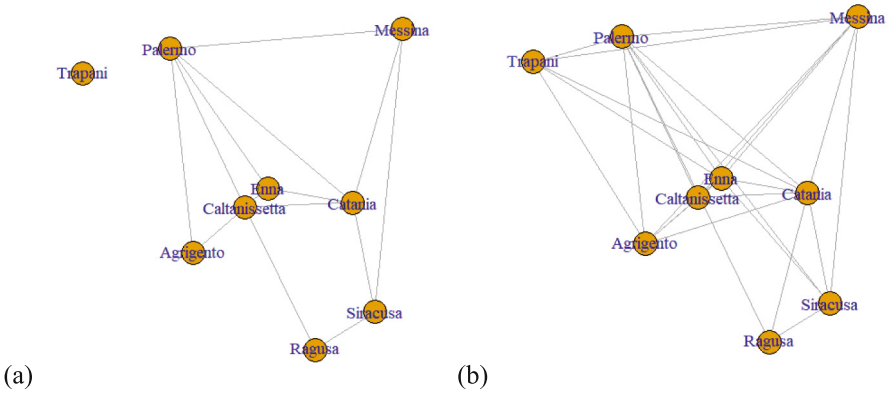


Fig. 2. (a) Railway and (b) Bus network.

The Degree Centrality values for the nodes of the two networks under examination are reported in Fig. 3.

Figure 4 defines the statistical distribution of the DC for the two networks.

The representation in Fig. 4 shows the cumulative DC for the two transport modes considered. For the railway network, the cumulative reaches 100% of the nodes at the value of 5 connections. This indicates that all the nodes have 5 connections, or less, out of the 8 total. The cumulative value of the bus network has a less steep trend and reaches 100% of the nodes at the value of $c_i = 8$, indicating that at least one node has all the possible connections. This further confirms that the bus network shows a greater interconnection than the railway network. The maximum value of DC for the train network (5) is reached by three nodes (Palermo, Catania, Caltanissetta), while the

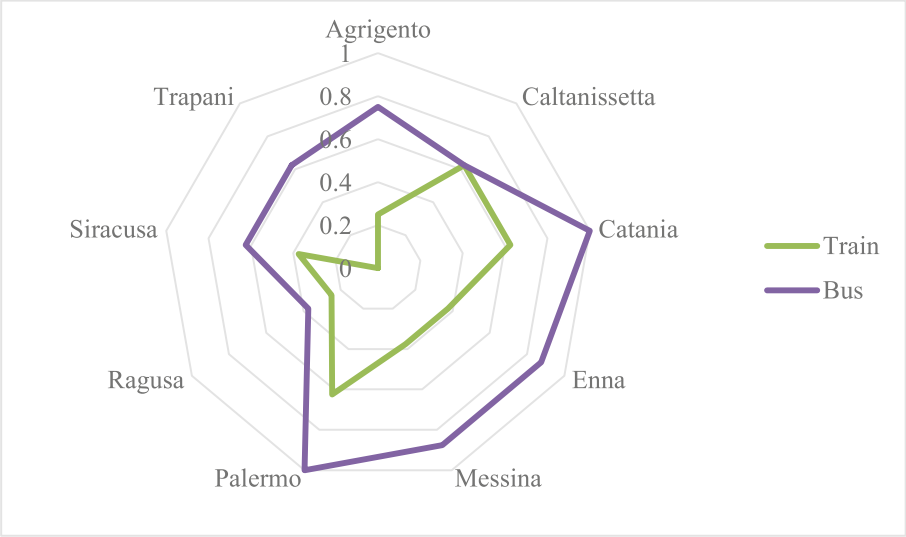


Fig. 3. Rail and bus network node degree centrality (ci)

