A LEAN Approach for High-Speed Railways: General Elements for Extending the Italian Network in the South

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Abstract. High-Speed rail (HSR) infrastructures are developing all over the world. This represents a sustainable travel option according to sustainability goals. Recent works have proposed adopting the LARG (Lean, Agile, Resilient, Green) approach to realise new high-speed rail (HSR) lines. This is a paradigm derived from industry and logistics. The adoption of the LARG paradigm in transport systems and railway infrastructures has different implications. The main objective of this paper is to investigate the main implications of the Lean component for realising a new HSR line. The Lean paradigm focuses primarily on cost reduction by eliminating waste and activities that do not generate added value. In the context of High-Speed Rail systems, this approach directly influences both infrastructure design criteria and service planning. It requires comparing the requirements defined during the design phase with the actual, measurable outcomes observed during operation (ex post). This study focuses on the LEAN component applied to a case study relative to the extension of the Italian high-speed rail network along the southern corridor. The case study raises significant questions about the effectiveness of national infrastructure investments, emphasising the need for a broader discussion about the technical criteria used to develop existing high-speed rail lines. This work is of interest to the scientific community, as well as to public and private decision-makers involved in transportation planning connected to high-speed rail infrastructure.

Keywords: Network design; Transport supply · Transport infrastructures · Transport services · Sustainability

1 Introduction

High-speed rail systems are one of the most effective tools for promoting sustainable mobility. Rail transport, in fact, has a lower environmental impact than air travel, especially for medium and long-distance travel. This makes rail transport particularly relevant in the context of the global action of the United Nations, with reference to two Sustainable

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Development Goals (SDGs) [1]. SDG 9 "*Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation*" directly concerns infrastructure in its target 9.1, which promotes the realization of "*quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure*"; this aspect adds to the decarbonisation, expressed by SDG 13 "*Take urgent action to combat climate change and its impacts*". The reduced environmental impact in terms of CO_2 emissions, more in general in terms of GHG, and the need to support the economic development of the corridors through infrastructure make rail transport a central element of sustainable development.

The European Union intends to achieve the SDGs of the 2030 Agenda through the development of the Trans European Network – Transport (TEN-T) and the related corridors [2]. In this context, in November 2025, the European Commission presented a comprehensive plan to accelerate the development of the high-speed rail network, with the aim of improving connectivity between major European cities, reducing travel times and strengthening the EU's global competitiveness [3]. The plan defines the reduction of travel times, considering different tools, including the opening of new cross-border connections that will enable rapid connections within individual member states and between different countries. By 2040, the goal is to create a European high-speed network, interoperable and integrated into the EU's multimodal system. The European plan aims to eliminate current infrastructure bottlenecks and harmonise operating rules with a coordinated approach involving all member states.

European perspectives underline the importance of the railway system, and high-speed rail in particular, in achieving economic, social, and environmental sustainability objectives, as well as promoting Europe's territorial cohesion.

This research has the general objective of identifying the main criteria that can guide the planning and design of high-speed railway lines (HSR), solving the programming phase.

The LARG (Lean, Agile, Resilient, Green) approach is one of the possible frameworks for developing new high-speed rail (HSR) lines during the programming [4].

These approaches emphasise the importance of studying transportation demand and related behavioural models that represent user choices in the field of Transportation System Models [5]. Modelling tools are needed to estimate users' travel choices [6] and therefore diverted [7] and induced demand [8]. However, it is necessary to use approaches that focus on the design of the transport supply component [9].

In this context, the main specific objective of this paper is to investigate the main implications of the Lean component for realising a new HSR line. This approach is used in other sectors such as industry and logistics. The Lean paradigm focuses primarily on cost reduction by eliminating waste and activities that do not generate added value. In the context of High-Speed Rail systems, this approach directly influences both infrastructure design criteria and service planning. It requires comparing the requirements defined during the design phase with the actual, measurable outcomes observed during operation (ex post).

The factors that influence the programming of HSR infrastructures include: physical characteristics, with reference to the development of planimetric and altimetric profiles;

technological characteristics, with reference to energy systems; and performance characteristics of high-speed rail services (HST), with reference to routes, travel times and frequencies.

