New Economic Regulation for Transport in Case of Emergency Events

Outcome 1 – Innovation in Transport Including the Adoption of New Technologies for Infrastructure Security

Output 2 – Categorisation of Potential Shock Events

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1 Introduction

The present document represents Deliverable number 2 of the research project "New Economic Regulation for Transport in Case of Emergency Events", an Action under the Structural Reform Support Programme of the DG Reform.

The document reports activities made under the output 2 of the Grant Agreement signed by the Università degli Studi di Genova (UNIGE) – Centro Italiano di Eccellenza sulla Logistica i Trasporti e le Infrastrutture (CIELI).

Briefly, the scope of the Output 2 is to identify what can be considered as an emergency event and to graph the network of motorways and railway in order to elaborate some network indicators able to highlight the critical nodes or edges of the national infrastructural transport system.

The planning of the Actions is as follows:

- Literature review
- Taxonomy of Emergency Events
- Construction of the network graph
- Network indicators

A final workshop opened to the wider public will be organized by CIELI with the contribution of the direct Beneficiary, in order to debate the relevant outcomes of the Output with the relevant Stakeholders.

2 Literature review: vulnerability, resilience and interdependency of critical infrastructures to disruptive events

2.1 Introduction

Network infrastructures are essential elements for the economic activity that is deeply dependent on the use of transport systems, power grids and gas pipelines, information and communication systems, water and sewerage handling, among others. Such networks have evolved over time and have turned out to be progressively interdependent and complex. These features make them more vulnerable to technical failures or disruptions associated to natural extreme events or other manmade threats; moreover, failures can spread more easily across interdependent systems, thus inducing a higher level of instability and higher potential damages. Indeed, Nagurney (2012) notes that the average number of "disasters" has been increasing over the last decades thus highlighting how the robustness of network infrastructure has become increasingly critical.

Such issues have spurred research trying to better understand which mechanisms and characteristics are associated to networks weakness. In particular, the concepts of vulnerability and resilience have attracted the interest of researchers and have been extensively analyzed, both theoretically and empirically. The economic literature has shared the importance of analyzing infrastructure networks as complex network systems, where vulnerability and resilience need to be studied within the framework of network inter-dependent systems.

However, before delving into discussing on vulnerability and resilience, it is important to briefly consider what scholars mean by shock, emergency or disruption, given that vulnerability and resilience are always, implicitly, or explicitly, associated to the occurrence of a shock.

With respect to this, Mattson and Junelius (2015) argue that it is useful to distinguish between external and internal causes of disruption, on one side, and between accidental events and intentional interferences on the other one. Internal events are associated to human mistakes, degradation of parts of the network, technical failures; in turn, external disruptions tend to be associated in the literature to nature-made events, such as hurricanes, snowfalls, earthquakes, etc.

A useful distinction is that between hazard and disaster (Okuyama, 2007), with the first referring to the occurrence of the physical event per se and the second which in turn refers to the consequences associated to the event.

In turn, Hasan and Foliente (2015) classify disruption or emergency events on the basis of the time available to prepare for the event and the duration of the actual event; the latter does not only depend on its physical duration (e.g. a few seconds for an earthquake or a few days for a flood), but also on the post-event recovery period, which in turn is affected by the reaction of both policy makers and the local community. Hasan and Foliente (2015) also note the importance of probability theory, since the nature of major disruptions can be classified as low likelihood events but with possibly major effects; according to the authors, in recent years the literature has increasingly focused on the investigation of extreme events, i.e. those characterized by an extremely low probability of occurrence but with extremely important negative consequences (e.g. "black swan" events).

Altay and Green (2006) provide a very useful distinction between daily emergencies and disasters: using their own words, "the transition to a higher category of emergency occurs when resources become stressed, when non-standard procedures must be implemented to save life or when special authorities must be invoked to manage the event".

Lastly, before surveying studies on vulnerability and resilience, it is worth explaining the literature selection process that we have followed.

The literature review has been conducted through the database Scopus, a citational and bibliographic database managed by Elsevier that collects scientific publications (books, articles, conference proceedings) published from 1996 on from more than 4,000 publishers.

The selection strategy was based on a set of keywords and the search has been limited to documents published from 2000 on, so it was limited to the last twenty years.

The keywords used were the combination of:

Transport network Transport infrastructure	+	Emergency Disaster Crisis Vulnerability Resilience Crisis Management

This research strategy resulted in the selection of 8,105 publications distributed as reported in Table 1.

	2000-04	2005-09	2010-14	2015-19	2000-19
Article	138	388	1303	3802	**5631**
Book	9	34	103	113	**259**
Book Chapter	5	49	125	212	**391**
Review	21	42	88	207	**358**
Conference Paper	77	238	352	762	**1429**
Conference Review	-	1	1	-	**2**
Short Survey	1	-	2	3	**6**
Editorial	-	2	2	14	**18**
Note / Letter	1	1	2	7	**11**
	252	*755*	*1978*	*5120*	***8105***

Table 1. Results of the research strategy
(*Source: Own elaboration on Scopus*)

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It is noteworthy that about 63% of the results have been published in the last 5 years. From a temporal viewpoint the investigated topics has gained relevance and attention among scientists from the early 2000s on.

Table 2 highlights the journals more involved in discussing these topics over the last twenty years.

