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Vulnerability and robustness of interdependent transport networks in north-western Italy

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Abstract

Infrastructure networks have become increasingly complex, whose progressively higher levels of interdependence make them even more vulnerable. This empirical analysis based on the Morandi bridge collapse examines the robustness and vulnerability of the motorway and railway networks in north-western Italy. By following a network topology-based approach, motorways and railways are studied as one single interconnected multi-layer transport infrastructure. Based on the concepts of geographic and functional interdependence the study provides insight into which nodes (and links) should be restored as quickly as possible when an emergency and destructive event renders them inaccessible. Moreover, it highlights the greater fragility of the intermodal network which opens up the debate on regulation and coordination of restoring measures carried out by the relevant authorities.

Keywords Transport infrastructure, Robustness, Vulnerability, Interdependence, Network based approach

JEL Classification R42, O18

1 Introduction

Economic activity is deeply dependent on network infrastructure, be it electricity, transport, water or communication networks (see, among others, [15]. Infrastructure networks have become increasingly complex, showing progressively higher levels of interdependence that make them even more vulnerable, as shown by several worldwide emergency episodes caused by both natural and man-made disasters [35]. Since networks-of-networks are inherently more fragile than isolated ones [8], identifying and understanding interdependencies is one of the biggest challenges in analyzing the complex infrastructures on which our national systems rely [37].

The focus of this analysis is on transport infrastructures, which are fundamental to the functioning of societies. These systems not only must be able to meet mobility needs and guarantee access to resources and markets [38], but in emergency situations they make it possible to rescue people and also repair other damaged infrastructure systems [31]. The study of the vulnerability and robustness of transport networks in the event of emergencies is of prime importance for making the transport systems resilient.

This work originates from the collapse of the Morandi bridge in Genoa in August 2018 when both urban and motorway mobility of people and goods was drastically disrupted, and the underlying rail network was also damaged. In addition, the flows of goods originating from the port of Genoa, one of the largest in the Mediterranean, were inevitably impacted. Episodes like this show that damage to one component of the network can spread and cause damage on a large scale. The importance of having a robust transport system from an economic and social welfare perspective has led to the emergence of a large

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body of literature on the mechanisms that can cause system vulnerability, including interdependence [31]. This work fits into this literature by proposing an empirical analysis of the robustness and vulnerability of the motorway and railway networks in north-western Italy.

We adopt a network-based approach, i.e. we describe the network using nodes representing the network components and links representing the physical connection between each pair of nodes [31].[1] Indeed, network theory is recognized as an effective methodology for studying complex networks (see, among others, [11, 12, 29]. Although it is necessary to recognize the importance of the dynamic study of networks, the structural analysis of networks such as transport networks can also be very informative, since the robustness of the system is a prerequisite for efficient rescue and recovery planning after the occurrence of a shock [11, 12].

The objective of the study is twofold. First, the identification of critical components, i.e. nodes crucial for the functioning of a network [28], of the transport network in the northwest of Italy, by accounting for the geographic interdependence of two transport infrastructures, i.e. motorway and railway networks. In particular, we consider the case in which the condition of one infrastructure does not influence the condition of another, but their elements are in close spatial proximity [37]. To determine whether and to what extent each of the nodes in the network contributes to the vulnerability of the interconnected system, we first calculate the loss of *efficiency* associated to the removal of each node of the network by relying on the *efficiency* measure proposed by Latora and Marchiori [27]. Furthermore, we observe which vertex when removed causes a reduction in the size of the largest connected component, i.e. we detect *cut vertices*, and we calculate each vertex *betweenness centrality*, as a proxy for the ability of a node to connect other nodes in the system.

Turning to the second objective, we consider the concept of functional interdependence in the spirit of Zhang and Peeta [50] and we analyze functional connection between the two transport networks to investigate the robustness of the resulting multimodal graph. This analysis is based on a multi-layer graph in which in each main city in the northwest of Italy the modal change can take place and the motorway exits and the railway stations are connected. Following previous literature, we use as a measure of the robustness of the network the size of the giant component during all possible "attacks" on the system (see, among others, [13, 40]. We perform the robustness analysis to observe the different behaviour of the multimodal network with respect to the corresponding uni-modal ones.

Results from both these analyses show that interdependence (in its various definitions) is a determining factor in topological analyses. In our framework, considering interconnections turns out to be fundamental for the analysis to be informative.

The major contribution of this work is to focus on the vulnerability and the robustness of two interdependent systems by performing the empirical analysis on two transport networks, i.e. motorways and railways, in a multi-regional scale. Indeed, the economic literature has recognised the importance of studying concepts such as resilience and vulnerability within the framework of complex networks, and it has been argued that it is crucial to study the critical components of a system accounting for (geographic) interdependence of networks [29]. Nevertheless, even though there exist some important exceptions such as Schintler et al. [39], Jin et al. [26], Bocewicz [6] and Apricio et al. [2], multilayer transportation systems have received little attention in the literature [48], and studies in transport economics often focus on one transport mode only.[2] Furthermore, investigating vulnerability in multimodal transport networks appears to be one of the directions in which research into transportation network performance should be directed [19], and we believe that our robustness analysis moves precisely in this direction. In addition, along with the valuable contribution of jointly analyzing two transportation networks, the analysis focuses on a geographic area never analyzed in previous studies. Moreover, in this case study we analyse an area that includes multiple NUTS-2 regions: with some exceptions, such as Schintler et al. [39], where the authors analyze Florida's road and rail network, studies often focus on urban areas (see, for example, Jin et al. [26] for a case applied to the public transportation system in the central part of the city of Singapore, and Apricio et al. [2] for a case study related to the city of Lisbon).

This work was produced on the basis of considerations emerged from the New Economic Regulation For Transport In Case Of Emergency Events project, a project funded by the European Union via the Structural Reform Support Programme.[3]

The rest of the paper is organized as follows. Relevant literature is analysed in Sect. 2. In Sect. 3 the methodology is presented. Section 4 shows the case study and results. Finally, conclusions are drawn in Sect. 5.

[1] From henceforth we use the terms node and vertex interchangeably.

[2] For example, on rail [25, 30], air transport [51, 52] highway [4], urban road [23], metro [42, 43]. For an application related to resilience of Intelligent Transportation systems, see also Ganin et al. [18].

[3] The deliverables of this project are available at: https://cieli.unige.it/en/SRSP.

2 Related literature

This study contributes to literature on the vulnerability and the resilience of transport infrastructures. Important surveys on resilience and vulnerability in transportation studies are, among others, Reggiani et al. [36], Mattsson and Jenelius [31], Gu et al. [19], Sun et al. [41].[4]

Even though there is no a common definition of vulnerability, there are definitions that summarize much of the literature on the subject. Berdica [5] argues that vulnerability in the road transportation system is "the susceptibility to incidents that can result in considerable reduction in road network serviceability," and according to Jenelius and Mattsson [24] vulnerability of all transport system is the "society's risk of transport system disruptions and degradations." From an empirical perspective, the vulnerability of infrastructures is investigated under two main approaches: network topology and system-based [31]. The network topology approach relies on graph theory and is strictly connected to the concept of *efficiency*, which in turn refers to average minimum distance between pairs of nodes in the network [27]. Typically, network *efficiency* indicators are used to evaluate the vulnerability of transport networks and typically researchers focus on the variation in levels of *efficiency* after the removal of a network component. In Latora and Marchiori [28], the authors evaluate the drop in network performance caused by the removal of a network component using *efficiency* as a proxy for system performance.[5] Another important index belonging to the category of topology-based vulnerability indices is *closeness*, which relies to the average shortest distances between all nodes, while *efficiency* relies on the reciprocal of distances [19]. Other methods used in the literature to investigate critical network components include that of Demšar et al. [10] according to which two measures have to be used to identify critical locations in vulnerability analysis: *cut vertices* (a vertex is a cut vertex if its removal causes an increase in the number of connected component) and each node *betweenness centrality* (the higher the value of this measure, the more critical a node is).[6] The second approach, the system-based one, also considers the effect of congestion, and thus travel cost issues [19] and is deeply related to the concept of *accessibility*: "a network node is vulnerable if loss (or substantial degradation) of a small number of links significantly diminishes the accessibility of the node, as measured by a standard index of accessibility; a network link is critical if loss (or substantial degradation) of the link significantly diminishes the accessibility of the network or of particular nodes, as measured by a standard index of accessibility" [44]. Within this approach, the graph theory is integrated with transport supply and demand analysis with the aim of investigating real responses to shocks by analyzing demand and supply of transport according to different vulnerability scenario. The advantage of the topology-based approach is related to the limited need for data and also the relative simplicity of the methodology used, but at the same time it does not allow for the incorporation of a realistic description of the response to a destructive event. In this sense, the system-based approach can be interpreted as an attempt to overcome the limitations of the topology-based approach, even though this requires a volume of information that is not always available and also makes comparability between different networks less immediate [31].