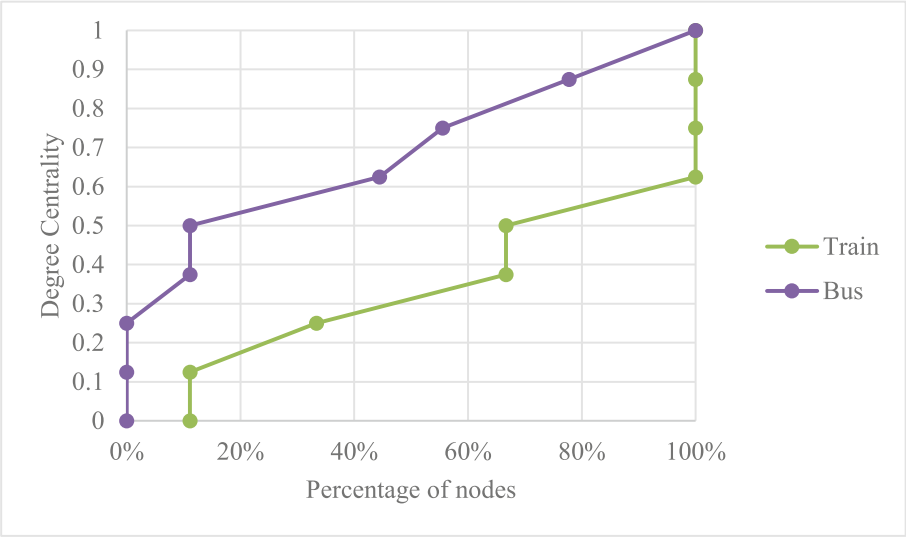


Fig. 4. Railway and Bus network cumulated DC

maximum value of DC for the bus is 8 (the Catania and Palermo nodes are connected with all the other possible nodes), but the value of 7 is reached by Enna and Messina. The result therefore shows a greater interconnection of the bus network.

The result regarding Strength Centrality is reported in Fig. 5.

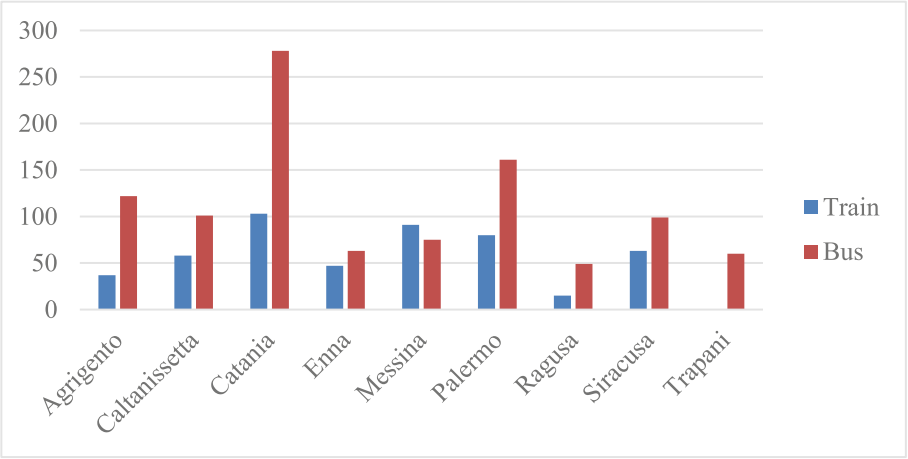


Fig. 5. Strength Centrality

The strength centrality relative to the two networks considered sees a higher value for the bus for all the nodes of the network, except for Messina for which there are more train connections than bus connections. This is mainly because the two most heavily trafficked railway lines converge on Messina; this is due to the particular geographical conformation and demographic distribution of the Messina area, where most of the population lives close to the coast near the railway. We also note the high number of bus connections to and from Catania, also linked to the presence of the airport.

The distributions of the Constrained Degree Centrality for the two modes of transport are reported in Figs. 6 and 7, comparing them with the Degree Centrality of the basic case. The interval considered as a time cutoff is $\Delta = 2$ h. The two-hour time threshold considered is compatible with a return trip during the day, associated with various types of travel reasons (regional commuting, occasional trips). The times taken as reference for each relationship are the minimum times among those declared by the companies.