Journal	Number of documents
Transportation Research Record	189
Sustainability (Switzerland)	129
Transportation Research Part A: Policy and Practice	90
Physica A: Statistical Mechanics and its Applications	86
Transportation Research Part E: Logistics and Transportation Review	82
PLoS ONE	70
International Journal of Disaster Risk Reduction	60
Reliability Engineering and System Safety	60
Networks and Spatial Economics	57
Transportation Research Procedia	55

Table 2. Top 10 journals for papers published on the research topics (2000-2019)
(*Source: Own elaboration on Scopus*)

In the top ten list appear journals with different approaches, from physics to civil engineering as well as transport engineering and economics, but also with different perspectives, from resistance, to resilience of transport systems together with its sustainability.

This great amount of documents has been investigated in order to highlight the type of disasters considered, the types of infrastructure affected by disruptions, the different approaches and methodologies applied as well as the geographical locations of the case studies analysed.

Results are summarised and represented in the following four aerograms. It is noteworthy how natural disasters prevail as the causes of emergencies followed by the crisis due to climate change, while infrastructure disruptions – falling under anthropogenic disaster, those caused by human action - cover a limited share of the documents surveyed.

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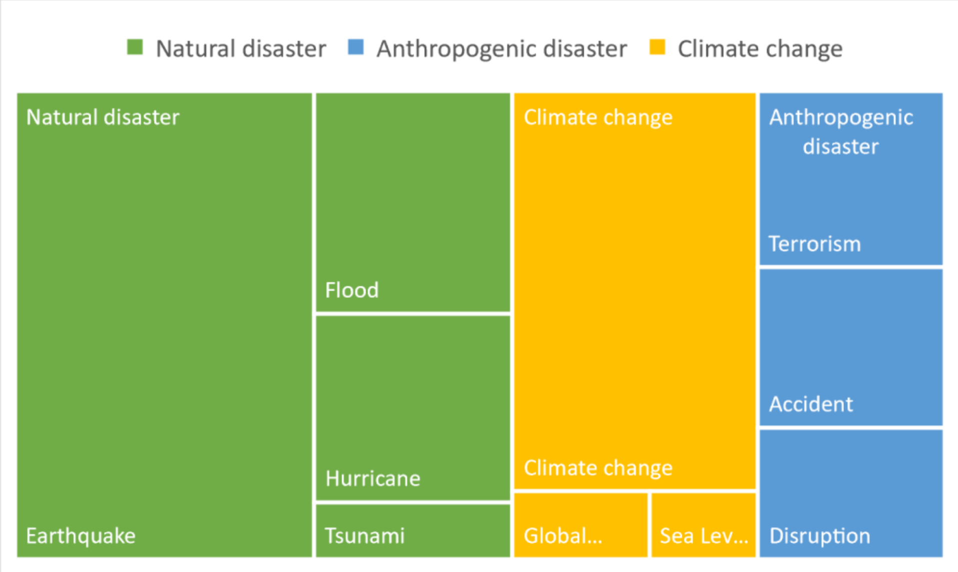

Figure 1. Types of disaster investigated
(*Source: Own elaboration on Scopus*)

From the transport mode point of view (Fig. 2), the majority of the documents considered deals with road transport, and disruption involving road bridges in particular. Only a small part of them investigates multimodal transportation.

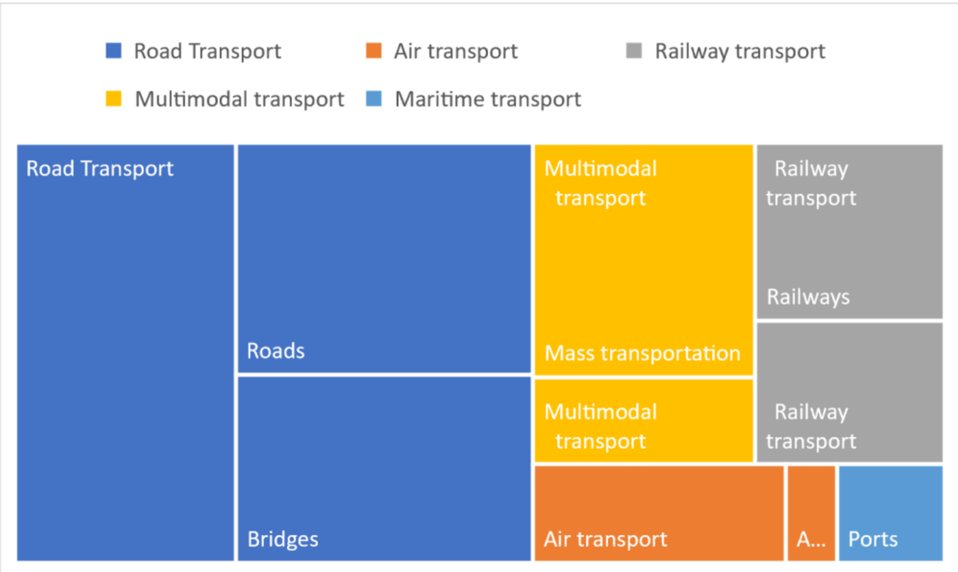

Figure 2. Transport mode involved by infrastructure emergencies
(*Source: Own elaboration on Scopus*)

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From a disciplinary perspective point of view, infrastructural emergencies are usually dealt with simulation models and more recently using spatial planning models as those based on GIS information. It is worth noticing that the economic assessment of disruptions represents a relevant part of the publications indexed by Scopus.