In this context, the Lean component is regarded as a decision-oriented approach in which designing choices are evaluated based on their ability to reduce inefficiencies and enhance system performance. Any infrastructure or network feature that generates unnecessary travel time, indirect routing, capacity mismatches, or discontinuities in service is a waste; improvements in accessibility, travel time reduction, reliability, and effective network integration are values.

Within this perspective, standard railway design and evaluation criteria can be reinterpreted as components of Lean principles. Alignment choices directly affect route directness and operating conditions, thus contributing to the minimization of time-related inefficiencies. Technical Specifications for Interoperability (TSI) ensure system compatibility, continuity, and capacity adequacy, reducing the risk of operational disruptions and underutilization. Network centrality indicators, in turn, measure the ability of the infrastructure to enhance connectivity and accessibility, thereby capturing the generation of user-oriented value.

This step-by-step mapping allows framing conventional engineering criteria within a coherent Lean approach. Rather than representing a separate layer of technical assessment, these criteria constitute the measurable dimension through which waste reduction and value generation are implemented in railway infrastructure planning, consistently with their interpretation in industrial engineering and logistics.

This paper focuses on the Lean component of infrastructure planning, isolating it from other complementary perspectives such as economic appraisal, environmental assessment, or governance-related considerations. This choice is motivated by the need to clarify how Lean principles can be translated into operational criteria for railway network design and evaluation. The paper aims to provide a more explicit and methodologically consistent interpretation of waste reduction and value generation within the specific domain of transport infrastructure and services.

The proposed approach is tested through an application to Southern Italy, a context characterized by heterogeneous infrastructure quality and ongoing high-speed rail developments. This case study is used to evaluate network performance and to identify structural gaps and missing links within the existing railway system.

In accordance with its objectives, the paper, following this introduction, is organized into three sections. Section 2 describes the main materials and methods used to identify the factors of the Lean approach with reference to the physical and performance characteristics of a high-speed railway line. Section 3 presents some examples of the application of the Lean approach to the extension of the HSR network in the case study of the extension of the Italian network towards Southern Italy. Section 4 concludes the paper with a discussion of the results obtained, with some concluding remarks and future research developments.

2 Lean Approach in HSR Programming: Main Factors

According to Campos and De Rus [10], four main models of high-speed rail networks can be identified:

- Model 1 – Exclusive model: High-speed and conventional networks are completely separate, with no interoperability. Services are only possible if both origin and destination are on the same network (e.g., Japanese maglev lines).
- Model 2 – High-speed–mixed model: High-speed trains can run on both high-speed and conventional lines, allowing through-services between the two networks. Conventional trains cannot access high-speed lines (e.g., France and Italy).
- Model 3 – Conventional-mixed model: Certain conventional trains can operate on high-speed lines, enabling through-services, but high-speed trains cannot run on conventional lines. This occurs where different gauges coexist (e.g., Spain).
- Model 4 – Fully mixed model: Full interoperability between high-speed and conventional networks, allowing continuous services across all routes (e.g., Germany).

The implementation of each model requires the specification of the characteristics of the infrastructures (Sect. 2.1) and of the services that travel on them (Sect. 2.2).

2.1 Infrastructure

A high-speed line must be planned, programmed and designed to shorten distances and therefore reduce travel times between the physical locations it connects (two cities or two railway final terminals). International technical and scientific literature identifies the main criteria that guideline planning, programming and design. These criteria concern the geometric, physical, and technological characteristics of high-speed rail lines.

In this context, it is necessary to recall the Technical Specifications for Interoperability (TSI) published by the European Community in 2024 [11]. These are the standard technical and operational characteristics necessary to standardise the railway infrastructures belonging to the Trans European Network – Transport (TEN-T). The TSIs ensure the interoperability of the railway system of the European Union, in relation to the passengers and freight mobility components. The specifications regard different transport system supply components in relation to railway infrastructures, management, and rolling stock. The final aim is to eliminate trade barriers for both industry and consumers within the European Union (EU).

