

A Network Analysis for HSR Services in the South of Italy

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Abstract. Railway transport represents a travel alternative coherent with the European and international long-term sustainability perspectives. Different European countries are planning and developing the realization of High-Speed Rail (HSR) lines along the main Trans-European Network corridor. For instance, Italy is developing the design of the HSR line Salerno – Reggio Calabria to extend the current network towards the south of Italy. In this context, this paper presents a framework for performing a network analysis. Network analysis allows the evaluation of the centrality and connectivity of a network. Methods and specifications for calculating a set of indicators (degree centrality, strength centrality, eigenvector centrality) are proposed. The framework highlights the inputs, parameters and outputs needed for calculating the proposed indicators. A first pilot application of the framework regards the current railway services offered in the south of Italy. The resulting framework and relative methodology can be useful in a transportation planning process aimed at showing the current main gaps in terms of transport connectivity in the south of Italy. The framework and the results obtained from the pilot application can support decision-makers and takers involved in the railway transportation planning process aimed at increasing accessibility and sustainability goals for people's mobility in the region where HSR lines are developing.

Keywords: railway transport services · sustainable mobility · accessibility · network analysis · TEN-T

1 Introduction

Railway transport represents a travel alternative coherent with the European and international long-term sustainability perspectives. The main international instrument adopted which defines the sustainable development objectives is Agenda 2030 which considers 17 Sustainability Goals specified through indicators and targets [1].

Sustainable Development Goal 9, "Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation" is focused on resilient infrastructure. High-Speed Railway (HSR) is heavily interested in pursuing this goal; also, Goal 13,

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"Take urgent action to combat climate change and its impacts" is about decarbonization. HSR is also a mode of transport that produces small amounts of CO2.

Different European Countries are working on the development of infrastructures and services belonging Trans European Transport Network (TEN-T) and relative core corridors [2]. This paper focuses on people's mobility on TEN-T corridors that cross the European Countries from south to north. The extension of HSR lines is one of the main European policies for implementing the TEN-T corridor concept.

For these reasons, there are different projects for extending the HSR lines in other parts of Europe. The final aim is to increase European cohesion, by enhancing accessibility and travel opportunities for European citizens.

The study of the evolution of railway networks must take into consideration the difference between HSR services and infrastructures, considering that there is no one-to-one relationship between the two components. By focusing on the Scandinavian–Mediterranean core corridor, Italy is developing the design of the HSR line Salerno – Reggio Calabria (infrastructure) to extend the current network towards the south of Italy [3]; now, southern Italy is served, however, by HSR services on conventional lines. It is possible to have a system where HSR services use conventional lines, a system where conventional services use HSR lines and a system where both services use both lines [4].

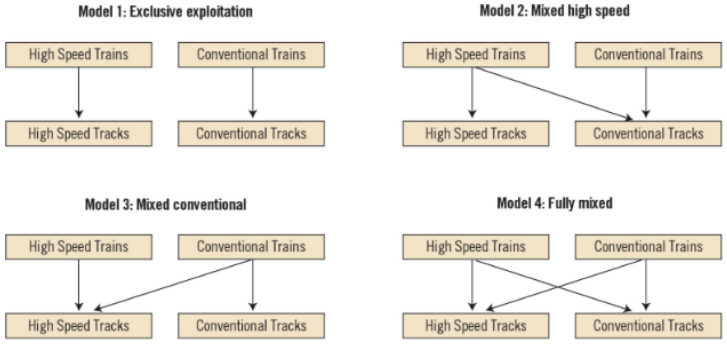


Fig. 1. HSR services according to the relationship with conventional services (Source: [4])

The final aim is to increase cohesion for southern regions (Campania, Apulia, Basilicata, Calabria and Sicily) that in the current situation are not served by HSR lines. In this context, this paper presents a framework for performing a network analysis that allows the evaluation of the centrality and connectivity of a network, in general, and of HSR transport network services in specific. The main aim is to understand the current state of HSR services in Southern Italy, in terms of connectivity and to underline first elements of accessibility. For pursuing these objectives, a network analysis specification is proposed for calculating a set of indicators (degree centrality, strength centrality, eigenvector centrality) in a pilot application performed for the South of Italy.