When it comes to the resilience of transportation network, literature is not yet so well established as literature on vulnerability [31].[7] Following Reggiani et al. [36] it is possible to distinguish between ecological and engineering studies. The latter refers to the ability of a system to return to the old steady state equilibrium, while the former to the ability of a system to get to a new steady state equilibrium. Moreover, according to the authors, in this literature the concept of robustness is often used, and it seems to be used with a similar meaning to that of resilience. Robustness describes the performance that can be preserved under disturbance, and can be considered as the inverse of vulnerability (see, among others, [19, 36].[8] The concepts of resilience and robustness lead to similar results, but through different processes: in fact, a system is more resilient the greater its ability to recover after a shock, while a system is robust if it remains intact after a destructive event [16, 17].[9] With regard to quantitative resilience indices [51, 52], refer to three categories:

[4] In particular, refer to Annexes A and B in Reggiani et al. [36] for a systematic cross-classification of articles on resilience and vulnerability.

[5] The authors consider communication-information and transportation infrastructure networks. For another application related to transport networks, see, for example, Dehghani et al. [9], where the authors investigate the efficiency of a road network. Variants of this efficiency measure have also been proposed in the literature to capture not only the topology of the network, but also the flows, costs and behaviour of travellers [33],

[6] It is worth noting that the authors use a so-called line-graph where initial edges are translated into vertices. They test the importance of three measures: *cut vertices*, *betweenness* and *clustering coefficient*. Results from their analysis using data from the street network of Helsinki Metropolitan Area suggest not to include the latter in their vulnerability risk measure.

[7] From a theoretical point of view resilience has been defined in different ways by researchers depending on the field this concept has been applied to. An in-depth discussion on the different definitions is given in Hosseini et al. [22]. Overall, different definitions ground on the idea that the concept of resilience is associated to the ability of a system to absorb a shock.

[8] It is worth noting that in "the 4Rs" paradigm, resilience includes: robustness, redundancy, resourcefulness, and rapidity [7].

[9] For a discussion on distinctions between the concept of resilience and those of risk, efficiency, robustness, and sustainability see [17].

topological metrics, attributes-based metrics, and performance-based metrics.[10] Metrics belonging to the first category, are often similar to those of vulnerability. This is due to the fact that, as already pointed out, vulnerability captures the ability of a network to withstand shocks, and this is one of the components of the multi-faceted concept of resilience [19]. Examples of metrics belonging to the second category are those that focus on the recovery phase, i.e. recovery speed and recovery efficiency. As argued by [51, 52], most of the methods proposed in the literature to assess resilience are hardly applicable to large-scale transportation network. Only topological methods can be considered more efficient in this sense, although it is necessary to recognize the limitation of not including traffic flow aspects. Because of these reasoning, since our case study refers to a multiregional scale, we refer to topological robustness measures in this analysis.

Finally, this paper also relates to the literature on critical interdependent infrastructures. Researchers have often described interdependence in terms of criticality, since when two networks are involved in a shock the final effect is more than proportional to the sum of the outcomes that would occur in the case of destructive events involving only one of the two infrastructures [34]. Moreover, there are often several organizations in charge of each single infrastructure, which leads to coordination issues in emergency management [1]. Hasan and Foliente [20] argue that when a disruptive event occurs also indirect effects that percolate through the set of interconnected networks have to be considered. Ouyang [35] identify different categories of approaches to investigate infrastructure interdependencies and this work is related to the literature that adopts the network-based approach, where vertices represent different components of the infrastructure, links represent the physical or virtual connections among them, and inter-links describe interdependencies between infrastructures. Typically, researchers using this approach model the failure of one of the network components to observe its cascading effects on the entire interdependent infrastructure. Depending on how the infrastructure is modelled, within this approach we can furthermore distinguish between analytical methods and simulation methods (for an in-depth analysis of these approaches see Okuyama [34].

3 Methodology

A graph, $G = (v, e)$, is a symbolic representation of a network and its connectivity. A vertex, v, is a terminal point or an intersection point of a graph. In our study, each vertex can be the abstraction of a transport terminal (a motorway exit in the motorway graph and a railway station in the railroad graph, respectively) or, alternatively, an intersection point. An edge e is a link between two nodes. The link (i,j) is of initial extremity i and of final extremity j. Each link is the abstraction of a transport infrastructure supporting movements between nodes, i.e. an existing highway or a railway line.[11] We rely on both unweighted and weighted graphs; in the latter case the weight used is the distance (expressed in kilometers). In this study both the railway and the highway networks are symmetrical.

Since our analysis focuses on interconnected infrastructures, defining the way motorways and railways networks are interconnected, i.e. to identify inter-links, is fundamental. Critical infrastructures are interdependent in several ways, and scholars provide different classifications (see [14, 37, 47, 50, 53]).[12] We use two different definitions of interconnection, serving to different purposes. Indeed, depending on how two infrastructures are connected, different aspects of the multi-layer network arise.

3.1 Joint network based on geographic interdependency

As transport networks are geographically constrained, geographical interdependence is of particular importance. Geographical interdependence occurs when the condition of one infrastructure does not influence the condition of another, but their elements are in close spatial proximity [37]. Assuming, for example, the collapse of a bridge, one can imagine that the event may damage another underlying infrastructure. This is what happened in Italy in 2018 when the Morandi bridge collapsed, when the rubble interrupted rail traffic for a few days on the line running underneath. In this study the concept of geographical interdependence is used to create the first multi-layer network. Consequently, the connection points are defined as the points where the motorways bridges overpass the railway network, or where the railways bridges overpass a motorway. This means that the motorway network and the railway network are interconnected through *overpass points*. In this case, the two infrastructures are directly connected, i.e. there is a first-order interdependence or first-order effect.

Following Havlin et al. [21], the interconnected system can be transformed into a complex-valued $n \times n$ adjacency matrix Ω. Each row and column represent a node

[10] For completeness see a recent paper by Auerbach and Kim [3], where the authors propose a set of new robustness indicators to be applied to multi-line networks.

[11] For what concerns railway network, refer to Von Ferber et al. [46] for a list of all possible representation of a public transport system, i.e. L-space, B-space, P-space, and C-space.

[12] See Ouyang [35] for a summary of interdependency types defined by different scholars and their evidence.

and the connection between two nodes, h and j, is (h,j). There exist three types of links: motorways, railways, or connections (inter-links). Each entry, ω_{hj}, can take values as follows:

$$\omega_{hj} = \begin{cases} m \text{ if } (h,j) \text{ is a motorway link} \\ r \text{ if } (h,j) \text{ is a railway link} \\ c \text{ if } (h,j) \text{ is an inter-link} \\ 0 \text{ otherwise} \end{cases}$$

The resulting adjacency matrix is a square matrix whose elements can take values of 0, m, r, or c, where 0 indicates no connection, m a motorway connection, r a railway connection, and c the connection between two nodes belonging to the two different uni-modal networks.[13]

Once the multi-layer graph is constructed, the first measure to analyse the topological vulnerability of the system and to assess the importance of each network component is the drop of *efficiency* caused by the removal of each node. We use the measure of *efficiency* proposed by Latora and Marchiori [27] that considers the shortest path length, d_{hj}, between each pair of nodes, h *and* j[14]:

$$E = \frac{1}{(v-1)} \sum_{hj \in V, h \neq j} \frac{1}{d_{hj}}, \quad (1)$$

where distance is infinite if the pair of nodes is in different components of the network and the contribution to the sum is zero, while it gives greater weight to those pairs of nodes that are closer in proximity.

Then the *efficiency* loss is[15]:

$$\Delta(Y) = \frac{E(Y) - E(Y-1)}{E(Y)}. \quad (2)$$

Furthermore, following Demšar et al. [10] we investigate the criticality of each network component by considering two other relevant measures. In some cases, the removal of a node results in the formation of several clusters in the network, leading to the disconnection of some nodes from the main cluster, thus dramatically reducing the accessibility of the region served by the infrastructural network. A cut vertex is a vertex whose deletion disconnects a connected graph, recalling that when a node is deleted, we also remove its incident edges [49].[16] Following the authors, all *cut vertices* can be considered critical locations. However, the identification of *cut vertices* is not sufficient to conclude the analysis of critical elements, and this must be complemented by the analysis of *betweenness centrality*. This measure reflects the ability of a node to connect all other nodes, indeed the vertex *betweenness* is defined by the number of shortest paths going through a vertex. In this case, a node is more central the more it is on shortest paths between each pair of nodes in the network. In this work we rely both on an unweighted and a weighted measure of *betweenness*, i.e. we also account for distance weighted shortest paths.

3.2 Joint network based on functional interdependency

The second multi-layer network is built with the aim of studying the robustness of a multimodal network compared to the respective single-modal networks. Then, we rely on the above-mentioned concept of functional interconnection [50], and we allow motorway exits and the railway stations to be connected in each main city assuming the possibility of a modal shift.

To construct the multimodal graph, where inter-links correspond to places where the modal shift can take place, we assume that each motorway exit is connected to the (closest) railway station via an interchange node, i.e. a passenger interchange parking, and consequently also via two urban roads connecting the latter to the rail station and the motorway exit, respectively. In this case, three layers are used to build the multi-level network, as we also consider interchange nodes. Each entry, ω_{hj}, in the resulting adjacency matrix can take values as follows:

$$\omega_{hj} = \begin{cases} m \text{ if } (h,j) \text{ is a motorway link} \\ r \text{ if } (h,j) \text{ is a railway link} \\ u \text{ if } (h,j) \text{ is a urban connection link} \\ 0 \text{ otherwise} \end{cases}$$

where 0 indicates no connection, m a motorway connection, r a railway connection, and u the urban road connection through which nodes on the motorway network and nodes on the railway network are connected to the interchange nodes.