In accordance with the aims of this paper, Table 1 lists the main characteristics of a high-speed railway line indicated with the acronym “INF TSI”. The table shows the TSI codes relating to rail passenger transport with speeds between 120 and 350 km/h. Both “hard” characteristics, like the gauge and the axle load and “soft” characteristics, as the line speed and usable length of platform, are included. The traffic code “P1” indicates the greatest values and then the best performances for interoperability HSR lines. These target values must be considered for realising new HSR lines or renewing existing conventional railway lines.

Furthermore, with reference to the programming and designing of a high-speed railway line, it is necessary to recall the geometric characteristics:

- of the planimetric layout which describes the geometry of the tracks in the plane, composed of straight lines connected by circular curves and transition curves which guarantee gradual variations in curvature and lateral acceleration to increase the safety, comfort and dynamic behaviour of the train; for high-speed lines the planimetric

Table 1. Performance parameters for passenger traffic (source [11])

Traffic code	Gauge	Axle load [t]	Line speed [km/h]	Usable length of platform [m]
P1	GC	17*	250–350	400
P2	GB	20	200–250	200–400
P3	DE3	22.5 (**)	120–200	200–400
P4	GB	22.5 (**)	120–200	200–400

layout guarantees to shorten the distances between the places to be connected in accordance with the horizontal alignment criterion [12] (Fig. 1a);

- of the altimetric layout that defines the vertical direction of the track axis consisting of constant slopes (gradients) connected by vertical connecting curves; the layouts are designed to control variations in gravitational acceleration and limit the longitudinal forces acting on the train; the altimetric layout guarantees optimal conditions of safety, operational efficiency and passenger comfort; along high-speed lines, altimetric variations are significant because they influence the performance of the train and the travel comfort of passengers, in accordance with the vertical alignment criterion [13, 14] (Fig. 1b).

Both criteria aim to ensure that the performance of high-speed rail systems is competitive with alternative transport systems over medium and long distances.

A synthetic measure of horizontal alignment is straightness centrality, which measures how directly a station is connected to the others, and is defined by the ratio between the shortest path and the Euclidean distance [15]. The measurement allows to identify stations with high path linearity, highlighting efficient and direct connections.

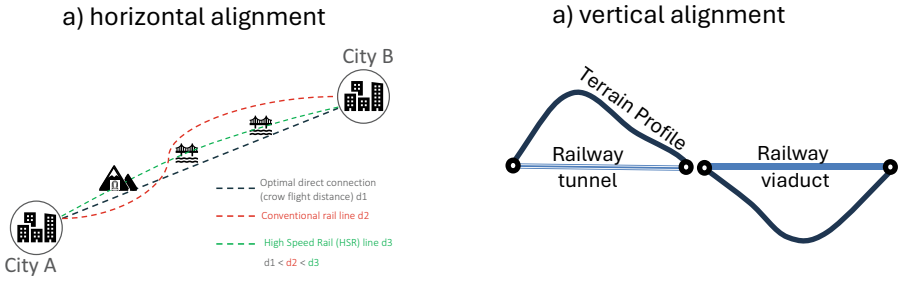

Fig. 1. Horizontal and vertical alignment

Some recent works have analysed ex post the planimetric and altimetric characteristics of the high-speed lines built in the world. Russo et al. [16] analyzed lines built in Italy, France, and Spain, comparing the lengths of existing lines in terms of: the length of conventional lines, the length of high-speed lines, and the straight-line length connecting

the pair of locations (e.g., cities). The authors demonstrate that with advancing technological progress, the length of railway lines tends to decrease asymptotically toward the straight-line length.

However, it should be noted that reducing the length of the tracks from a planimetric point of view could impact on the altimetric characteristics of the route and therefore the vertical alignment. Achieving these standard characteristics impacts the structures to be constructed (e.g., tunnels and viaducts). Following the horizontal and vertical alignment criteria implies the need to construct structures aimed at ensuring straight planimetric routes and low gradients, within the limits indicated by the TSI.

From the point of view of electric power technologies, it should be noted that the hybrid service model implies critical issues in the transition of railway trains from one network to another.