After this introduction, the paper has 4 sections. Section 2 reports the main related work on accessibility and network analysis. Section 3 describes the proposed framework for calculating indicators through a network analysis approach. Section 4 reports the main

results of a pilot application of the framework for the south of Italy. Section 5 discusses the obtained results with some final remarks.

Due to the topic covered, the paper is useful for researchers, railway service operators, infrastructure managers and public administrations.

2 Related Works

This research investigates the structure of HSR services in the southern regions of Italy, which, as described, represent the least accessible part of the country. This section recalls the main works on the topic of railway accessibility (Sect. 2.1) and railway connectivity (Sect. 2.2), underlining the role of these issues in the development of a territory.

2.1 Rail Transport Accessibility

Transport systems play a relevant role in enabling people and businesses to perform their daily activities. The final aim of transport infrastructures and services is to ensure accessibility that measures the ease of performing activities distributed in space and in time [5, 6]. Then, accessibility is a characteristic of one or more locations that are the origins or destinations of the trips performed by people or businesses. Accessibility indicators measure both the ease of a user in reaching localized opportunities in the area from their residence to carry out their activities (active accessibility), and the ease with which an activity located in a certain area (e.g. tourist) can be reached by potential users (passive accessibility) [7]. A location characterized by a high level of accessibility implies the possibility of having a great quantity of opportunities [8]. On the other hand, a poorly accessible territory is characterized by transport and mobility inequalities, and it risks social exclusion [9]. Then, accessibility is a possible measure of the interactions between transportation systems and territorial activities.

A classification of accessibility measures is proposed by Geurs and Wee [10] that consider: two perspectives in relation to infrastructures and services performances (infrastructure–based) or the spatially distributed activities (location–based); four components in relation to the opportunities at each destination (land-use), the travel disutilities from origin to destinations (transportation), the temporal constraints for performing a specific activity (temporal). Literature offers different specifications in relation to the two perspectives and the four components, providing assessment measurement of accessibility.

Some authors specify accessibility in relation to transport modes [5]. This paper focuses on the rail accessibility and the opportunities offered by High-Speed rail, by considering the empirical evidence in terms of impacts on socio-economic, territorial and transport systems in several countries, for instance, Italy [11–13]. In this context, rail connectivity, measured through a network analysis, plays a relevant role in the quantification of rail transport accessibility (see next section).

2.2 Rail Transport Connectivity

In the study and analysis of transport systems, it is of fundamental importance to determine the characteristics of the nodes, their centrality in the network and the characteristics of the interactions between them.

As will be discussed below, the mathematical degree of connection shows very well, and in different contexts, the social and economic integration of a territory.

Among the tools that allow the evaluation of the centrality and connectivity within a network, it is possible to refer to the network analysis. It is a method for modelling systems in which there are elements which, adopting certain criteria, can be defined as connected. There is a wide range of applications in the literature. This method was applied to evaluate economic trade between countries [14–16], both on a global and regional scale. There are also applications in social sciences [17, 18] and urban planning [19].

Given the possibility of describing systems of relationships, network analysis is widely used for analyses of transport systems.

Applications are also common for describing problems related to local public transportation [20, 21], air transport [22, 23] and maritime transport [24, 25].

The characteristics of network analysis are specifically suited for the analysis of relationships in the railway sector. Among the different applications proposed, examples of railway network analysis studies in India [26], Pakistan [27] and China [28] are highlighted.