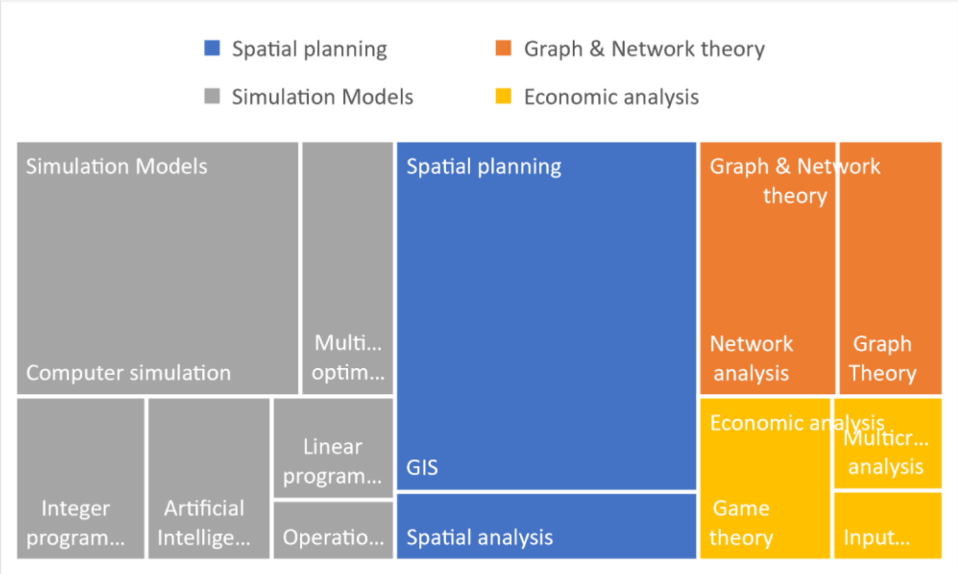

Figure 3. Methodological approaches to transport emergencies
(*Source: Own elaboration on Scopus*)

Lastly, the majority of papers analyse case studies in China and USA. Focusing on Europe, the case studies considered are from UK, Greece Italy and Spain, al accounting for a similar number of documents.

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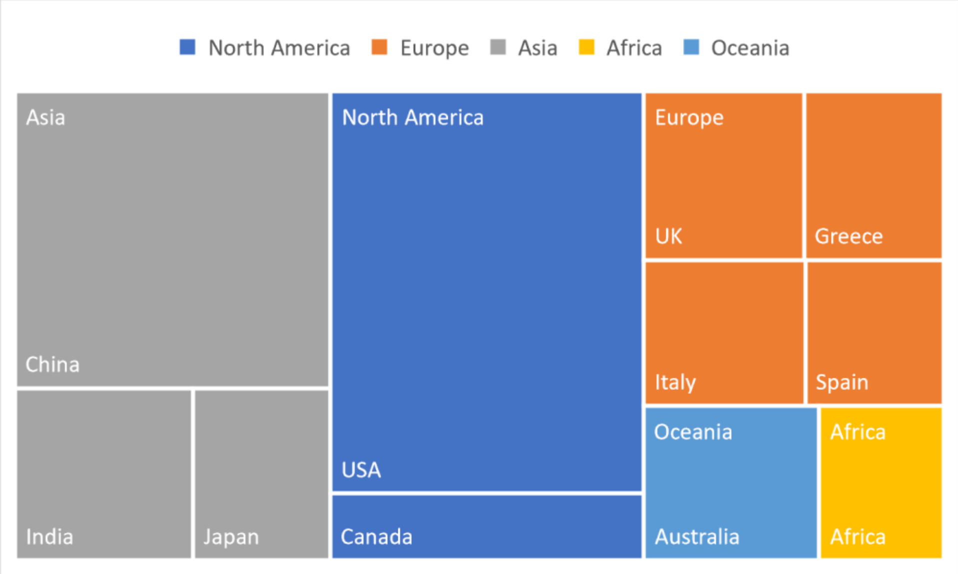

Figure 4. Regions involved by transport emergencies
(*Source: Own elaboration on Scopus*)

Due to the large amount of paper selected in this first stage of the analysis, a deeper investigation has been carried out selecting the top 30 cited papers. This second stage of review has been primarily conducted on the abstracts in order to perform a semantic analysis whose results are reported in the following chart.