In this paper, the focus is mainly on Model 2 and, to some extent, on Model 4, as classified by Campos and De Rus [10]. The problem of discontinuity in the power supply between networks is therefore central. Although this discontinuity is generally addressed and resolved effectively through electromechanical solutions, this paper aims to highlight the aspects related to the functional components of passenger services, defined in the literature as "hybrid" services.

The interruption of electrical voltage—and therefore of traction power—requires the creation of a short neutral section where trains cannot draw energy. In this phase, the driver (or the on-board system in the case of multi-voltage locomotives) switches from one power system to the other.

Two main problems may arise. The first concerns the train being left without power, even if only for a few moments, resulting in a power outage for on-board equipment with potential repercussions on service efficiency. The second is more general and concerns the reduction in line capacity, due both to switching procedures and to the temporary reduction in power available for traction.

2.2 HST Services

Considering the "full mixed" high-speed rail services [10], the Lean paradigm can be assessed by starting from some fundamental elements characterising the transportation supply. To analyse the rail service supply, a rail service network analysis can be used. The analysis concerns the current structure and an initial assessment of the effects produced by hypothesizing changes. In the discussion below, the four main elements are highlighted sequentially, according to the purposes of the analysis to be conducted.

a) **Travel distances.**

The first element is the distances covered by rail travel. Rail services are used for different trip distances and purposes. Rail services are used for metropolitan and regional connections, with distances of less than 50 km. In this case, rail services compete directly with local or extra-urban road public transport. In the range between 50 km and 600 km, services, generally national, primarily concern connections between very distant centers within the same country or macro-region; competition primarily involves air transport and, in certain geographically defined circumstances, ships. For connections exceeding

600 km, whether national or international, rail services remain competitive compared to air transport, which remains privileged at these scales.

b) **Type of service.**

Once the travel distance scale has been defined, it is possible to identify the main characteristics of the network to be studied. As previously defined, rail services depend largely on the identified distance scale and on competition from other modes of transport. In a general way, high-speed, conventional, and metropolitan services can be identified among railway services, according to operating speeds and frequencies. While metropolitan systems serve travel on a local and regional scale, high-speed and conventional services may vary, considering specific characteristics of the national transport supply system. According to Campos and de Rus [10], four models of high-speed and conventional systems may be defined; this depends on how the trains (HS and conventional) use the infrastructure (HS and conventional). In general, services operated by HS trains are referred to as HS even if they run on a conventional network, as is the case in Italy. In turn, conventional services can be divided based on the scale of the connections (regional, intercity) or the operating conditions (night).

c) **Operator.**

Identifying the operator is necessary to select the transport services operating in the study area. Depending on the distance classes and the type of service, it is possible to identify the railway operators that offer high-speed services. There may be a single railway operator that operates under monopoly conditions on the entire network, or in a liberalized market, there may be multiple railway operators operating on the same origin-destination connections. Operators often coincide with specific administrative extensions and service classes; for example, some operators manage their services on a national railway system; others operate services only within specific classes (e.g., Nuovo Trasporto Viaggiatori covers only HS services in Italy). Once the operators that manage the services identified in the chosen study area have been identified, it is possible to access their respective timetables.

d) **Network nodes.**

From the previous step, it is necessary to filter the relevant nodes within the timetables according to two sequential processes of exclusion and aggregation. These steps depend on the study area, the services chosen, and the type of analysis to be conducted. This choice influences the "granularity" of the study. The exclusion step is motivated by the need to remove stations that are not relevant to the analysis. In a study that focuses on connections between large urban centers on a national scale, some peripheral stations may not be considered. Aggregation is necessary to concentrate attention on a single node, ensuring a functional representation at the scale being analyzed. A national-scale study to evaluate connections between cities implies the need to select the most representative station (for example, the one serving the city centre) to avoid overestimation within the same urban area. The maximum level of disaggregation possible is linked to the individual station if it appears in at least one of the services identified in point b). All possible aggregations, starting from this set of stations, depend on the type of analysis one wishes to conduct and the scale of the study. On a national scale, it is possible to

aggregate and restrict the set to regional capitals; the same aggregation, on a regional basis, would not be possible.