The main element of network analysis applied to railway service systems is the definition of the elements and their mutual relationships. At least two methods are possible for representing the railway service network [29]:

- A first method where the network may be represented as *a bipartite train–station network*, with a set of nodes *S* representing stations and a set of nodes *T* representing train services; the link between generic station s ∈ S and generic train-service t ∈ T exists only if t makes a stop in s.
- The second method identifies the graph composed by a set of nodes S, representing stations considered; nodes i and j, both belonging to S, are connected if there exists at least one train service that makes a stop in both stations. The obtained network is referred to as the weighted station-station network. This second method is often used in modelling railway networks, as it provides a more immediate representation of the topology of services.

The framework proposed in this work refers to the second type of method mentioned, weighted station-station network.

3 The Proposed Framework

The proposed framework is aimed at analysing the railway services by using the network analysis system. It is organized into several steps summarized in Fig. 2. The HSR database and characteristics of both infrastructure and services are data needed in the first step, (1. Data collection – Sect. 3.1). Data are processed following the operations described in Sect. 3.2; the main objective is to transform the raw data into input data for network analysis. Network analysis is performed, and indicators associated with this are evaluated as final output (Sect. 3.3).

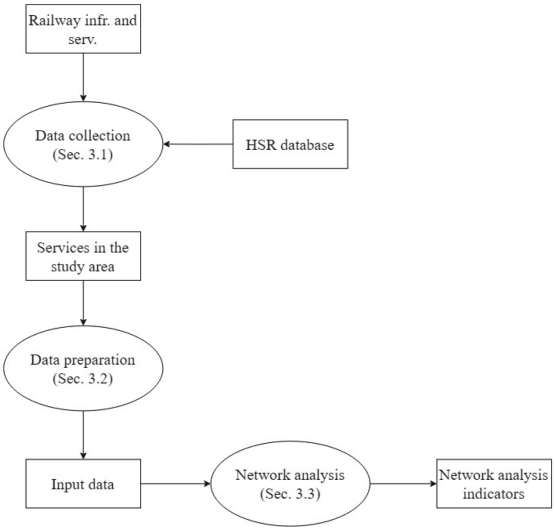


Fig. 2. The proposed framework

3.1 Data Collection

The elements to take into consideration are:

- A reference geographical area, where rail connectivity has to be studied;
- A reference time interval (t). Given the systematicity of railway service, it may be useful to consider an average weekday;
- At least one rail service operators, who manage railway services in the study area;
- A network of railway services operating within the study area in the time interval t; scheduled services that make at least two stops within the geographical area of reference are selected;
- A quantitative criterion to define the weights of each link on the network.

Let any pair of railway stations (i, j con $j \neq i$) located within the area be considered.

Let any pair of railway stations (i, j with $j \neq i$) present within the geographical area considered be given. Every railway service that, without interruptions, connects the pair (i, j) in the time interval t must be considered among the inputs.

A generic station is considered within the study if, in the time interval t, there is at least one service $r(t)_{i,j}$ that operates continuously serving both stations of a generic pair.

In the proposed framework, the frequency of services $f(t)_{i,j}$ is considered as the weight of the link.

3.2 Data Preparation

Once the basic elements have been described, it is necessary to define the adjacency matrix of the network; it can be obtained starting from the existence of at least one direct

connection between station i and station j in the time interval t. The adjacency matrix $A_{i,j}(t)$ is defined as

$$A_{ij}(t) = [a_{ij}(t)] \tag{1}$$

Where

$$a_{ij}(t) = \begin{cases} 1, & \exists r_{i,j}(t) \vee r_{j,i}(t) \neq 0, i \neq j \\ 0, & \nexists r_{i,j}(t) \vee r_{j,i}(t) \neq 0, i \neq j \end{cases} \tag{2}$$

Once the adjacency matrix has been defined, it is possible to describe an undirected graph G = (N, E), where N indicates the stations and E the connections between them through services without transfer.

For the study, it is also necessary to define the frequency of services between i and j as $f(t)_{ij}$, calculated as the sum of services without transfers between stations i and j operating in the time interval t.