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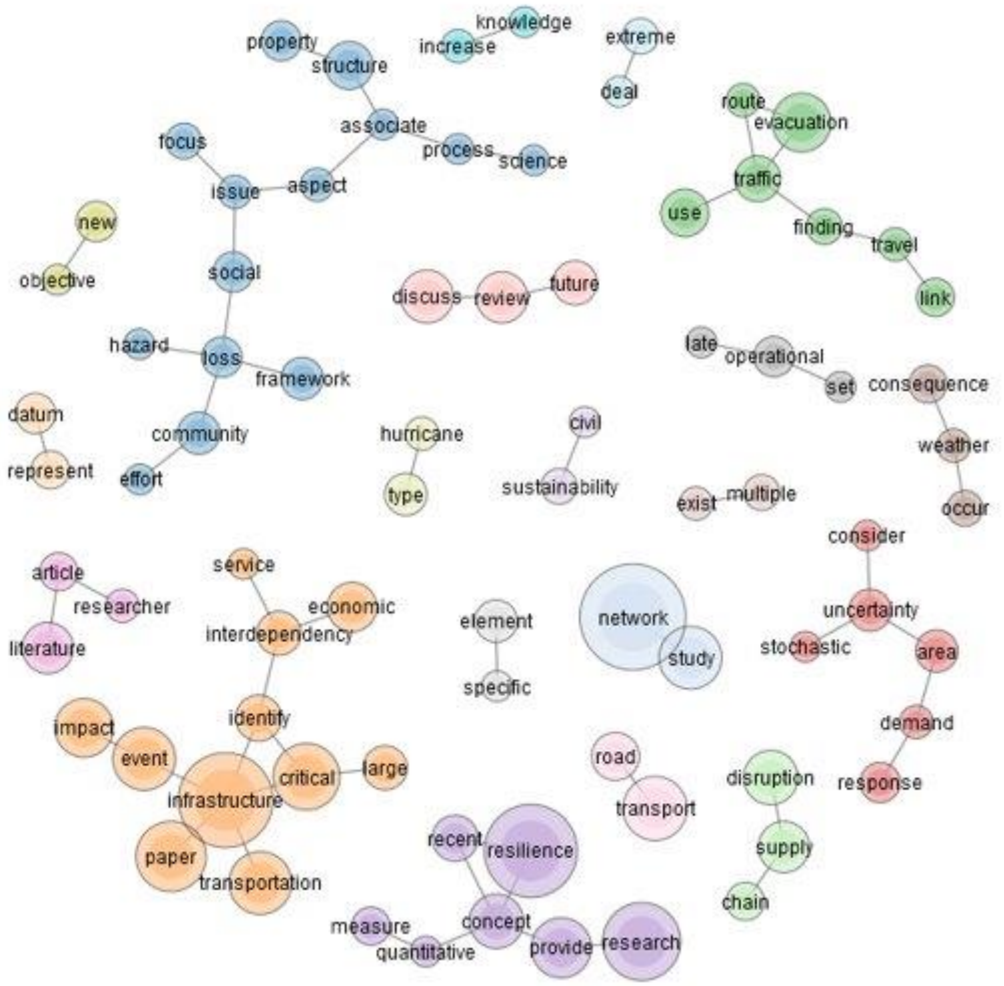

Figure 5. Results of the semantic analysis
(*Source: Own elaboration on Scopus*)

Some cluster emerges that can be summarized into three main concepts:

- The vulnerability of transport infrastructure networks
- The resilience of transport infrastructure
- The interdependence of transport infrastructure as well as methods and models to assess the impact of emergency events.

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2.2 Vulnerability

The word vulnerability derives from the Latin word *vulnerare* (to be wounded) and describes a system potential to be harmed from exposure to perturbation and stresses.

Alternatively, it can be defined as the degree to which a system is exposed or is unable to manage adverse effects. Indeed, several definitions can be found in the literature, depending on the dominion of the analysis and on the research field.

In this section we focus on analysing vulnerability of transport systems, the most critical infrastructures for the functioning of an economic system, that guarantees people and goods mobility. Within this framework, the definition of vulnerability proposed by Berdica (2002) has gained a wide consensus: the author defines "vulnerability in the road transportation system as the susceptibility to incidents that can result in considerable reduction in road network serviceability". Extending the vulnerability concept to the entire transport system, Jenelius and Mattsson (2015) define ''transport system vulnerability as ... society's risk of transport system disruptions and degradations''.

Networks disruptions can have more or less severe impacts depending on the causes of disruption. Interrupted roads, trains break down or flight cancellations cause higher travel times for people and goods and are associated to social and direct economics costs; terrorist attacks or severe infrastructure collapse can generate direct and indirect damages and injuries. However, sometimes intermodality can reduce the consequences of such disruptions, since people/goods can find alternative transport options, particularly in urban areas.

Starting from 2000s several studies on transport network vulnerability have focused on rare catastrophic events associated to overwhelming consequences on economic systems. During the same period, network theory developed (e.g. Barabasi and Albert 1999) and provided useful tools for analysing complex network features, so that a significant share of studies has started to analyse transport network vulnerability from the point of view of network topology.

Another strand of the literature has studied vulnerability with a system-based approach that integrates the topology approach with transport supply and demand analysis. Following Mattsson and Jenelius (2015), who provide an extensive review of the previous literature, we distinguish between "topological" and "system based" transport network vulnerability studies[1] and we illustrate the main methodological approaches adopted in both strands of the literature.

2.2.1. Topological vulnerability analysis.

Within this approach, a transport network is represented by a graph, an ordered pair G that includes V nodes (vertices) and L links (edges). Links can have the same length (unweighted network) or different lengths (weighted), can have a definite direction (directed network) or no direction (undirected). By defining the distance d_{ij} between any pair of nodes $i \neq j$ as the shortest distance among all possible alternatives, it is possible to define network cost/efficiency

[1] See also Reggiani et al. (2015) for a complementary review of the literature.

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measures of a graph with N nodes, as the average distance (or its reciprocal) across all node pairs:

$$C(G) = \frac{1}{N(N-1)} \sum_{i \neq j \in G} d_{ij}; \qquad (1)$$

$$E(G) = \frac{1}{N(N-1)} \sum_{i \neq j \in G} 1/d_{ij} \qquad (2)$$

Lower values of the first indicator are associated with higher network efficiency, but in case of network interruptions $C(G)$ becomes zero, while $E(G)$ is defined also in case of non-connected networks ($d_{ij} = \infty$).