The summary of the relationships between the analysed components is reported in Fig. 2.

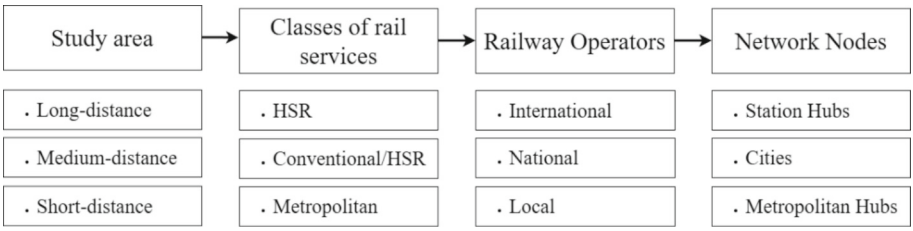

Fig. 2. The four elements to specify for the service analysis

3 Case Studies: HSR Lines for Extension in the South of Italy

The case study concerns the potential development of the high-speed rail network along the TEN-T ScanMed corridor, which connects Italy's southern regions. Currently, the national high-speed network extends to the Campania region, specifically to the Naples Afragola hub. Routes to Bari to the east and Reggio Calabria to the south are currently being programmed and designed. This paper considers the impact on the supply system of the construction of the Naples-Bari and Napoli/Salerno-Reggio Calabria lines.

In the following, in accordance with what was presented in Sect. 2, the infrastructures (Sect. 3.1) and services (Sect. 3.2) are analysed in the current situation and in hypothetical scenarios along the ScanMed corridor.

3.1 Infrastructures

In order to verify the application of the horizontal alignment criteria (Sect. 2.1), the characteristics of some existing high-speed railway lines in Europe were compared. Some lines are present in:

- Italy, considering the six HSR lines that develop from the north (Turin-Milan-Rome) to the south (Rome-Naples/Salerno);
- France, considering the six HSR lines that run from east to west (e.g., Strasbourg-Paris) and from north to south (e.g., Paris-Lyon-Marseille);
- Spain, considering the four lines that run from east to west (Barcelona-Madrid) and from north to south (Valladolid-Madrid-Malaga).

For the purposes of the analysis, the following variables were collected:

- l_{HS}, indicates the linear extension of an HSR line;
- l_{CN}, indicates the Conventional line;
- l_{SL} indicates the Straight line or crow flies line.

The data collected has been analysed and compared. The results of the analyses lead to several considerations. The average length of high-speed rail lines (l_{HS}) in the three countries is about 13% longer than the straight-line distance (l_{SL}) between the terminal stations considered. However, when compared with the average length of conventional rail routes (l_{CN}), the high-speed lines extension shows an average reduction of 15%.

Regarding the verification of vertical alignment, the data on the average gradients of the high-speed railway lines built in the European countries under analysis were compared. It should be noted that the lines built in the three European countries refer to different models of the classification proposed by [10]. The Italian system can carry both freight and passenger trains, and therefore the gradients do not exceed 30%. In France and Spain, the rail infrastructure is dedicated to high-speed passenger trains. These lines are not designed to support heavy freight traffic. Therefore, the maximum gradient is higher, up to 30%, but this allows freight traffic for the shippers.

With regard to the power-supply systems, the existing HSR networks have no homogeneous characteristics between different countries and, in some cases, within the same country. For instance, in the Italian HSR there are nodes powered by 25 kV AC (Reggio Emilia node), where a transition occurs between the 25 kV AC to the 3 kV DC. For instance, at the Napoli Afragola railway station, there is a discontinuity from Roma–Napoli to the Napoli–Salerno lines. In general, there is a high number of nodes directly affected by the introduction of hybrid operations. In general, and regardless of the historical evolution of national electrification systems, lines supplied at 25 kV AC provide superior performance compared with those operating at 3 kV DC.