3.3 Network Analysis

The indicators proposed below intend to recall the main quantities relating to connectivity.

The first element to define is the connectivity of an element within a network considering the number of other elements with which it is connected. Given a station node i, we intend to define the number of stations, whose generic is j, with which it is connected. This measure is defined starting from Total Degree Centrality, defined as

$$c_i(t) = \frac{\sum_j a_{ij}(t)}{N-1} \tag{3}$$

where the terms have known meaning.

The sum of the connections of node i defines the total number of nodes with which it is connected. The term in the denominator represents the total number of possible connections in a network of N nodes.

The total degree centrality allows the quantification of the number of destinations that can be reached starting from origin i, without transfers in the railway case. The main limitation of the total degree is linked to not attributing weight to these relationships. The existence of a single connection between i and j is enough to determine $a_{ij}(t) = 1$. This results in an increase in centrality (of both node i and node j) regardless of the number of links. This can give rise to distortions: two stations could share an equal total degree centrality value, but one of the two could have many more services than the other.

The second indicator proposed by the framework is proposed to better explain this aspect; the strength centrality measure is defined starting from frequency $f_{i,j}(t)$.

$$s_i(t) = \sum_j a_{ij}(t) f_{ij}(t) \tag{4}$$

The strength centrality indicator allows to take into account the intensity of the connections provided by the railway links. A node is more central depending on the

total number of services that connect it with the other nodes of the network. Reading the strength centrality therefore allows the centrality of the network nodes to be defined more completely.

A third indicator allows us to better define the influence of the node within the network. It defines itself

$$Av = \lambda v \tag{5}$$

Where

A is the adjacency matrix

v is the eigenvector associated to eigenvalue λ

Recalling Perron [25], it is possible to define several properties: a real square matrix with positive elements has a single largest real eigenvalue; the corresponding eigenvector has a strictly positive real eigenvector.

The positive eigenvalue, v_i, is the third indicator named the eigenvector centrality parameter. This indicator measures the centrality of a node i starting from the centrality of the node j with which it is connected. This measure is given by the sum of the centralities of neighbouring nodes multiplied by a normalization parameter. The indicator $v_i(t)$, measured for time t, therefore shows the centrality of a node while considering, at the same time, the centrality of its connections. This allows to provide further information for the case studied. Connecting a station i with a less central station j contributes less to the eigenvector centrality of station i.

Therefore, the third indicator can be connected to the first, because it provides indications on the presence or absence of services without transfers, but also allows to make basic assumptions on the degree of connection obtained by considering the interchanges.

The three proposed indicators will subsequently be implemented in a pilot study, the subject of the following section.

4 The Pilot Study

The pilot study covers current hybrid HSR services operating in the Southern regions and using both the HSR network and the conventional network where necessary, following the mixed high service model, as defined by Da Rus et al. [4]. The area considered includes the four southern regions, Campania, Apulia, Basilicata and Calabria. The study was extended to Molise and the southern part of Lazio and Abruzzo.

The area is considered less developed by European Union standards. All four regions are less developed; reference is made to the note from the European Parliament on the European Regional Development Fund [26], in which the criterion for access to funds is defined as a function of the region's GDP per capita/average EU GDP per capita ratio, as shown in Fig. 3.

The main objective of the pilot study is to test the proposed framework by analysing the network of direct HSR services within the study area considered. The aim is to highlight the main characteristics of centrality and connectivity of the network, in its current structure.