By defining G_{id} as a theoretical network (with the same number of nodes as G), where all nodes have direct links as measured by the Euclidean distance, alternative measures of network efficiency can be built (Latora and Marchiori (2001)):

$$E_{glob}(G) = \frac{E(G)}{E(G_{id})}; \qquad (3)$$

$$E_{loc}(G) = \left(\frac{1}{N}\right) \sum_{i \in G} E_{glob}(G_i) \qquad (4)$$

Where G_i is a subset of the graph G that includes all the neighbouring nodes of i and the links between them. Global efficiency (3) measures how direct are the connections between all node pairs with respect to the theoretical network, while local efficiency (4) is measured for the neighbourhood of i[2].

Indeed, such measures assume different meanings depending on the assumptions on the representation of the network (von Ferber et al. (2009)). For example, in public transport network, each station can be considered a node and two consecutive stations are assumed to be connected by a link, or stations are nodes and the link exists if two nodes are served at least by one common line; alternatively, the nodes are the lines with a link between any two of them if they have a station in common. Finally, all stations and lines are considered as nodes, and each line node is linked to all station nodes that it services. Similarly, other graph topological indicators, like nodes degree, have different interpretations under different network settings.

Network efficiency indicators have been employed to measure transport network vulnerability. Typically, $E(G)$ variations after the removal of a network component (either node or link) have been object of analysis and provide useful information on network components criticality (Latora and Marchiori (2005)).

[2] A "small world" network has high values for both efficiency indicators. See also Porta et. Al (2006) for the relation between these efficiency measures and other measures of centrality.

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Different graph component topological indicators have been considered in vulnerability studies, like “cut” links and node betweenness. A link represents a “cut” link if its removal splits the network in two non-connected sub-networks, while node betweenness is the number of shortest paths (between any couple of nodes in the graphs) that passes through the target node[3]. Vulnerability studies often simulate network disruptions by successively removing nodes, randomly or in accordance with their degree of centrality, as measured by different measures, like betweenness.

The comparison of network efficiency before and after the perturbation sometimes is based on the evaluation of the relative size S, i.e. the ratio between the number of nodes of the largest portion of network still connected after the shock, and the number of nodes of the whole network before the shock.

Vulnerability has also been studied by simulating the removal of links, where the degree of a link is measured as the sum of end nodes degree minus 2. Studies that have compared the effects of link vs nodes removals suggest that the link scenario has a lower disruptive impact on the network with respect to the node deletion.

Finally, some authors have analysed the properties of scale free networks, whose degree distribution follows a power law. In these type of networks new nodes tend to connect to other nodes that have already a certain number of links, thus generating high-degree nodes called "hubs". Hubs are both a strength and a weakness of scale-free networks, since the preserve connectivity in case of random disruptions, but if few major hubs are disrupted the network is turned into a set of scarcely connected graphs. This structure is often found in air passenger and freight transport networks, frequently organized with a hub and spoke design.

From the analysis of the applied literature it emerges that the vulnerability of transport networks has been studied trough the identification of critical components of the network, either nodes or links. Indeed, the detection of weak components of transport networks not only allows to reduce vulnerability, but also provide useful guide for priority rebuilding after disruptive events.

2.2.2. *System based vulnerability analysis*

System based studies basically adopt the same approach as topological ones and model transport network with the help of graph theory; however, they integrate such models with transport supply and demand analysis. Nodes and links correspond to real networks components and weights given to links are typically related to actual lengths, travel times and costs, among others. Such approach is strictly connected to the definition of vulnerability proposed by Taylor and D’Este (2007) who define vulnerability on the basis of accessibility and suggest that “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”.

[3] Betweenness describes the influence of the node on the transmission of information. In a telecommunications network, a node with higher betweenness would have more control over the network, because more information will pass through that node.

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Various measures of accessibility have been proposed: for example, Chen et al (2007) build a utility based accessibility measure, derived from a travel demand and route choice model and evaluate the long term impact of links closure in road networks, while others propose to use remoteness indexes as proxies for accessibility.

Some authors compare road network cost efficiency before and after the disruption of a link by using different generalizations of the cost indicator $C(G)$ shown in the previous section. These vulnerability indicators are built to consider real traffic flows, link capacities, travel times (or their reciprocals), availability of alternative routes and increase in users travel times. In particular, Jenelius (2009, 2010) suggest calculating travel time variations associated to links closure as the waiting time for the re-opening (in case of disconnections) or as the travel time of the shortest alternative route. Within this framework the criticality of a network component is thus related to the duration of the closure.

Rupi et al. (2014) suggest that link importance can be defined at local and global level. Local importance can be described by the average link traffic, while global importance can be proxied by increased travel times caused by link disruptions and consequent excess demand[4]. Indeed, Mattsson and Jenelius (2015) note that local importance can be considered as a “demand weighted betweenness measure” that helps to identify network weakness; moreover, they report the use of an index called “critical closeness accessibility” as an indicator of link criticality, based on the topological definition of closeness in graph theory.

Vulnerability measures, like the increase in total road network travel time after link disruptions, have been analysed by mean of regression models, where the network structure and the average user travel time enter as explicative variables; other covariates, including link capacity, traffic flows, link length, flow speed and congestion density, are found to be highly correlated with link importance.