3.2 HST Services

Regarding the service analysis, the following reports some of the results obtained by applying the study to some variable results. Three indicators derived from the network analysis are primarily analyzed for the resulting network:

- Degree Centrality, measures the number of connections of each node with other nodes in the network. Degree Centrality equal to 1 indicates that the node is connected to all other nodes;
- Strength Centrality, measures the number of connections of each node, weighted by a quantitative value. Considering frequencies as the value, the total daily connections of each node is obtained;
- Eigenvector Centrality, measures the node's score, assigning higher values to connections with nodes with higher scores.

The analysis is proposed at three different territorial scales: national sub-national and regional. This approach is intended to both reflect the hierarchical nature of railway planning decisions and to introduce independent levels of analysis. Each scale addresses a specific decision layer: the national level defines the strategic corridors and long-distance connectivity, the sub-national level refines these structures by considering intermediate territorial systems, and the regional level focuses on network performance in terms of accessibility and internal connectivity in peripheral areas. The three levels are therefore analytically distinct but functionally interdependent, as choices made at the higher scale constrain and inform the evaluation at the lower ones. In this framework, the transition

between scales is both a change in spatial resolution and a shift in the type of performance being evaluated: from corridor efficiency (national level) to territorial coverage (sub-national level), and finally to accessibility and network cohesion (regional level).

National

The first case study involves a national analysis of HS rail services operated by the two Italian HS operators (Trenitalia and NTV). The reference nodes are metropolitan cities, specific territorial entities identified in the Italian administrative system as significant centers of demand generation and attraction. Of the 14 metropolitan cities in Italy, the study analyzed 10 across the peninsula. The study calculated Degree Centrality and Strength Centrality based on the frequencies of the Italian HS network to identify any territorial differences between the ten cities. Compared to the network classification defined in Sect. 2, the Italian system is a Model 2 system, with HS trains able to travel on conventional lines. Therefore, services declared by operators as HS can travel on both HS and conventional lines. Results obtained from the evaluation are reported in Fig. 3. The study shows that the more peripheral centers such as Reggio Calabria and Bari have very low values of Strength Centrality based on frequencies: connections exist but are few. The priority axis of connections is the one that links Milan with Naples, an area served by the HS infrastructure. The Reggio Calabria hub remains largely peripheral, reflecting the lesser development of services in the south, due to the lack of HSR infrastructure. This marginalization of Reggio Calabria's network also determines the peripherality of Sicilian cities; Sicily, about 3 km from the mainland at its narrowest point, is home to a population of over 4.5 million, excluded from the national HSR network [17].

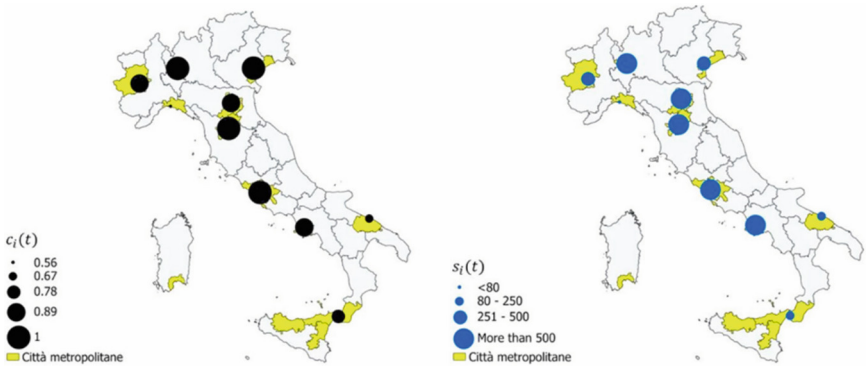

Fig. 3. National. Results for degree centrality and strength centrality. Source: [17]

Sub-national

In this study, the analysis was conducted on a macro-regional scale (less than 500 km), considering the case of central and southern Italy. The services analyzed are HS services, and the two network operators (Trenitalia and NTV) were considered. The considerations to be made regarding the nature of the service are the same as for the National case previously described. It should be noted that, with regards to the study area, only

the connections between Rome and Naples operate on a HS infrastructure, while the remaining part of the analyzed system travels on conventional lines. No aggregation or exclusion was performed; the reference nodes of the network are the railway stations involved in at least one of the services. The main results of the analysis are reported in Fig. 4. The network is divided into two main routes, an Adriatic one centered on Bari and a Tyrrhenian one centered on Naples. Naples and Bari are the two local hubs, while only two stations cover both routes (Fig. 4 right), Rome Termini and Taranto. While Rome has very high values on all indicators, Taranto has low values, linked to the limited presence of connection services. The analysis shows a network centered on Rome, the country's capital, despite its geographic proximity to other centers; even a large city like Naples has very low centrality values [18].