Furthermore, a second approach for representing a multimodal network is also followed: each of the main railway stations is directly connected to the (closest)

[13] It worth noting that in the resulting graph, links are weighted according to kilometric distance, and that connection links have a weight of 0, indicating perfect overlap.

[14] It is worth noting that Eq. (1) can also be interpreted as the reciprocal of the harmonic mean of the shortest path length d_{hj} between each pair of nodes, h *and* j.

[15] For an example of an application in the context of interconnected infrastructures see Milanović and Zhu [32].

[16] We denote a vertex as a *cut vertex* when a *separating set*, defined as a set of vertices whose deletion disconnects the connected graph, contains only one node [49].

Fig. 1 Motorway and Rail Infrastructure in the north-western area of Italy. *Source*: Authors' elaboration in MapInfo using Openstreetmap data. Red lines indicate motorways, yellow lines indicate railways

motorway exit, without the presence of an interchange, i.e. only via an urban road.

As already mentioned, we use the intermodal graph to assess its robustness and to compare it with the robustness of the single-modal networks. Typically, the analysis of network topological robustness focuses on the critical fraction of attacks in which the network fully collapses, but when road system are concerned networks can experience large damage without completely failing [13]. We then consider the number of nodes in the largest connected component on the number of nodes in the initial network, i.e. the relative size of the largest connected component, as a measure for evaluating network robustness. In particular, we follow Schneider et al. [40] and Duan and Lu [13] and we measure the robustness of a network with the size of the giant component during all possible "attacks" on the system. Finally, notice that according to this procedure, vertices have to be sorted according to a measure of "strength" of some kind and, in this case, vertices are ordered both by their *degree* and by their *betweenness centrality*, the two most used measures of node importance in targeted attacks [13].

4 Application

Our case study refers to the north-west of Italy as shown in Fig. 1.[17]

To conduct the analysis and construct the graphs, the first methodological choice concerns the identification of relevant railway lines. The latter are selected starting from the full list provided by RFI, the company managing the railway infrastructure in Italy, in its Online Network Statement, and focusing on the lines classified as *fundamental*. In some cases, urban junction lines are also considered to allow fundamental lines to be connected. On the other hand, as far as motorways are concerned, we consider the most important exit stations and also relevant intersections.[18] Finally, all vulnerability and robustness analyses are performed using *iGraph* R Package.

4.1 Vulnerability analysis: critical component of the interconnected network

Through a georeferenced approach, it was possible to map all the motorways bridges overpassing the railway

[17] The source of both road and rail infrastructure data is Openstreetmap.

[18] The intersections are given the name of the nearest town or of the two road segments that intersect in that point.

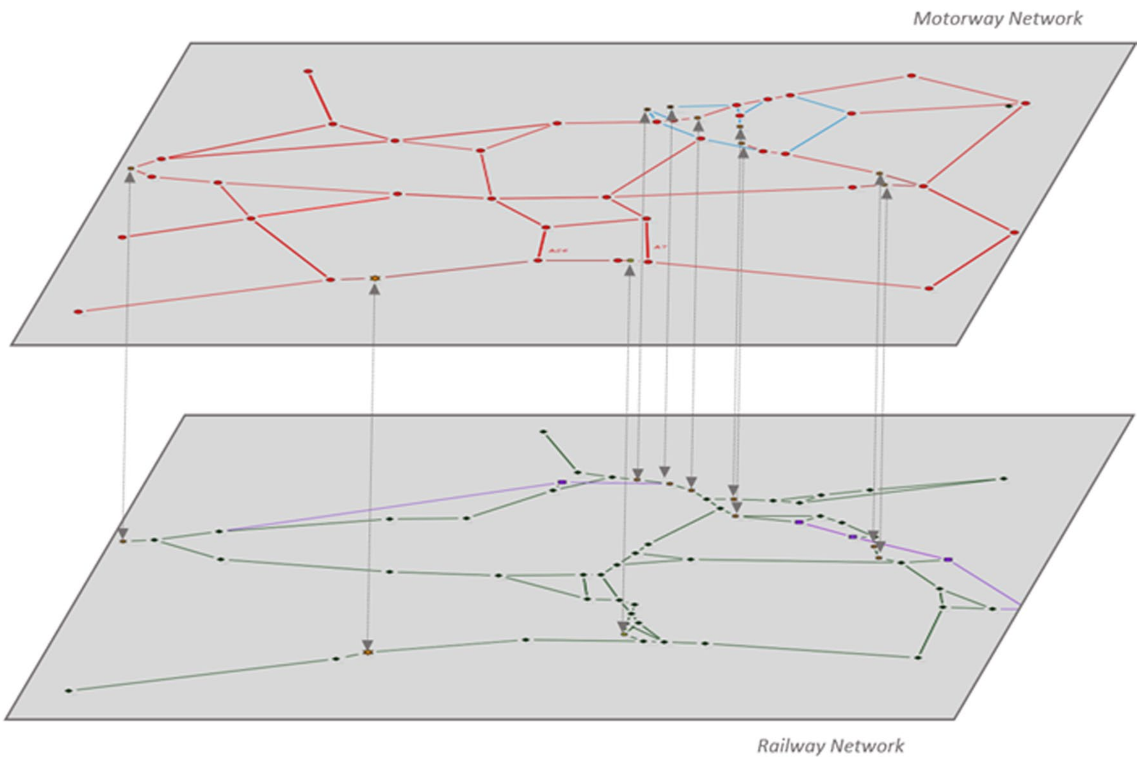


Fig. 2 Multi-layer Network—overpass points. *Source*: Authors' own elaboration

network and the railways bridges overpassing a motorway.[19] The analysis returned 66 *overpass points* in the north-western Italy.[20] Then, considering only the most densely populated locations and *overpass points* affecting only fundamental railway lines (or relevant urban rail junctions), it was possible to identify ten points considered most relevant for the purposes of this analysis (see Fig. 11 and Table 3 in "Appendix 1").

Figure 2 shows how the two networks are joined using the *overpass points*. The graph considered are:

- $Graph_m = (v_m, e_m)$, a symmetric graph, with $v_m = 1, \ldots, 46$, and where each link, e_m, represents a highway connection or a ring road, with $e_m = 1, \ldots, 62$.
- $Graph_r = (v_r, e_r)$, a symmetric graph with $v_h = 1, \ldots, 58$, and where each link, e_r, represents a fundamental railway connection, with $e_h = 1, \ldots, 76$.

The resulting graph, $Graph_z = (v_z, e_z)$, is a bidirectional graph, in which each node, v_z, represents alternatively a motorway exit, a railway station, or an *overpass point*, with $v_z = 1, \ldots, 94$, and each link, e_z, represents a motorway or a railway connection, with $e_z = 1, \ldots, 138$. Figure 3 shows a graphical representation of the graph where motorway links are colored in red and railway lines in green (including high speed railways). *Overpass points* are indicated with yellow stars.[21] Finally, notice that we construct both an unweighted and a weighted version of $Graph_z = (v_z, e_z)$, where link weights correspond to distances (km).

Using the multi-layer network in Fig. 3 it is possible to assess the vulnerability of the network using different methods: *efficiency* loss, *cut vertices*, and *betweenness centrality*.[22]

Figure 4 reports the *efficiency* loss caused by each removed node according to Eqs. 1 and 2. In particular, on the y-axis we indicate the *efficiency* loss, while on the x-axis we indicate the node that has been removed. On average, the removal of one of the *overpass points* leads to an *efficiency* loss of about 7%, while the average loss associated with the removal of motorway

[19] The complete infrastructure network has been mapped using Mapinfo software, which allows for a geo-referenced visualization of the motorway and railway networks in the north-western Italy.

[20] For further details see Fig. 10 in "Appendix 1".

[21] The full list of nodes is reported in "Appendix 2".

[22] See Sect. 3 for further details.