Another strand of the literature has developed theoretical models and have applied optimisation techniques to identify best responses to worst case setups. Some authors models traffic flows after link disruptions, while others identify the best network design that reduce vulnerability. However, such models are computationally demanding, so that they often consider just the neighbourhood of disrupted links. Indeed, road transport network disruptions might affect wider geographical areas so that their effects need to be studied with appropriate techniques. Jenelius and Mattsson (2012) present a grid-based approach to analyse area-covering disruptions and suggest that population density and associated traffic determines the impact of disruptions in term of increased total travel time[5].

Turning to rail and public transport networks, despite their higher sensibility to disruptions with respect to road networks, they have been relatively less studied. Indeed, it is quite difficult to find alternative routes for trains in case of link disruptions and train delays pile up on the network.

[4] Excess transport demand has been considered as a measure of reduced network serviceability and, together with network efficiency indicators, has been used to evaluate not only link importance, but also to analyse regional exposure

[5] There is also a significant number of studies, briefly revied by Mattsson and Jenelius (2015), that just focus on the analysis of the economic impact of disasters like earthquakes, flooding and other disruption hazards affecting road networks by applying different approaches and evaluating different economic activity indicators, including traveller economic losses and restoration costs.

Some authors have adopted the same approaches employed for analysing roads network vulnerability, while other have proposed novel methodologies. The concept of network survivability, ''as the ability of a network to maintain its topological and functional state when a certain level of disruptions on stations occurs simultaneously'', has been introduced and measured through connectivity loss and passenger flow losses for subway networks. An extension of the measures of betweenness centrality and link importance, in a dynamic-stochastic setting from the perspectives of both operators and passengers, have been used to identify crucial links in public transport networks and criticality has been measured as the reduction in welfare (considering travel time, number of transfers, etc.) associated to capacity reductions of the link. Finally, predictions on link disruptions probabilities, interacted with the number of trains using the link (proxy for betweenness), have been used to identify those link that most deserve maintenance to reduce disruption probabilities and reduce network vulnerability.

2.2.3 Data requirements and methodological issues.

Vulnerability analysis based on the topological approach has limited data requirements, since it applies basic graph theory, with undirected and unweighted networks, where typically intersections/stations/airports are considered as nodes, while links are represented by road/track segments/air routes. Vulnerability is studied by comparing different network efficiency measures before and after the disruption of some network components selected randomly or on the basis of topological properties (e.g. betweenness, degree, or other centrality measures) or according to attack strategies. Most studies suggest that network vulnerability is lower when nodes/links disruptions are randomly assigned and that link removals have a lower impact when based on attack strategies.

The application of such approach is computationally easy and allows networks comparisons and various simulation exercises. However, representing a real network by means of an abstract one is an oversimplification that do not take into account different aspects that can be relevant for vulnerability analysis.

As a way of example, Mattsson and Jenelius (2015) suggest that "calculating average distance $C(G)$ and efficiency $E(G)$ for the joined road networks of Sweden and Denmark after the opening of the Öresund bridge would indicate a higher average distance and a lower efficiency than calculating the same indicators separately for each national network. The reason is that distances between very remote node pairs with limited interaction will also be included in the calculation for the joined network". Indeed, the main drawback of this approach is that it neglects static and dynamic behavioural responses associated to network disruptions; nevertheless, it can provide useful insights on networks weaknesses.

System based vulnerability studies try to incorporate information on various real networks characteristics and on real responses to shocks by analysing transport demand and supply associated to different vulnerability scenarios. This approach is entails high data requirement and high computational complexity that often limit the analysis to a single component removal scenario. Moreover, studies that adopt this approach are more heterogeneous, since data availability is highly variable across situations, so that it is more difficult to conduct comparison analysis and to extrapolate empirical regularities.

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The main advantage of this approach, when compared to topological vulnerability studies, is that it provides more intuitive impact indicators, like increase in travel times, measures of reduced accessibility or consumers' surplus variations. However, a comparison between a topological-based measure and a system-based measure of vulnerability proposed by Dehghani et al. (2014), suggests that topological measures can act, in certain settings, as valid substitutes for more data demanding system-based indicators.

A final consideration before turning the discussion to network resilience is due to underline: studies analysing the impact of networks failures at an extended geographical level are relatively scant. This is due the fact that such kind of analysis is quite challenging both in terms of computational complexity than in terms of data requirements.

2.3 Resilience

This Section deals with the multifaceted concept of resilience. The discussion will be largely based on a number of studies that have been selected as explained in Section 2.1 above and, in particular, on three recent literature reviews that have explored the concept and the use of the term resilience either across scientific domains or, more specifically, in transportation science.

Indeed, the definition of the term resilience varies according to authors and the scientific field and, although a certain convergence and agreement in the literature seems to have emerged in the past few years, it is still important to examine in some detail not only the various definitions, but also the types of resilience (e.g. static versus dynamic) that have been discussed in the literature.

In this short survey, we will first explore and discuss various general definitions of resilience, and we will then turn to address the concept of resilience of transportation networks. In doing this, not only we will explore the discussion on the theoretical concept of resilience, but we will also review how the literature has sought to empirically operationalize the various concepts of resilience, which is still an area of very active research, particularly in the case of transportation networks.

2.3.1 Theoretical definitions of Resilience

Turning to the theoretical concepts of resilience, Hosseini et al (2016) have discussed many of the different general definitions for system resilience that exist in the literature. Given the many fields to which scholars have applied the notion of resilience, it is not surprising that there is a wealth of definitions.