Regional

The third case study concerns a regional-scale analysis, considering the Sicily region in Southern Italy. The island is not currently served by a high-speed rail (HSR) network. However, this characteristic is precisely what makes it relevant within the proposed framework. Sicily represents a context in which HSR is in the planning and implementation phase, limited, for now, at the Palermo–Catania corridor, allowing the analysis to focus not on the performance of an existing system, but on the identification of structural gaps and missing links in the current network configuration. From this perspective, the case study serves two purposes. First, it provides an application of network analysis tools at the regional scale, highlighting deficiencies in accessibility and connectivity that would not emerge from a purely national-level assessment. Second, it allows testing the proposed approach in a "pre-HSR" context, where Lean-oriented principles can support the prioritization of interventions by identifying where infrastructure improvements would generate the highest system-wide value. Sicily is a representative case of regions undergoing transition towards higher-performance rail systems. For this analysis, all conventional services are considered, as there is no high-speed rail network on the island. The operator studied is Trenitalia, which is the only operator on the main standard-gauge regional network. The nodes considered concern the nine former provincial capitals, to capture the relationships between the main centers of generation and attraction of demand. The indicators studied are Strength Centrality and Degree Centrality. The study carried out a comparison with extra-urban bus connections on the same relationships. The main results are reported in Fig. 5. The resulting rail network graph is disconnected, since Trapani, the westernmost city on the network, is excluded from connections with other cities. In general, the bus network dominates the rail network for all stations in terms of degree centrality. Messina is the only city better connected by train than by bus, due to the better rail lines on the network. The result shows a system of connections which, although present, tends to prefer some routes – due to greater demand or better condition of the infrastructure – over others, and to a general lower presence of rail services compared to road services [19].

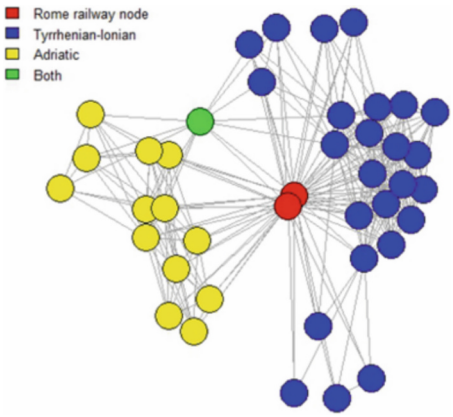

Fig. 4. Subnational. Results for degree centrality, eigenvector centrality and strength centrality (left) and graph representation of relations (right). Source: [18]

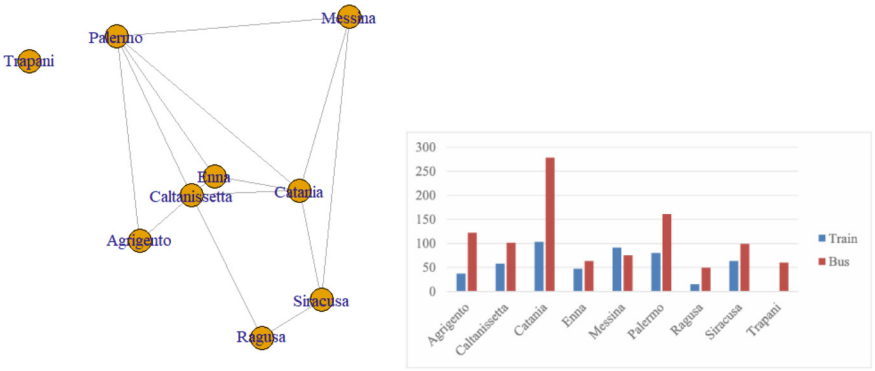

Fig. 5. Regional results. Graph representation (left); Strength Centrality (right). Source: [19]

4 Discussion

Based on the findings of this paper, it appears that the design, programming and planning criteria for HSR infrastructure lines follow specific criteria. The construction of high-speed lines around the world follows a lean approach from an infrastructure perspective through the application of horizontal and vertical alignment criteria.