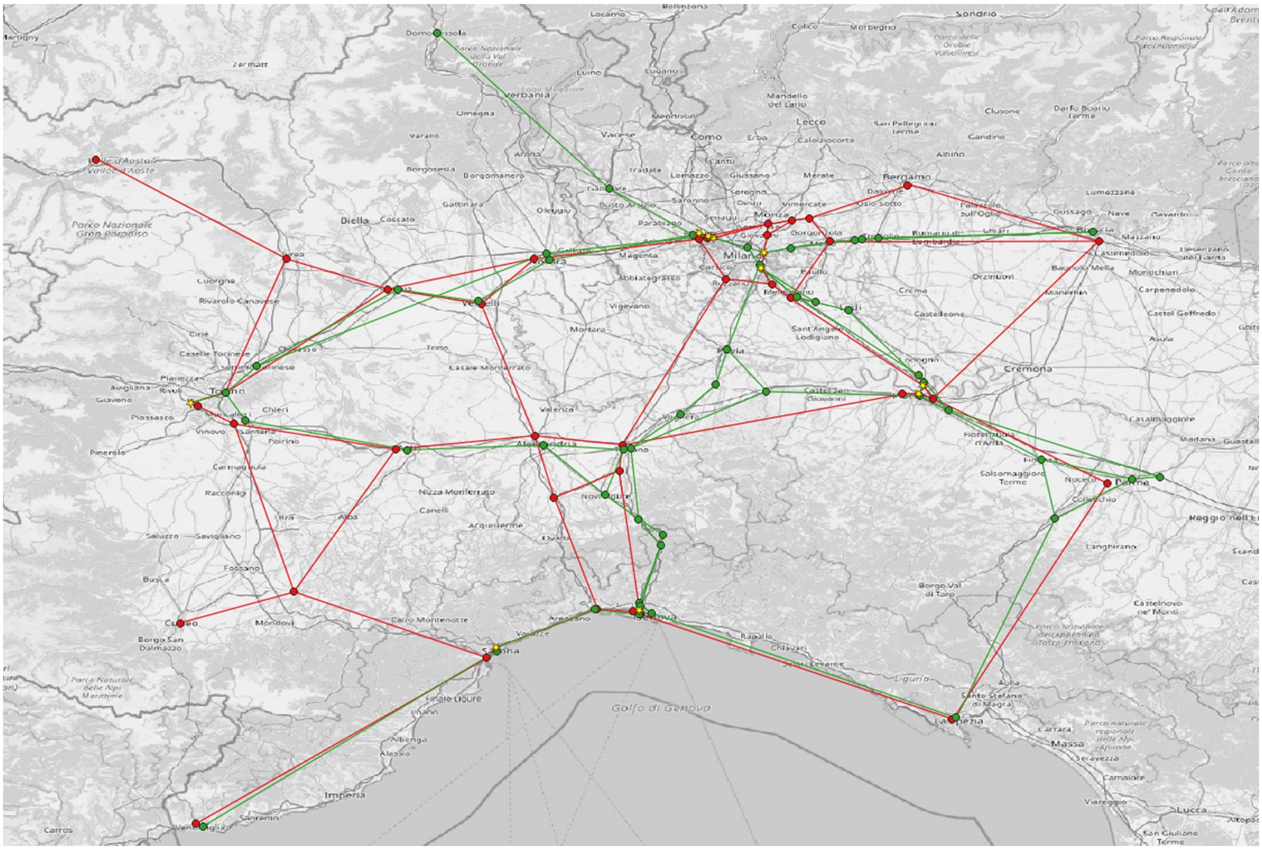


Fig. 3 Overpass Multi-Layer Network. *Source*: Authors' elaboration in QGIS Software. Red and green lines indicate motorway and railway networks, respectively. Yellow stars indicate overpass points

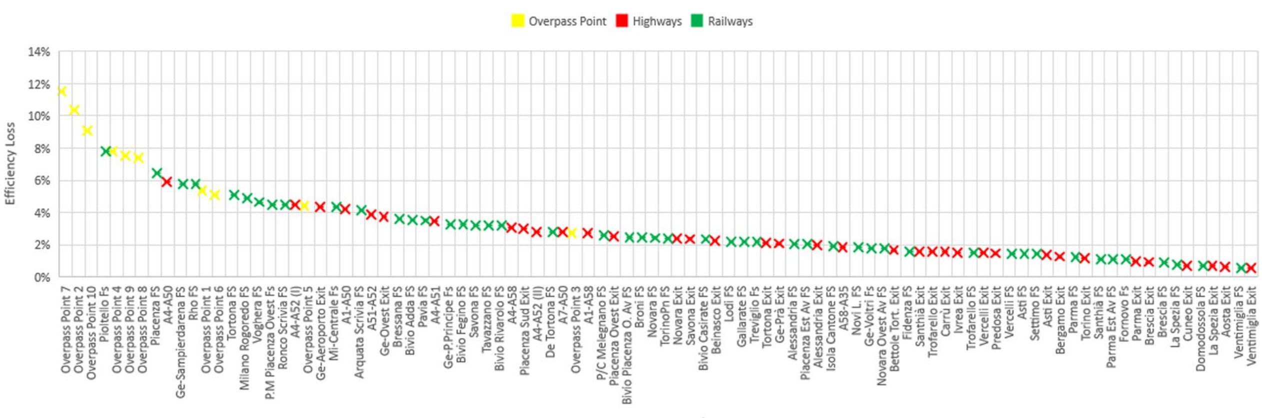


Fig. 4 Efficiency loss—Nodes Removal

and rail nodes is about 2.2 and 2.8%, respectively. As expected, the *overpass points* are among the most critical points in the network, generally making the network most vulnerable.

Furthermore, Table 1 shows *cut vertices* identified in the network. Our analysis leads to the identification of 9 *cut vertices*, while in all cases where a node other than

Table 1 Identification of Cut Vertices in the Multi-layer Network

Cut Vertices	N° nodes in the giant component	% Nodes in the giant component	N° nodes in the new cluster	% Nodes in the new cluster
Savona exit	92	98.92	1	1.08
Ivrea exit	92	98.92	1	1.08
Carru exit	92	98.92	1	1.08
Savona FS	92	98.92	1	1.08
Gallarate FS	92	98.92	1	1.08
Overpass point 1	91	97.85	2	2.15
Rho FS	91	97.85	2	2.15
Pioltello FS	89	95.70	4	4.30
Overpass point 7	88	94.62	5	5.38

nodes listed in the Table is removed, the giant component contains 93 nodes, indicating that all nodes remain in the main cluster.[23]

The removal of some nodes leads to the disconnection of only one node from the network, and this occurs in the case of pending nodes. Narrowing the focus to only those nodes that cause the creation of components with a number of nodes greater than 1, two of the four nodes identified are nodes of interconnection because of geographical proximity, i.e. *Overpass Points* 1 and 7, which are located in Savona and Milan, respectively. When the *Overpass Point 1* is removed, two railway stations, i.e. Ventimiglia and Savona, form a new component; while when *Overpass Point 7* is removed the new component consists of five nodes, among which there are Pioltello, Treviglio and Brescia railway stations. In particular, the size of the largest connected cluster has the most pronounced decrease following the removal of *Overpass Point* 7, leading to a loss of about 6% of nodes and 7% of links. Removing one of the other *overpass points*, on the other hand, results in a drop in *efficiency*, although it does not imply the formation of different clusters.

Finally, results from the *betweenness centrality* analysis are illustrated in Fig. 5, where we provide a graphical representation of the network that highlights the *betweenness* of each node.[24]

In particular, each node is classified as follows: "Highly Critical", "Medium Critical", and "Low Critical". Highly critical nodes are those whose (normalized) *betweenness* index lies within the fourth quartile of the distribution, while nodes whose value is between the median and the third quartile are considered to be medium critical. Finally, all other nodes are of low criticality. The first category of nodes is represented in orange and the second in light blue, while the remaining nodes are colored in grey. Moreover, the size of each node belonging to the first two categories is proportional to the value of the centrality score. What emerges clearly is that the nodes corresponding to the points of geographic overlapping of the two networks are for the most part classified as "High Critical", and in a minority of cases "Medium Critical". The geographical proximity points identified in our network are never low critical points.

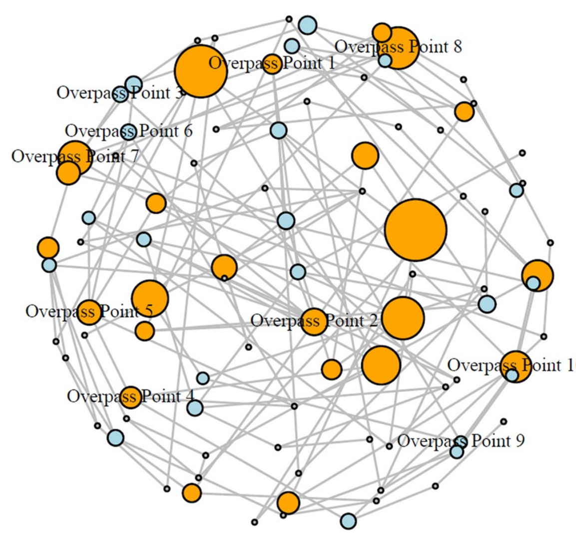


Fig. 5 Betweenness Centrality of Nodes. Source: Authors' elaboration from iGraph R Package. Orange coloured nodes indicate those nodes whose betweenness centrality value falls within the fourth 4th quartile of the distribution, while nodes whose betweenness value falls between the 2nd and 3rd quartiles are indicated in light blue. In addition, the size of the nodes reflects the value of the centrality indicator. All other nodes are indicated in grey and with fixed size

23 As expected, as a consequence of removing a node, the number of links also changes.

24 The analysis refers to the weighted index, i.e. accounting for the (km) distance between each pair of nodes, but all results are largely confirmed when the unweighted index is considered.