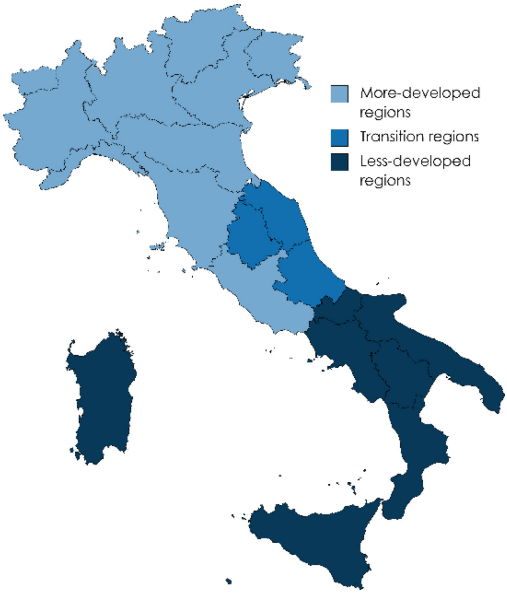


Fig. 3. – Italian Regions PO-FESR 2021-2027 (Source: author's elaboration based on Agenzia per la Coesione Territoriale, 2022) (Agenzia per la Coesione Territoriale, (2022). Programmazione 2021–2027, https://www.agenziacoesione.gov.it/lacoesione/le-politiche-di-coesione-in-italia-2014-2020/programmazione-2021-2027/,)

4.1 Data Collection

The study area includes the regions of central-southern Italy. The stations potentially affected by the study are all those south of the ideal axis that connects Rome Tiburtina/Termini with Pescara Centrale, served by at least one train classified by the operators as High Speed.

The time interval considered (t) is the average weekday of the winter period. Specifically, reference was made to Wednesday 7 February 2024.

The two railway service operators that manage high-speed services within the area considered were considered: Trenitalia and NTV. For Trenitalia, the highest-class services indicated as *FrecciaRossa* were considered; for NTV the services indicated as *Italo Alta Velocità* are considered.

Once the elements of the infrastructural network have been defined, it is possible to obtain the services, starting from the sites of the operators considered [27, 28].

The main services are divided along three lines:

- A Tyrrhenian route, which connects Reggio Calabria to Turin and Venice, and Sibari to Bolzano;
- An Adriatic route, which connects Apulia with the northeast (Venice) and the northwest (Turin);
- An Adriatic-Tyrrhenian route, which connects Apulia to Northern Italy through Rome.

Figure 4 represents the service network aggregated by region and by initial and final terminals.

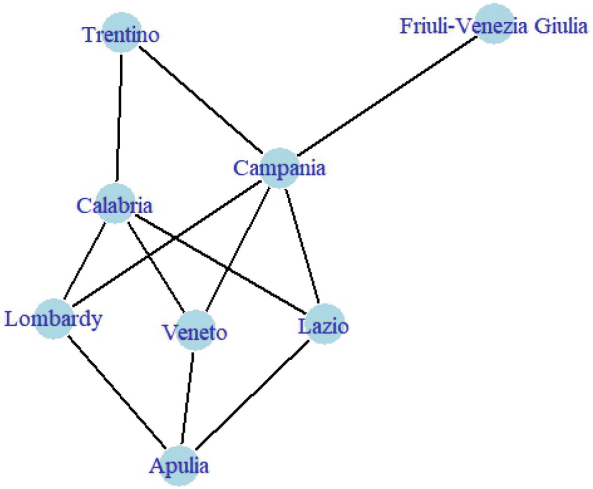


Fig. 4. Services network (by region e by O/D)

Starting from the selected services, the adjacency matrix represented in Table 1 was constructed, relating to regional connections.

Table 1. Adjacency matrix by regions and by O/D

	Apulia	Campania	Calabria	Friuli-Ven.Giu.	Lazio	Lombardy	Veneto	Trentino
Apulia	0	0	0	0	1	1	1	0
Campania	0	0	0	1	1	1	1	1
Calabria	0	0	0	0	1	1	1	1
Friuli-Ven.-Giu.	0	1	0	0	0	0	0	0
Lazio	1	1	1	0	0	0	0	0
Lombardy	1	1	1	0	0	0	0	0
Veneto	1	1	1	0	0	0	0	0
Trentino	0	1	1	0	0	0	0	0

The coverage of the HSR services selected for the study area is represented in Fig. 5.