For both networks and for most nodes, a significant decrease in the number of connections is appreciable. This is due both to the large geographical distances between some capitals, but also, and above all, to the travel times that can be greatly improved, especially in the case of rail. It is in this sense that the intervention on the doubling of the PA-CT railway line should be considered favorably, which should bring the travel time of the Catania-Palermo connection to 1 h 45 min, making it possible to connect Catania with Palermo, Caltanissetta and Enna in less than 2 h by rail. Similarly, the reopening of the Palermo-Trapani line should allow for a rapid connection between the two capitals. Currently, Trapani is not connected by rail to other regional capitals.

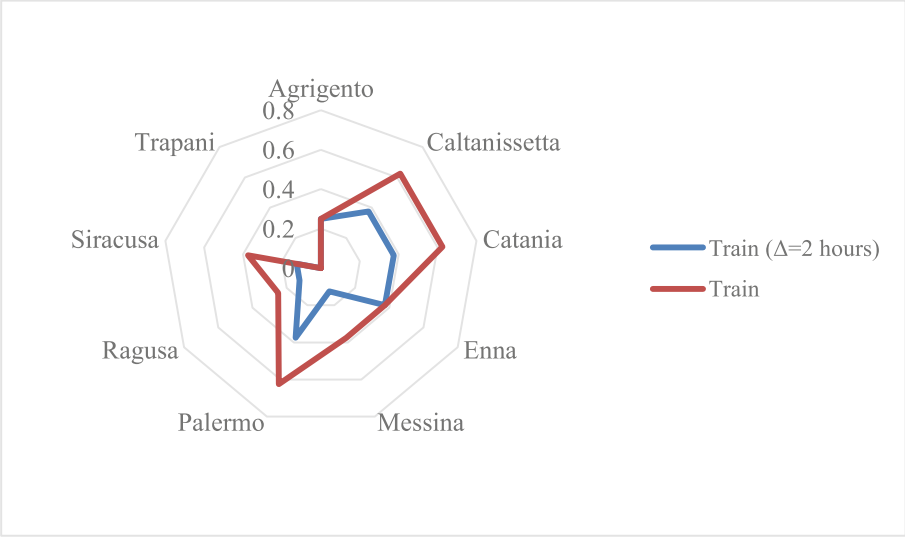


Fig. 6. Degree centrality vs. Constrained Degree Centrality ($\Delta = 2$ h, m = train)

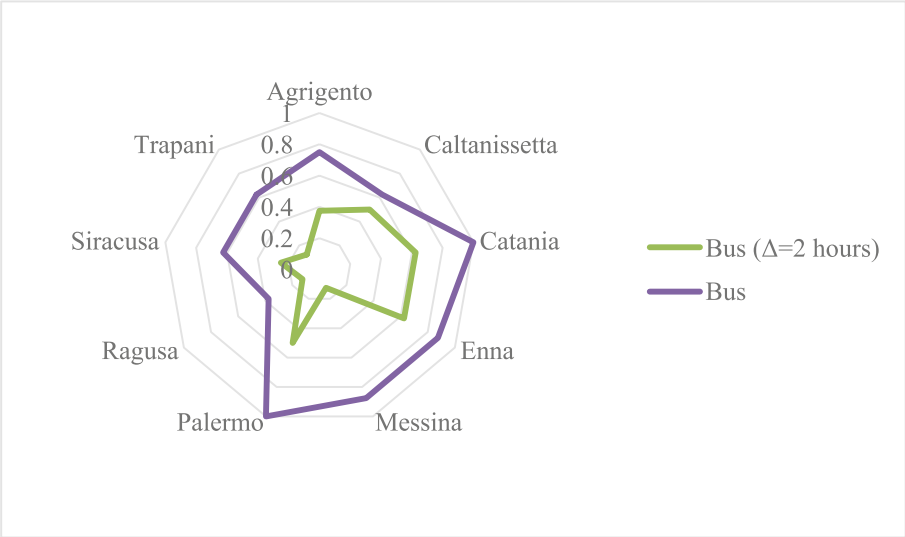


Fig. 7. Degree centrality vs. Constrained Degree Centrality ($\Delta = 2$ h, m = bus)

5 Discussion and Conclusion

In the evaluation process of transport systems, there are several elements that must be taken into consideration. The most connected nodes of the network, with the highest centrality values, are those linked to the three metropolitan cities (Palermo, Messina, Catania), where the largest quantities of residents are also recorded. An overall poorly

interconnected network emerges; the exceptions are two central nodes (Catania and Palermo) which, due to the greater population and the presence of key infrastructures, such as airports, are connected to all the other nodes of the network.