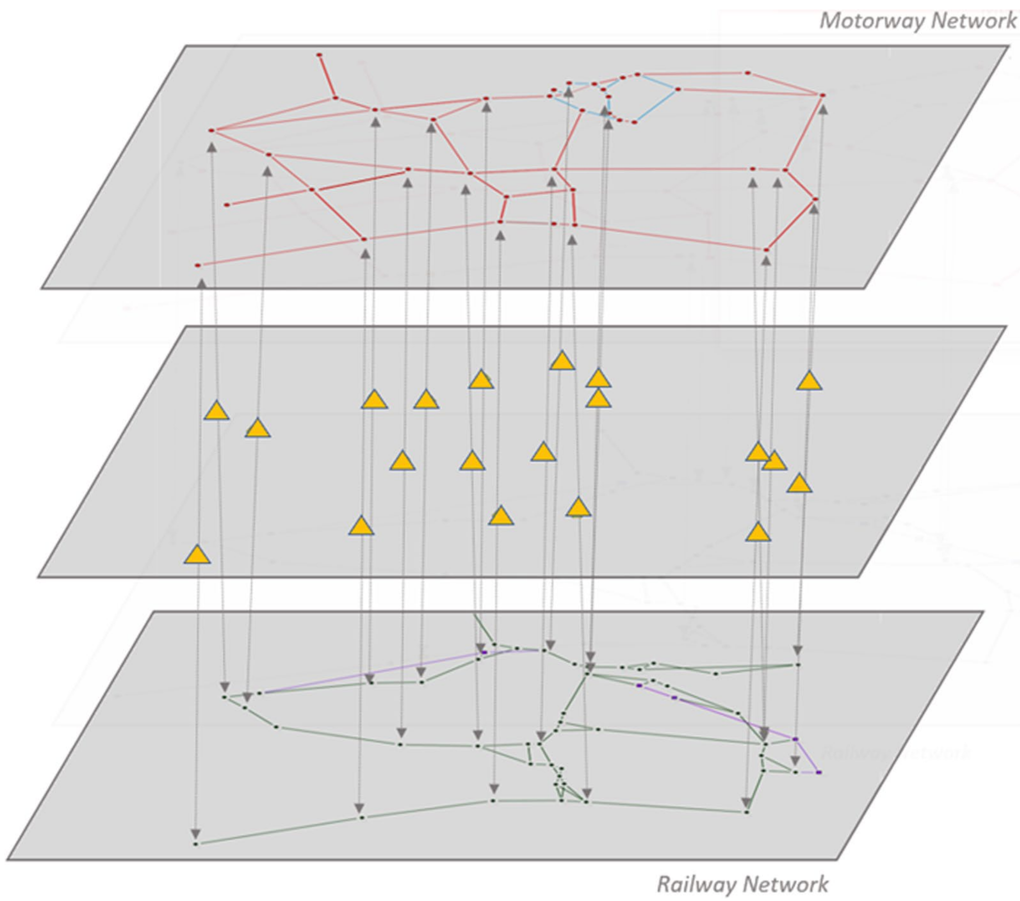


Fig. 6 Multi-layer network using railways, motorways, and artificial interchange infrastructures

Wrapping up, the vulnerability analysis shows that the points of geographical proximity in the network are often also the most critical, and this result is obtained using three different criteria. This finding suggests the importance of a multimodal management of transport networks, especially in the phases of elaboration of prevention policies that require knowledge of the critical points of the network that make the infrastructure very vulnerable. If the topological analysis can be very informative with respect to the vulnerability of a transport network, not considering the points of geographical interdependence would make it much less efficient.

4.2 Robustness analysis of a multimodal network

This analysis in based on a network in which in each main city in the north-west of Italy the intermodal shift can take place since in these places the motorway exit and the railway station are closely connected. In particular, places considered suitable to simulate an interchange point are Ventimiglia, Savona, Genova, La Spezia, Parma, Piacenza, Tortona, Alessandria, Asti, Torino, Santhià, Novara, Milano, and Brescia.

First, to make the railway stations and motorway exits intermodal, new and artificial infrastructures are inserted in the network, i.e. interchange node. In each of the aforementioned cities, the main motorway exits and the main railway stations are connected to the corresponding interchange node. Figure 6 shows the three layers of our multi-layer graph. The layers considered are:

- $Graph_m = (v_m, e_m)$, a symmetric graph, with $v_m = 1, \ldots, 39$, and where each link, e_m, represents a highway connection or a ring road, with $e_m = 1, \ldots, 55$;
- $Graph_r = (v_r, e_r)$, a symmetric graph with $v_r = 1, \ldots, 50$, and where each link, e_r, represents a fundamental railway connection, with $e_r = 1, \ldots, 68$;
- 20 interchange points where the modal shift can take place.

The resulting graph, $Graph_z = (v_z, e_z)$, is a bidirectional graph, in which each node, v_z, represents alternatively a motorway exit, a railway station, or an interchange point, with $v_z = 1, \ldots, 109$, and each link, e_z, represents a

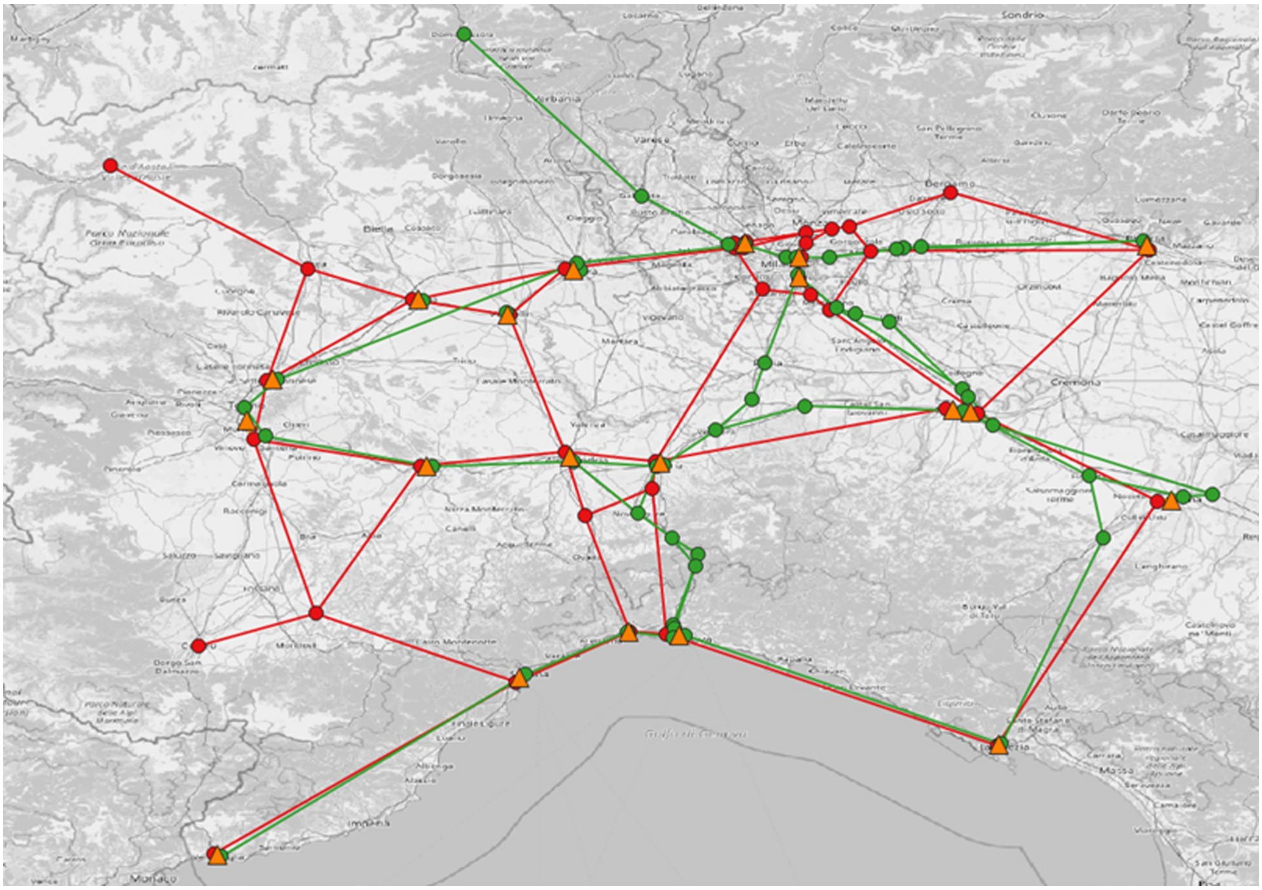


Fig. 7 Multi-layer graph—Artificial interchange nodes

motorway or a railway connection, with $e_z = 1, \ldots, 163$. The number of nodes is the sum of motorways, railways, and interchange nodes. The number of edges is the sum of the motorway and railway links plus the (road) links connecting each interchange station with the corresponding railway and motorway stations (2 edges for each interchange node, for a total of 40 additional links).[25] Figure 7 shows a graphical representation of the multi-layer graph: motorways are the red lines, railways are the green one (including high speed railways), interchange points are indicated with yellow triangles, and roads connecting the latter to the corresponding railway stations and motorway exits are yellow.

Once the multi-layer graph is constructed, a robustness analysis is performed comparing three different networks separately: motorway network, $Graph_m = (v_m, e_m)$, railway network, $Graph_r = (v_r, e_r)$, and the multimodal network $Graph_z = (v_z, e_z)$. For each of the three networks, nodes are successively removed, and the maximal component size is calculated. Results are shown in Fig. 8, where the ratio of the remaining maximal component size to the initial maximal component size (y-axis) is related to the ratio of vertices removed (x-axis). The red line refers to results obtained performing the analysis on the motorway network ($Graph_m = (v_m, e_m)$), while the green line refers to the analysis conducted on the railway network ($Graph_r = (v_r, e_r)$). Finally, the blue line shows results obtained on the multimodal network ($Graph_z = (v_z, e_z)$). Combining results from the analyses in a single graph, it is possible to compare the behavior of the three networks (Fig. 8).[26] In particular, we used the *degree centrality* (left-hand panel) and *betweenness centrality* (right-hand panel), respectively, as criteria for ordering and then removing vertices. In

[25] The full list of nodes is reported in "Appendix 3". It is also worth noting that in this case, we only rely on an unweighted graph.