Indeed, these range from the capability of a system to maintain its functions and structures in the face of external shocks, to the ability of a system to absorb unpredictable changes (similar to the notion of ecological resilience proposed by Holling (1973) and discussed in Mattsson and Junelious (2015)), to the ability of a system to withstand an external shock and to recover within a suitable time framework, to the ability of a system to minimize the deviations from a target performance levels due to an external shock. Moreover, Ouyang (2014) sees resilience as the ability of a system to resist any possible hazard (resistant capacity), to absorb the initial damage caused by the shock by minimizing possible losses (absorptive capacity) and to recover to normal operations as quickly and effectively as possible (restorative capacity).[6]

Overall, these different definitions (and the many others that can be found in the literature) share the idea that resilience refers to the ability of a system to absorb a shock; nevertheless, there are also non-negligible distinctions, for instance as far as it concerns the role played by time. Indeed, while some definitions mainly refer to what happens after a shock hits the system, others also stress what happens before the shock (see below). Similarly, some definitions refer to the costs associated to the degradation of the systems, while others do not (Haimes, 2009).

Husseini et al (2016) have been able to identify four main domains that are useful to systematize the different notions of resilience that have been proposed in the literature.

One of such domains is the organizational one, which refers to the ability of firms and other institutions to adapt to rapidly changing environments. Although different definitions exist, they have in common the identification of resilience with the ability of the organization to keep on operating after being hit by a shock, as well as the ability to return to a steady state, i.e. to a normal performance level.

The second domain identified by Hosseini et al (2016) is the social domain. Also in this case, the various definitions relate to the ability of groups to deal with external shocks in ways that allow the group itself to keep on functioning, with some authors that stress the ability of the group to recover quickly. Within this domain, an interesting paper is that by Chang et al (2004) who empirically evaluate the resilience of a community to a disruption to the water system in Memphis (US) caused by an earthquake.

The third domain is the economic one. A widely cited definition in this domain is that of Rose and Liao (2005) who define resilience as the "inherent abilities of firms and regions to avoid maximum potential losses".[7] In this domain, a useful distinction is that between a static notion of resilience (e.g. the ability of the economic system to keep on functioning during a shock at the highest possible level through an efficient use of existing resources) and a dynamic one (e.g. the speed of recovery of the economic system to the steady state by means of a reconstruction of the capital stock), both highlighted by Rose (2007).

Finally, Hosseini et al (2016) identify an engineering domain, which is a relatively more recent field relative to the previous ones. Authors identify various definitions in this strand of literature; we can mention four. One refers to network resilience as the sum of the reliability (i.e. the passive survival rate) and the restoration of a system (Youn et al 2011). A second definition, from the American Association of Mechanical Engineers, defines resilience as the ability of a system to absorb both internal and external disruptions without being forced to discontinue its operations and, if forced, to rapidly recover. A third definition, from the US National Infrastructure Advisory Council, identifies resilience of infrastructure systems as the ability to "predict, absorb, adapt, and/or quickly recover from a disruptive event such as natural disasters". The originality of this definition is that it does not confine resilience to what happens after a shock; indeed, it considers

[6] Ouyang (2014) also lists a series of resilience improvement strategies for each of the three components of resilience.

[7] Rose and Liao (2005) also distinguish between inherent resilience, i.e. the ability under normal circumstances to face shocks, and adaptive resilience, i.e. the ability to cope to shocks under exceptional circumstances.

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also what happens before the event as being part of resilience, i.e. it includes preparedness[8] within the realm of resilience. Finally, Hollnagel (2011) provides a very comprehensive socio-technical view of resilience: indeed, according to the author, the resilience of a system emerges out of the joint interaction of vulnerability analysis (which aims to identify ex-ante unlikely but potentially major disruption events) with the monitoring, responding and learning abilities of policymakers (Mattsson and Junelious, 2015).

Interestingly, Reggiani et al (2015) compare ecological to engineering resilience. The first refers to conditions far from the steady state of the system and in particular to the ability of the system, if hit by a large shock, to eventually get to a different new steady state equilibrium. Ecological resilience is therefore linked to issues of multiple equilibria and suggests the possibility that, because of a shock, the variables that influence behavior (e.g., by travelling individuals) may permanently change. By way of contrast, engineering resilience would be more focused on the properties of a system near the steady state and, therefore, on the ability of the system to return to the (old) steady state equilibrium.

Finally, while traditional resilience analysis considers a system's reaction to the occurrence of a large shock, more recently a strand of the literature has extended the analysis to situations characterized by disasters that are followed by multiple related disasters, such as an earthquake followed by building collapses or the network effects that occur in the case of supply chain failures.[9] An example is the study by Zobel and Khansa (2014) who extend the conditional resilience concept to a multi-event framework.

2.3.2 Measurement of Resilience

Before turning to studies that have elaborated on the concept of resilience of transportation networks, we believe to be worthwhile to spend a few words on how different authors have addressed the difficult task of evaluating resilience. Hosseini et al (2016) identify two types of approaches, namely qualitative and quantitative.