4.2 Data Preparation

The sequence of trips belonging to the selected lines is processed to build the graph of existing railway relations. Following what is indicated in Sect. 3.2, the graph on



Fig. 5. HSR services in the south of Italy (Source: authors'elaboration based on QGIS [30] and OpenStreetMap [31])

which to evaluate centrality is the graph of relations without transfers. For the services considered, N = 41 nodes and E = 550 links are identified in the relationship graph. Figure 6 shows the relationship graph schematically. From a first visual reconnaissance of the relationship graph, the existence of two main routes of the network is highlighted: one along the Tyrrhenian axis and one along the Adriatic axis, highlighted in Fig. 6.

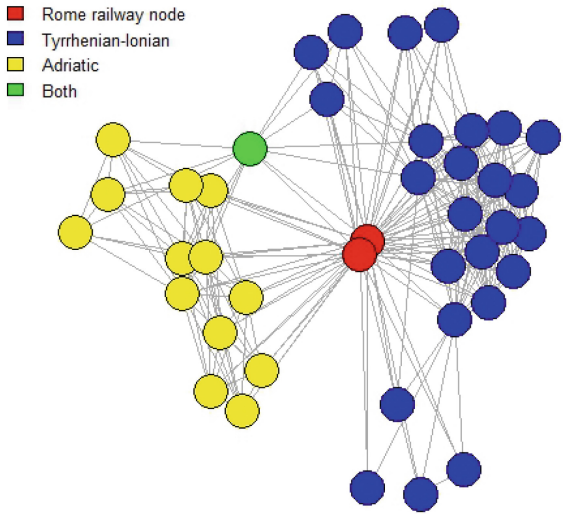


Fig. 6. Current HSR connections in the study area

4.3 Network Analysis

The values of the network analysis indicators (c_i, v_i and s_i), described in Sect. 3.3 are represented in Fig. 7.

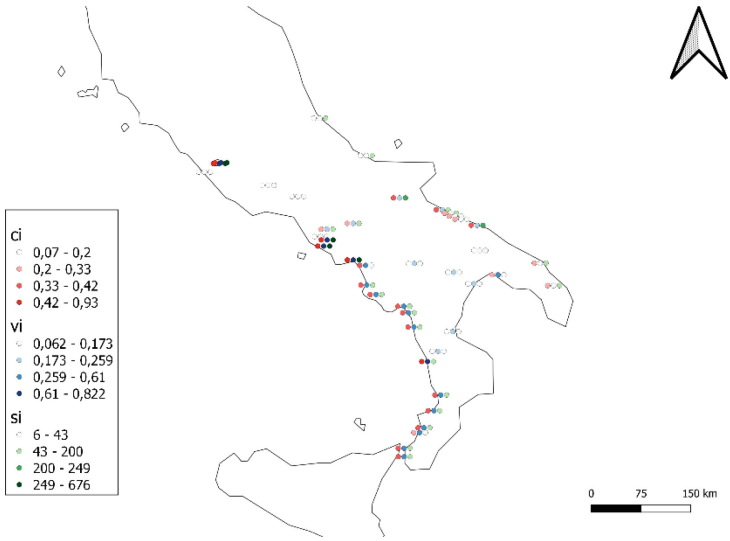


Fig. 7. Network analysis indicators (Source: authors'elaboration based on QGIS [30] and OpenStreetMap [31])

5 Discussion and Final Remarks

Territorial accessibility is one of the possible measures of the social component of sustainability. This paper focuses the attention on the structure of HSR services in southern Italy. In particular, network analysis was adopted to evaluate the connectivity offered by existing HSR links relative to the services.

The research focused on the proposal of a general framework and its application to a pilot case.