[26] It is worth noting that the number of nodes and the order in which they are removed from the network change according to the network under consideration; however, by expressing the results in percentage terms, it is possible to combine the results of the three separate analyses in a single figure.

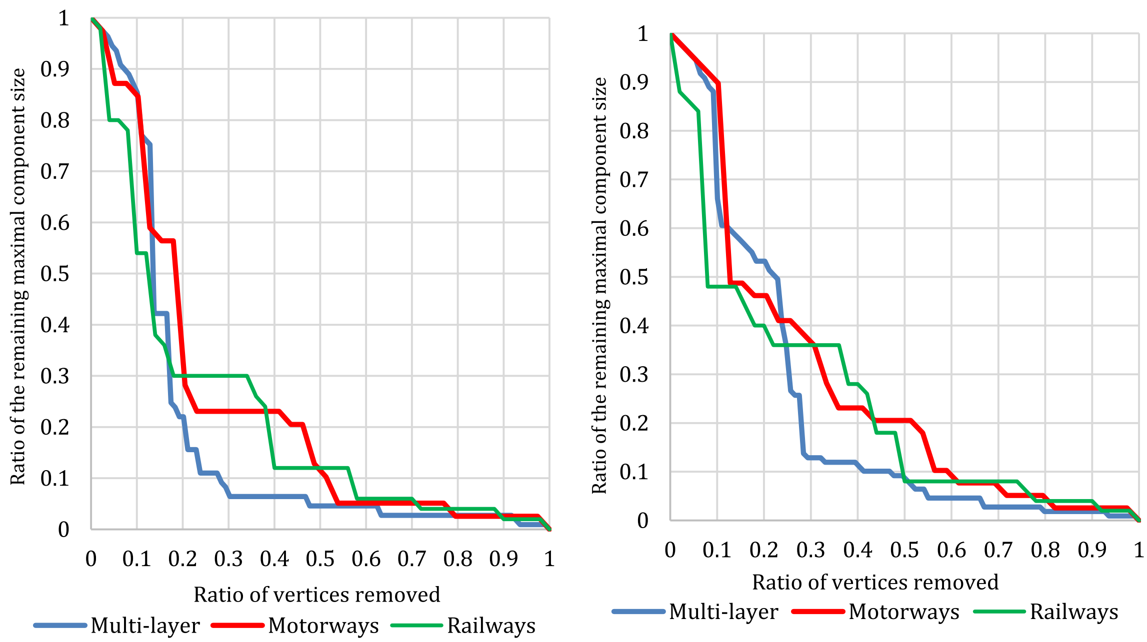


Fig. 8 "Targeted" attack to vertices. Comparison between motorway network, railway network, and multi-layer network with interchange nodes. *Notes*: Nodes are removed by Degree Centrality (left-hand panel) and by betweenness centrality (right-hand panel)

the left-hand panel of Fig. 8, the blue line shows a less pronounced decrease in the size of the main component after the initial removal of the most central nodes, while it lies between the green and the red lines when 15% of the most central nodes are removed. When about 20% of the nodes are removed, the blue line lies below the lines associated to the single-mode networks. In the right-hand panel of Fig. 8, the behavior of the interconnected network is slightly different. In fact, the blue line lies between the two red and green lines in the first section, and then the multimodal network shows a greater robustness than the two unimodal networks when more than 10% are removed. However, when slightly more than 20% of the nodes are removed, the blue line lies below both the other two lines in the graph. In general, the multimodal network, assuming that only a part of the nodes of the network are multimodal, looks more robust than the unimodal networks only until the share of nodes removals remains below a 10% or 20%. After this percentage, the curve for the multimodal network experiences a very pronounced'jump', indicating much greater fragmentation than the two unimodal networks. In the left graph, for instance, only 10% of the nodes remain connected to the main component when only 20% of the nodes have been removed. This result is in line with findings in Buldyrev et al. [8], a seminal paper on this topic, critically reviewed by Vespignani [45]. In Buldyrev et al. [8], authors investigate the fragility of a network building on the "percolation analysis", i.e. by progressively removing nodes from two interdependent networks. The complete breakdown of the network arises at a smaller scale of damage with respect to the two isolated networks and there is a sudden discontinuity in the operation of the interconnected network at the critical threshold.

To conclude the analysis, we also consider the case of an intermodal network without interchange stations, i.e. we consider the main railways stations directly connected to the main motorway exits via the urban road network. In general, results show that removing the interchange stations increases the robustness of the multi-level network. This is certainly related to the fact that the possibility of modal shift in this case depends on only two nodes, a railway station and a motorway exit connected by an urban road, without the need for a third infrastructure, i.e. the interchange station. However, assuming that there is no need for an infrastructure to enable modal shift leads to an oversimplification of reality. Indeed, modal shift is in itself very complex for freight, whereas for passengers it is much more realistic. However, excluding nodes that could, for example, serve as interchange car parks for passengers, makes the initial hypothesis even more complicated. For these reasons we consider more realistic the robustness results for a 3-layer network (railways, motorways, and interchange stations). In any case, this analysis also confirms that the intermodal infrastructure is more fragile, showing that a very pronounced jump in the size of the main component occurs at a lower percentage of nodes removed than in the case of the two uni-modal networks.[27]

Overall, the robustness analysis confirms that considering an intermodal network is necessary for the robustness analysis to be complete. Once again, therefore, considering interdependence is a central point in the topological analysis of the network. And this brings us back to the most urgent issue of multimodal regulation of transport infrastructures: inter-modality is an asset because it enables the transfer of demand from one mode to another, but it brings with it major weaknesses that cannot be ignored if an efficient management system is to be achieved. Indeed, if the robustness analysis is mainly used to propose improvements to the network, considering the single transport modes would often lead to an underestimation of the network vulnerability.

4.3 Discussion

The vulnerability analysis conducted on the transportation network in northwest Italy leads to some interesting considerations. Ten overpass points were identified on the network within the geographical area under consideration.[28] In particular, two nodes were identified in the Liguria NUTS-2 region, namely in Savona, where the A10 highway passes over the Savona-Genova Voltri railway line, and in Genoa, where the Morandi bridge was located. An overpass point is found in west of the Metropolitan City of Turin where the A55 ring road passes over the Torino Orbassano intermodal terminal.[29] The area where the majority of the overpass points have been identified is the Metropolitan City of Milan. In most cases, the railway lines involved are urban junctions, and in only one case a fundamental railway line is concerned, i.e. that between Milan and Lavino Bologna. Instead, three cases involve road segments classified as ring roads, and in two cases two highways, the A4 and A1. Finally, there is an overpass point in Piacenza where the A21 highway passes over the railway line between Milano Rogoredo and Lavino Bologna, and in Lodi NUTS-3 region. In the latter case, it is the railway line (Milan Rogoredo–Lavino Bologna) that passes over the A1 highway, and this represents an exception to all the aforementioned cases. All in all, four NUTS-2 regions are affected by the presence of overpass points: Liguria, Piedmont, Lombardy and Emilia-Romagna.[30]

[27] Results from this analysis are available upon request.

[28] See "Appendix 1" for a detailed description.

[29] The terminal has 5 tracks and a 50,000 sq m area for storage of Intermodal Transport Units.

[30] Formally, the NUTS-2 region Emilia Romagna does not belong to the NUTS-1 northwest Region, however, in order to model the network it was necessary to include a portion of this region, the westernmost, namely the cities of Parma and Piacenza.

Table 2 Results from the vulnerability analysis—efficiency loss

Node	Efficiency loss %	Rank efficiency loss
Overpass point 1	5.36	12
Overpass point 2	10.38	2
Overpass point 3	2.72	41
Overpass point 4	7.79	5
Overpass point 5	4.39	20
Overpass point 6	5.09	13
Overpass point 7	11.52	1
Overpass point 8	7.37	7
Overpass point 9	7.55	6
Overpass point 10	9.08	3

Interestingly, two of the ten identified nodes affect the A10 highway in Liguria, and two affect the A1 highway. The railway line between Milano Rogoredo and Lavino Bologna even exhibits three overpass points.

The first method used to assess vulnerability reveals that overpass points lead on average to a 7% decrease in efficiency. In detail, the node that causes the greatest vulnerability of the network is the overpass point where the A4 highway passes over the Milano Certosa-Rho railway urban line (*Overpass Point* 7). This node is followed, in order, by the point identified at the Morandi bridge (*Overpass Point* 2) and the one located in Piacenza (*Overpass Point* 10). Among the top ten nodes in order of efficiency loss, only *overpass points* are observed, with the only exceptions of the Pioltello and Piacenza railway stations, and an intersection node between the A4 highway and the A50 Milan ring road, which occupy the fourth, ninth and tenth positions, respectively. The two remaining overpass points (*Overpass Points* 3 and 5) still occupy positions in the first half of the distribution. Details are shown in Table 2, where the percentage decrease in efficiency and the corresponding rank associated with each *overpass point* are shown.