The value of Strength Centrality for the bus mode is higher for all the cities considered, with the exception of Messina, which is located at the convergence of two lines (the eastern Tyrrhenian and the Ionian) that have better infrastructural characteristics; the geography of the province of Messina, moreover, has determined the presence of the largest share of the population close to the railway.

The Constrained Degree Centrality for the 2-h case highlights a worsening of the connection conditions between cities, especially in the railway case, where a significant general worsening of the values can be observed for all connections, even though the geographical distances are often not excessive. In the case of the railway, this is mainly linked to the low travel speeds along the lines. Agrigento, Ragusa and Trapani are the cities with the lowest centrality values in the constrained case. This is due to the fact that, in addition to being the most geographically peripheral, they are linked to specific infrastructural interventions (such as the aforementioned intervention on the Palermo-Trapani railway line) that affect the number of connections and the speed of services.

The other ley element is the dominance of the bus network over the railway network. Travel between Sicilian cities, using public transport, mainly takes place via bus. This is due to the conformation of the territory, the distribution of the population and the presence of infrastructure. In Sicily there are numerous disused railway lines, mainly in the western and south-eastern parts of the island; conversely, the motorway system is expanding: among the planned interventions are the Catania-Ragusa and the completion of the Siracusa-Gela, which would complete the connections in the eastern part of the island. In this sense, the railway interventions already mentioned are recalled, including the doubling of the Palermo-Catania line, which would bring the travel time to approximately 1 h and 45 min. The structural limits remain: some railway lines seem to be more affected by flows; in particular the lines that converge on the city of Messina, thanks to the presence of the Strait and the connections with the peninsula; others, however, seem to mainly serve local or provincial mobility.

The policy implications of the contribution can be summarized. The study shows how, for both systems (bus and train) the typical basin structure of the Sicilian Region is confirmed; the region is typically divided into two macro-areas, a western one centered on Palermo and an eastern one centered on Catania. The two-basin structure of the Region struggles to find overall integration precisely because of the high internal travel times. In this regard, the role of the speeding up of the Palermo-Catania railway line is evident. The role, in the railway sector, of the city of Messina is also evident, being the only one of the nine nodes of the network to have a greater number of train connections than bus connections. The role of Messina must be further paid attention to precisely because of its geographical position as a pivot of the Sicilian Region in the case of a speeding up of the crossing of the Strait of Messina; as emerged from the contribution, the railway lines that converge on Messina are already the busiest. Finally, it is evident that the bus covers the majority of the connections in the smaller capitals, often, as in the case of Trapani, being the only possible alternative to reach other cities. In this regard,

the main interest of regional and local authorities must be to strengthen the service in these areas, in order to guarantee, even where there is no railway line, stable connections.

In light of the objectives of Agenda 2030, the modernization of railway infrastructures and the attempt to shift the modal shift towards rail, compared to the bus, are certainly in line with Goals 9 and 13. The predominant role of the bus in the infrastructure network remains to be defined.

The work has provided generalized indicators for railway and bus networks at regional level. In the highlighted case study, a region of just under 5 million inhabitants was considered, with 9 cities considered. The indicators provided allow for the synthesis of numerous information relating to the networks and travel times. The characteristics of the work carried out are of particular interest to public transport operators and for regional scale territorial and transport planners who, thanks to synthetic indicators, can define lines of intervention. The work represents a first step in an evaluation at regional scale in which the main indicators have been proposed. The research can be expanded with other aggregations, more specific to individual countries or public transport stations/stops. Further development regard demand analyses for supporting planning and programming of a new transport system configurations.

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Credit Author Statement. This paper is the result of the joint work of the authors. In particular, the "Abstract" were jointly written by the authors. AR and CR wrote "Background".AR and TC wrote "Methodology". AR and CR wrote "Results" and related subparagraphs. AR, CR and TC wrote "Discussion and Conclusion".

Disclosure of Interests. N.t.d.

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