The first element to be considered relevant from the study regards mutual connections between railway stations (Sect. 4.2). In the current configuration there are no HSR services available between Naples and Bari, as well as between Bari and Reggio Calabria. The evaluation of the HSR railway network of Southern Italy alone would be practicable, and the corresponding graph is connected, thanks to the Taranto. Taranto is the only node connected with both Naples and Bari; but, at the same time it is not relevant in terms of number of services, as suggested by the very low value of s_i. With the aim to obtain a network truly representative of relationships, the network considered nodes in central-southern part of Italy (Rome, Termoli, Pescara). The nodes of Rome (Termini, Tiburtina) are the main center of the network. The Adriatic axis is connected to the Tyrrhenian-Ionian axis through the Foggia-Benevento-Caserta-Rome route. Then, a first result underlines the lack of HSR services connecting the territories of southern Italy by HSR services. Even if they are formally connected through Taranto, these connections have no utility for users.

The current structure of the services network produces high values of the centrality indicators for the Rome railway node. The two railway stations have the highest values (Roma Termini: $c_i = 0.925$, $s_i = 676$, $v_i = 0.822$; Roma Tiburtina: $c_i = 0.9$, $s_i = 464$, v_i

$= 0.8$). The evaluation of the indicators for the Adriatic axis and the Tyrrhenian-Ionian axis is influenced by the presence of the hub in the capital. However, it should be noted that the station of the Naples (Napoli Afragola station) hub has rather high values of the indicators ($c_i = 0.6$ and $v_i = 0.7$), also considering the number of stations served along the Tyrrhenian-Ionian route. This is also due to the very high number of interconnected services (s_i) towards Rome and the north of Italy and its crossing for connections with Basilicata and Calabria. The network of connections with the Adriatic has a lower number of nodes (14, out of a total of 41) and this negatively impacts the value of c_i and v_i. In particular, the eigenvector centrality value is lower for the main nodes (Bari Centrale, Lecce) due to the lack of more relevant direct connections such as Naples. On the other hand, the values of s_i are higher for the Bari Centrale and Foggia nodes than for the other nodes, indicating a clear hierarchy of nodes with respect to the number of connections. The considerations on the Adriatic can also apply to the territories located along the southern Tyrrhenian and Ionian Sea. The values of c_i and v_i are quite high for the main nodes (Paola, Reggio Calabria, Villa S. Giovanni and Rosarno), due to the high number of nodes (19 out of 40 for Paola, 17 out of 40 for Reggio, Villa and Rosarno) with which they are connected. A different result is obtained for the evaluation of s_i.

The total of relationships for these nodes is lower than the value obtained for Bari and Foggia, compared to a higher value of c_i and v_i; the s_i value of these stations (169 for Paola, 155 for the other 3) is lower than the value of the main Adriatic stations but slightly higher than the value of Lecce (129 reports/d). This aspect is more highlighted considering the values v_i. Nodes on the Southern Thyrrenian side have higher values than the nodes on Adriatic side.

Recalling the number of nodes for each of the two node clusters (26 for the Tyrrhenian Sea, 14 for the Adriatic, considering Taranto in both clusters), the summary considerations that emerge from the results of the centrality are:

- The two main hubs are the nodes of Rome and Naples areas;
- The nodes of the northern Tyrrhenian Sea have a high number of connections and a high number of relationships;
- The Adriatic nodes have a small number of connections within the system considered, but a fairly high number of relationships, considering the main stations;
- The nodes of the southern Tyrrhenian and Ionian Sea have a high number of connections, but a lower number of relationships.

It is necessary to underline the discrepancy between the value of centrality in the service network, the presence of HSR infrastructure and the population of the area served. The misalignment is evident in the case of the stations in upper Calabria (e.g. Amantea). A specific case is the Villa S. Giovanni railway station. The high value of c_i and v_i is linked to the high number of nodes present on the services considered; similarly, the value of s_i, the total of relationships, is slightly greater than that of other nodes; in light of this, it is necessary to consider how Villa S. Giovanni plays a role as the main hub for relations with Sicily, the fifth region of Southern Italy, not considered in this study due to the evident absence of continuity in railway connections.