Turning to the analysis of *cut vertices*, the results are more mixed. In fact, among the vertices causing the formation of disconnected components are four railway stations, three highway exits and two overpass points. However, it is the removal of an *overpass point* that causes the most pronounced decrease in the giant component, namely the node corresponding to the point where the A4 highway passes over the railway between Milano Certosa and Rho (*Overpass Point* 7).

Finally, the analysis related to the *betweenness centrality* index largely confirms the result obtained in the efficiency loss analysis. In fact, once again, all the *overpass points* are in the first part of the distribution and have

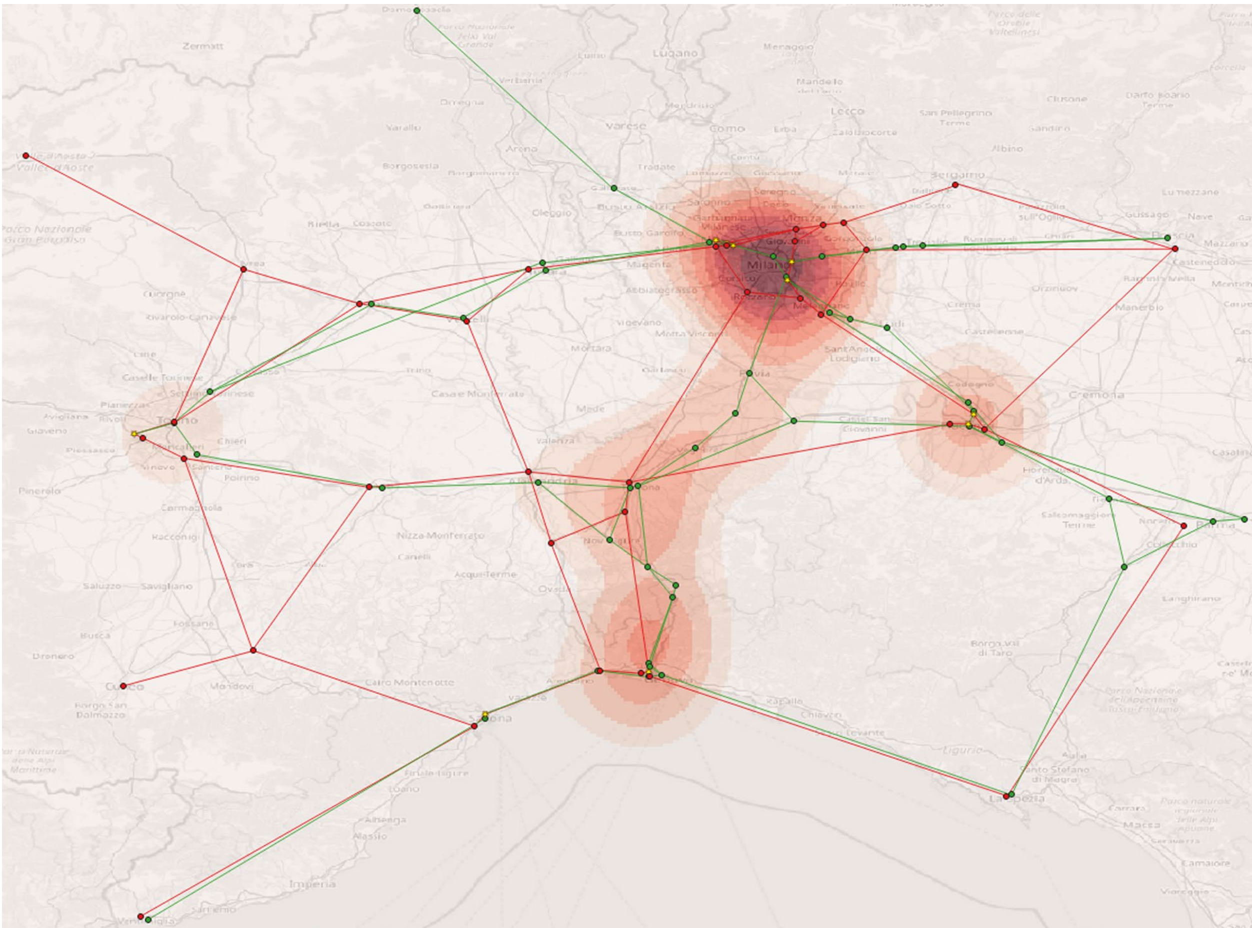


Fig. 9 Heatmap—Betweenness Centrality

been labeled as "Highly Critical" or "Medium Critical." Specifically, eight nodes belong to the former category and only two to the latter. Neither of the *overpass points* was rated "low criticality."[31] Fig. 9 shows the geographical areas that can be considered most critical following the *betweenness centrality* criterion. The map clearly reveals that the vertical axis between Genoa and Milan, that provides a connection to the rest of the northwest network, can be considered highly critical.

Turning to the robustness analysis, it highlights the possible percolation effects due to a disruption involving one or more elements of the networks and how a malfunctioning of a node or link on an infrastructure mode may propagate on the other ones. In fact, the multi-layer network appears less robust than the road and railway networks separately considered. This result leads to two considerations. On the one hand, in order to improve the robustness of a multimodal network, each node should have a multi-modal usage, thus resulting in an extremely redundant network and in an oversupply of capacity. On the other hand, emergency management, which is usually handled at the level of the individual network or infrastructure manager, should also consider possible damage to competing and complementary networks (i.e. the percolation effect). These considerations lead us to advice some form of coordination between the managers of the different infrastructures as interesting and advisable, at least for emergency planning.

5 Conclusions

In this work we have focused on the motorway and rail network in the north-western part of Italy, and we analyzed different aspects of these networks in the context of interdependent transport infrastructures. Based on a network topological approach, we relied on two different concepts of interdependence to build two multi-level networks that serve two different purposes. Firstly, we

[31] Results are largely confirmed when an unweighted index is computed.

analyzed the concept of geographical interdependence, and then we mapped the points at which motorways pass over railways, or vice versa, in the whole of the territory under analysis. Thus, we constructed a multi-level network in which it was possible to consider the points at which, if a shock occurred, it would also have cascading repercussions on the network not directly involved, precisely because it was geographically'close'. Using this multi-layer graph it was possible to evaluate the changes in network *efficiency* after removing one by one the nodes of the interconnected network. As expected, the removal of the nodes of geographic proximity generally leads to a strong decrease in network vulnerability, as measured by a typical *efficiency* measure. Even following other criteria, i.e. the identification of *cut vertices* and the analysis of *betweenness centrality*, the results confirm that points of geographical proximity are always very critical points and therefore points that worsen the vulnerability of the system. This analysis therefore provides a list of nodes (and links) that should be the focus of prevention policies to reduce the possibility of damage, but also gives an indication of which nodes (and links) should be restored as quickly as possible whenever an emergency and destructive event renders them inaccessible.

Second, using the concept of functional interdependence we assumed that in each of the main cities of north-western Italy a modal shift was possible. Using this second multi-layer network it was possible to evaluate the robustness of a multimodal network in comparison with the corresponding uni-modal networks. The analysis reveals that the intermodal network involves more fragility: multimodal networks have the advantage of being able to transfer demand from one mode to another, but this means that any problem occurring on one transport infrastructure also affects all the other infrastructures in the network. This result has a very important relevance for the debate on regulation and coordination between competent authorities since often the infrastructures are managed by different operators and the main problems concern the coordination of decisions. In this context, it is necessary to direct researches towards analyzing possible ways of increasing the resilience of multimodal networks.

Appendix 1: Description of the *overpass points*

In Fig. 10 the full list of *overpass points* is provided, while Fig. 11 focus on the selected most important ones.

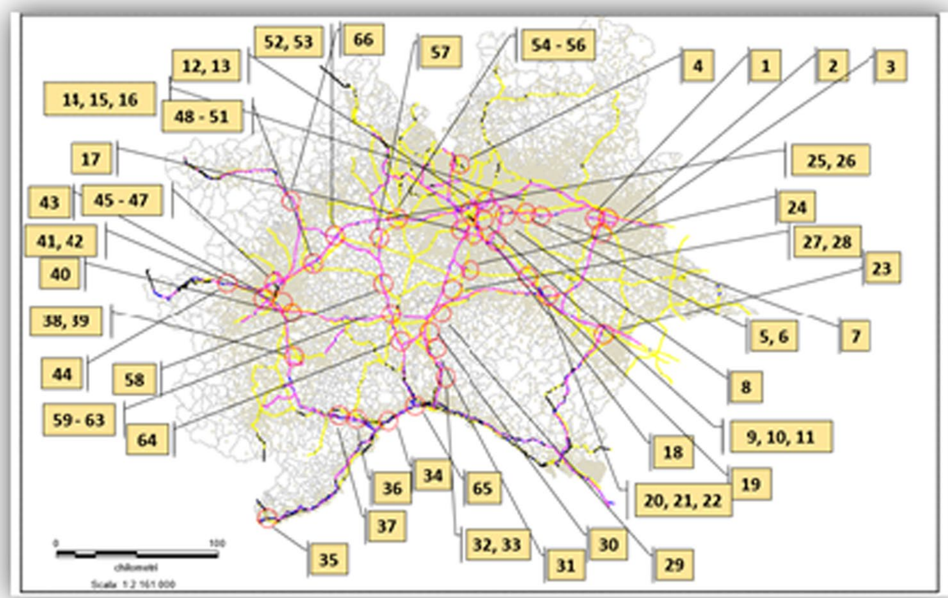


Fig. 10 Overpass points Between Motorways and Railways: Full List. *Source*: Authors' elaboration in MapInfo using Openstreetmap data. Red lines indicate motorways, yellow lines indicate railways

Fig. 11 Selected Major overpass points Between Motorways and Railways. *Source*: Authors' elaboration in MapInfo using Openstreetmap data. Red lines indicate motorways, yellow lines indicate railways

Finally, Table 3 gives details of the *overpass points* contained in the boxes numbered 1–6 in Fig. 11.