Consistent with the analysis of lines already built in Italy, France, and Spain, the results show an average reduction in the length of high-speed lines compared to conventional lines of 15%. Continuity between power supplies must also be ensured to limit disruption and ensure high speed performance.

The methodology described for services allows for a comprehensive and concise assessment of rail transport networks, considering four fundamental elements. The

assessments carried out on the network's operating conditions can be combined with scenario hypotheses. Consider the national case of HSR services in Italy. With the current high-speed service network, considering a travel time threshold of 3 h, two southern metropolitan cities, Bari and Reggio Calabria, are disconnected [9]. By adopting a "what if" approach that combines classic transport system models and network analysis, it was possible to compare different intervention scenarios.

Considering the major ongoing projects on the high-speed rail network (Napoli/Salerno-Reggio Calabria, Naples-Bari, and Terzo Valico dei Giovi), the main centrality indicators have improved significantly. This translates into an increase in connections. For example, Reggio Calabria will be connected to other metropolitan cities such as Rome and Bari in a travel time of less than 5 h; with Naples in less than three hours; similarly, Naples and Bari would be connected in less than three hours. These connections depend on the selected program to connect Rome and Reggio Calabria in 3 or 4,5 h. The two programmed options influence the quality of connection rates across the entire Southern Italy network. This would lead to a more even distribution of the opportunities offered by the new HSR connections between metropolitan cities. Furthermore, it would allow Sicily to become closer to the national network; Sicily, in fact, is home to three metropolitan cities, with more than 4.5 million inhabitants.

5 Conclusive Remarks

This paper analysed the Lean component of the LARG paradigm for the construction of high-speed rail lines. The results of ex-post analyses conducted on existing HSR lines were presented. The picture that emerges is not entirely homogeneous, especially across Europe. From an infrastructural perspective, it emerges that the existing lines were built following the principles of horizontal and vertical alignment. Indeed, the extension of the existing lines progressively approaches the distance as the crow flies; furthermore, the vertical gradients do not exceed 30%, also considering the type of traffic that can potentially transit them (passengers/freight).

From a service perspective, it is noted that where pure high-speed systems are present (maximum speed 300 km/h), connection times are significantly reduced, ensuring users can make round trips within the same day.

Although this paper has some limitations, it focuses specifically on one component of the LARG paradigm. The significant role of transport demand and the externalities produced are considered alongside the other components (ARG), also in relation to other medium- to long-distance transport modes. The paper has intentionally concentrated on the Lean dimension of railway infrastructure planning, without addressing other aspects such as economic feasibility, environmental impacts, or institutional constraints. While this represents a limitation, it is also a necessary simplification to make the contribution more clearly identifiable. The results should therefore be interpreted as a methodological exploration of how Lean principles can inform the identification of inefficiencies and the prioritization of interventions, rather than as a comprehensive decision-support framework.

Future research should aim to integrate the Lean-based approach proposed here with more established evaluation methods, in order to assess how efficiency-oriented

criteria interact with economic, environmental, and social objectives in complex planning processes.

The results obtained are consistent with existing studies on railway network performance and accessibility, which highlight persistent disparities between core and peripheral regions. Previous research has emphasized the role of network structure and service levels in shaping accessibility patterns, often identifying similar weaknesses in terms of connectivity and travel times. However, the contribution of this study lies in the interpretation of these findings through a Lean perspective. This shift in perspective allows not only to confirm known criticalities, but also to prioritize them based on their impact on overall system efficiency and value generation.

The analyses and results are nevertheless useful for public and private decision-makers involved in the planning, design, and construction processes of high-speed lines.

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