Another distortion emerges in relation to the absence of high-speed infrastructure from Salerno to Reggio Calabria. The nodes with high centrality values in terms of HSR hybrid services (such as the nodes in Calabria) operate in a context in which there is no

high-speed railway infrastructure. For each analysed station, Fig. 8a shows the value of strength centrality and Fig. 8b represents the quantity of population potentially served with a car journey with a travel time of less than 50 min. Regarding the nodes of the Strait of Messina, the population residing 20 min away by car from the port of Messina is also considered. From the comparison between the values reported in Fig. 8a and 8b, it emerges that high values of centrality (42–200) do not ever correspond to high values of population. An example is the station of Maratea. It serves a population of approximately 65,000 inhabitants, very low compared to the area of Reggio Calabria or Villa S. Giovanni (more than 500,000 inhabitants). For a population of approximately 9–10 times the population of Maratea, these two stations have a value of s_i quite higher (155 for Villa and Reggio, 57 for Maratea), a value of c_i of the same order of magnitude (0.375 for Maratea, 0.425 for Reggio and Villa) and a value of v_i very similar (0.56 for Maratea, 0.61 for Reggio and Villa S. Giovanni). This gives a result about this area: considered a great difference in terms of population interested, Reggio di Calabria and Villa S. Giovanni offer only a small number of more services and approximately the same destinations of Maratea.

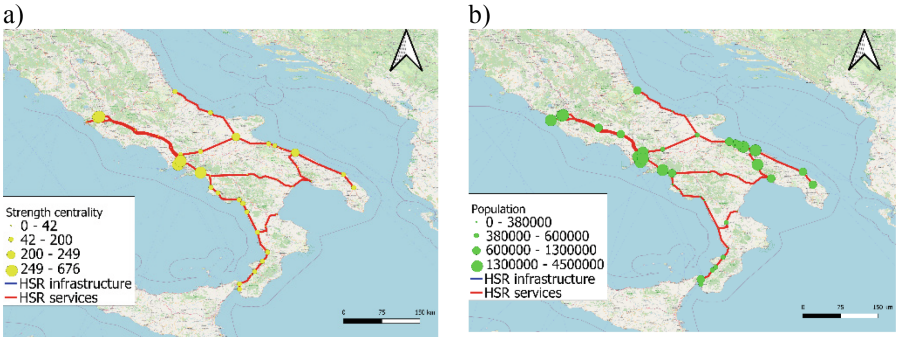


Fig. 8. Railway infrastructure network (centrality vs. population) in the south of Italy (Source: authors'elaboration based on QGIS [30] and OpenStreetMap [31])

Although some nodes analysed are very central in terms of services, the infrastructures have a conventional structure. Furthermore, the lack of a marked hierarchization of services on the Tyrrhenian axis is highlighted, with particular reference to the aforementioned node of Villa San Giovanni which, in addition to being attractive for the large southern part of Calabria, has a basin of influence that covers a good part of the Sicilian North-East.

The study has some limitations. For example, the study does not consider other transport service, including other classes of railway services (e.g. Frecciabianca). The resident population is only one of the possible territorial variables to consider. In the future, the analysis could be extended to other mobility components (e.g. tourist), considering that a part of the selected stations serves centres of high cultural, environmental and landscape interest.

The limitations highlighted for the Villa San Giovanni node translate into the need to develop a methodology that considers intermodality, as well as non-high-class high-speed services and conventional services.

Another possible line of research concerns the possibility of extending the proposed framework to connections with Northern Italy, considering the entire service network.

The work carried out is of interest for the developments of the ongoing design of the high-speed railway line that connects Salerno with Reggio Calabria. Furthermore, the results obtained are of interest to researchers and decision makers interested in territorial accessibility analyses.

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