Table 3 Selected Major overpass points: Description

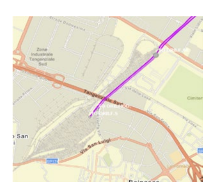
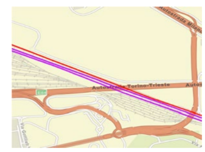
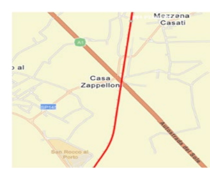
City	ID	Railway	Motorway	
Savona (1)	Overpass Point 1	Fundamental Line (Savona-Genova Voltri)	A10	
Genoa (2)	Overpass Point 2 (Morandi Bridge Colalpse)	Urban junction	A10	
Turin (3)	Overpass Point 3	Urban Junction	A55 (ring road)	

Table 3 (continued)

City	ID	Railway	Motorway	
Milan (4)	Overpass Point 4	Urban Junction (Milano Certosa-Rho)	A50 and A52 (ring roads)	
Milan (4)	Overpass Point 5	Urban Junction (Milano Certosa-Rho)	A52 (ring road)	
Milan (4)	Overpass Point 6	Urban Junction (Milano Certosa-Rho)	A4	
Milan (5)	Overpass Point 7	Urban Junction (Milano centrale-Pioltello)	A51 (ring road)	
Milan (5)	Overpass Point 8	Fundamental Line (Milano Rogoredo–Lavino Bologna)	A1	
Lodi (6)	Overpass Point 9	Fundamental Line (Milano Rogoredo–Lavino Bologna)	A1	
Piacenza (6)	Overpass Point 10	Fundamental Line (Milano Rogoredo–Lavino Bologna)	A21	

Appendix 2: Multi-layer Network with *overpass points*

See Table 4

Table 4 Full list of nodes: motorway exits, railways station and overpass points

Node	Type
A1–A50	Highway
A1–A58	Highway
A4–A50	Highway
A4–A51	Highway
A4–A52 (I)	Highway
A4–A52 (II)	Highway
A4–A58	Highway
A51–A52	Highway
A58–A35	Highway
A7–A50	Highway
Alessandria exit	Highway
Alessandria FS	Railway
Aosta exit	Highway
Arquata scrivia FS	Railway
Asti exit	Highway
Asti FS	Railway
Beinasco exit	Highway
Bergamo exit	Highway
Bettole tortona exit	Highway
Bivio Adda FS	Railway
Bivio Casirate FS	Railway
Bivio Fegino FS	Railway
Bivio Piacenza O. Av FS	Railway
Bivio Rivarolo FS	Railway
Brescia Exit	Highway
Brescia FS	Railway
Bressana FS	Railway
Broni FS	Railway
Carrù Exit	Highway
Cuneo Exit	Highway
De Tortona FS	Railway
Domodossola FS	Railway
Fidenza FS	Railway
Fornovo FS	Railway
Gallarate FS	Railway
Genova-Aeroporto exit	Highway
Genova-Ovest exit	Highway
Genova-Prà exit	Highway
Genova-P.Principe FS	Railway
Genova-Sampierdarena FS	Railway
Genova-Voltri FS	Railway
Overpass point 1	Overpass Point
Overpass point 10	Overpass Point
Overpass point 2	Overpass Point
Overpass point 3	Overpass Point
Overpass point 4	Overpass Point
Overpass point 5	Overpass Point
Overpass point 6	Overpass Point
Overpass point 7	Overpass Point
Overpass point 8	Overpass Point
Overpass point 9	Overpass Point
Isola Cantone FS	Railway
Ivrea exit	Highway
La Spezia exit	Highway
La Spezia FS	Railway
Lodi FS	Railway
Milano Centrale FS	Railway
Milano Rogoredo FS	Railway
Novara exit	Highway
Novara FS	Railway
Novara Ovest Av FS	Railway
Novi Ligure FS	Railway
P.M Piacenza Ovest Fs	Railway
P/C Melegnano FS	Railway
Parma Est Av FS	Railway
Parma exit	Highway
Parma FS	Railway
Pavia FS	Railway
Piacenza Est Av FS	Railway
Piacenza FS	Railway
Piacenza ovest exit	Highway
Piacenza sud exit	Highway
Pioltello FS	Railway
Predosa exit	Highway
Rho FS	Railway
Ronco Scrivia FS	Railway
Santhià exit	Highway
Santhià FS	Railway
Savona exit	Highway
Savona FS	Railway
Settimo Torinese FS	Railway
Tavazzano FS	Railway
Torino exit	Highway
TorinoPn FS	Railway
Tortona exit	Highway
Tortona FS	Railway
Treviglio FS	Railway
Trofarello exit	Highway
Trofarello FS	Railway
Ventimiglia exit	Highway
Ventimiglia FS	Railway
Vercelli exit	Highway
Vercelli FS	Railway
Voghera FS	Railway

Appendix 3: Multi-layer Network with Artificial Interchange Points

See Table 5

Table 5 Full list of nodes: motorway exits, railways station and artificial interchange nodes

Node	Type
A1–A50	Highway
A1–A58	Highway
A4–A50	Highway
A4–A51	Highway
A4–A52 (II)	Highway
A4–A52(I)	Highway
A4–A58	Highway
A51–A52	Highway
A58–A35	Highway
A7–A50	Highway
Alessandria exit	Highway
Alessandria FS	Railway
Alessandria interchange node	Artificial Node
aosta exit	Highway
Arquata Scrivia FS	Railway
Asti EXIT	Highway
Asti FS	Railway
Asti interchange node	Artificial Node
Bergamo exit	Highway
Bettole tortona exit	Highway
Bivio Adda FS	Railway
Bivio Casirate FS	Railway
Bivio Fegino FS	Railway
Bivio Piacenza O. Av FS	Railway
Bivio Rivarolo FS	Railway
Brescia Exit	Highway
Brescia FS	Railway
Brescia interchange node	Artificial Node
Bressana FS	Railway
Broni FS	Railway
Carrù exit	Highway
Cuneo exit	Highway
De Tortona FS	Railway
Domodossola FS	Railway
Fidenza FS	Railway
Fornovo FS	Railway
Gallarate FS	Railway
Genova interchange node	Artificial Node
Genova-Aeroporto Exit	Highway
Genova-Ovest Exit	Highway
Genova-P.Principe FS	Railway
Genova-Prà exit	Highway
Genova-Sampierdarena FS	Railway
Genova-Voltri FS	Railway
Isola Cantone FS	Railway
Ivrea Exit	Highway
La Spezia exit	Highway
La Spezia FS	Railway
La Spezia interchange node	Artificial Node
Lodi FS	Railway
Milano Centrale FS	Railway
Milano Lambrate Exit	Highway
Milano Lambrate FS	Railway
Milano Lambrate interchange node	Artificial Node
Milano Rogoredo FS	Railway
Milano Rogoredo interchange node	Artificial Node
Novara Exit	Highway
Novara FS	Railway
Novara interchange node	Artificial Node
Novara Ovest Av FS	Railway
Novi L. FS	Railway
P.M Piacenza Ovest FS	Railway
P/C Melegnano FS	Railway
Pantanedo	Highway
Parma Est Av FS	Railway
Parma Exit	Highway
Parma FS	Railway
Parma interchange node	Artificial Node
Pavia FS	Railway
Piacenza Est Av FS	Railway
Piacenza FS	Railway
Piacenza ovest exit	Highway
Piacenza ovest interchange node	Artificial Node
Piacenza sud exit	Highway
Piacenza sud interchange node	Artificial Node
Pioltello FS	Railway
Predosa exit	Highway
Rho Fiera exit	Highway
Rho Fiera FS	Railway
Rho FS	Railway
Rho interchange node	Artificial Node
Ronco Scrivia FS	Railway
S. Donato Exit	Highway
Santhià Exit	Highway
Santhià FS	Railway
Santhià interchange node	Artificial Node
Savona Exit	Highway
Savona FS	Railway
Savona interchange node	Artificial Node
Settimo interchange node	Artificial Node
Settimo torinese exit	Highway
Settimo torinese FS	Railway
Tavazzano FS	Railway

Table 5 (continued)

Node	Type
Torino interchange node	Artificial Node
TorinoPn FS	Railway
Tortona exit	Highway
Tortona FS	Railway
Tortona interchange node	Artificial Node
Treviglio FS	Railway
Trofarello exit	Highway
Trofarello FS	Railway
Ventimiglia exit	Highway
Ventimiglia FS	Railway
Ventimiglia interchange node	Artificial Node
Vercelli Exit	Highway
Vercelli FS	Railway
Vercelli interchange node	Artificial Node
Voghera FS	Railway
Voltri interchange node	Artificial Node

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Author contributions
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Declarations

Competing interests
The author's declared that they have no competing interests.

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