In the first case, they further identify two categories, namely conceptual and semi-quantitative indices. Conceptual studies are by far the majority and are extremely important because they can be applied to complex cases or when data are simply not available, which in turn can make the implementation of a quantitative approach quite challenging. Conceptual studies assess the resilience of a system by identifying the properties that a resilience system should have, which in turn may facilitate the task of policymakers to understand the degree of resilience of certain critical infrastructures. By way of contrast, semi-quantitative indices are based on the identification of certain features of a (network) system that might be associated with resilience, which are then scored, typically based on expert judgement and then aggregated.

Also quantitative approaches can be divided into two groups, namely general approaches, whose aim is to evaluate the resilience performance of a system without specifying its structure and, as

[8] Preparedness may be viewed as the set of activities finalized to enhance the capability of a system, network, or community to respond in the event of an emergency. See also Zobel and Khansa (2014).
[9] The fall of the Morandi Bridge in Genoa, with the associated temporary interruptions of some railways lines as well as local roads, is a possible additional example.

such, they can be useful across domains, and structural models, which instead seek to reproduce a specific real word network.

General approaches, which can be deterministic or probabilistic; static or dynamic, compare the system performance before and after the shock. Most studies belonging to the "general" categories tend, according to Hosseini et al (2016), to emphasize four dimensions of resilience, namely robustness[10], rapidity[11], resourcefulness[12], and redundancy[13] (Bruneau et al, 2003).[14] The studies in this tradition typically derive some degradation metric (the so called "resilience triangle") associated to loss of output, percentage of rationed demand, time required to come back to normal operations, etc. The degradation metric is then compared to some target performance, such as pre- disaster performance, or a maximum level of drop in performance, as in Rose (2007).

In turn, structural approaches -which are classified by Hosseini et al (2016) into optimization, simulation and fuzzy logic models, depending on the methodological approach adopted by the authors- aim to model a specific real-world network. This type of approach is information-intensive, given that modelers need to observe and be able to include into the model or simulation exercise the main features of a particular network.[15]

2.3.3 Resilience of transportation networks

We now turn to the theme of resilience of transportation networks, the definitions employed in the transportation literature as well as their empirical operationalization. First, it is important to note, as acknowledged by Mattson and Junelius (2015) that, unlike in the case of the literature on the vulnerability of transport networks, the literature on transportation resilience is not yet so well established.

Having said this, within this literature, Reggiani et al (2015), as noted above, distinguish between ecological and engineering resilience studies, and argue that, in the transportation field, most papers tend implicitly or explicitly to follow an engineering notion of resilience. Nevertheless, they note that an ecological interpretation might still be included in the analysis whenever modal shifts following a shock to a particular transport mode are allowed for in the analysis. Moreover,

[10] Robustness refers to the ability of a system to withstand a certain level of stress without suffering major degradation.
[11] Rapidity can be understood as the ability of a system to achieve a certain target of performance in a timely manner.
[12] Resourcefulness refers to the ability of the organization to mobilize resources in the aftermath of a disruption.
[13] Redundancy refers to the existence of alternative elements of the system that might be active in the case of a disaster (e.g. an additional road).
[14] Worton (2012), mentioned in Mattson and Jenelius (2015), associate resilience to preparedness, response, recovery and adaptation.
[15] A similar classification is offered by Reggiani et al (2015) who classify studies on resilience in the transportation science field into general and specific. The first are characterized by the fact that the same approach might be fruitfully applied also in cases where the context is different with respect to the original application; in turn, the second are based on simulations of real-world networks.

Reggiani et al (2015) argue that most studies dealing with resilience of transportation networks are by far in the general category (see above).

As far as the precise definitions of transportation resilience is concerned, the review in Reggiani et al (2015) highlights two “stylized facts”.

First, several studies refer to the robustness of a network which, according to the various definitions given in the literature to the term, can be de facto interpreted as a synonymous of engineering resilience.

Second, some authors discuss the reliability of a transport network, which broadly refers to the stability in the level of service after major events or, using the definition in Berdica (2002), to “the operability of the networks under various strenuous conditions”. In relation to this, Reggiani et al (2015) argue that the incorporation of behavioural responses and therefore travel demand modelling into resilience analysis has been increasingly attracting the attention of researchers. The main intuition of why this is important is that, after major events that may have disrupted important nodes of the network, users start exploring the network or interconnected networks in order to find better connections. In this case, it is even possible that, after major events, changes in behavioural responses lead to permanent new equilibria, which points towards the notion of ecological resilience. Therefore, in order to develop a more comprehensive and effective resilience analysis, a modelling of behavioural responses becomes crucial.

As far as it concerns empirical measurement of resilience, according to Reggiani et al (2015) very few papers model resilience of real world networks, an exception being Cox et al (2010) -who empirically address the theoretical notions of ecological and engineering resilience for the London subway after the London bombing of 2005. The other studies tend to interpret engineering resilience as robustness or reliability, although their empirical measurement still seems problematic. Be as it may, the empirical applications can be divided into simulations or case studies (Reggiani et al, 2015). Simulations tend to take an ex-ante approach, and their main aim is to conduct forecast on network resilience; in terms of methodological approach, the empirical applications typically rely on percolation theory or on network topology, i.e. they identify certain key topological features of the network and in particular of the critical nodes. In turn, case studies tend to take an ex-post approach, are generally based on real data of the network, and are also focused on economic indicators (Reggiani et al, 2015).

Among the most widely used metrics for transportation resilience, Reggiani et al (2015) argue that graph theory plays a relevant role and that resilience is often interpreted in terms of the number of node or edge failures that the network can sustain. One related example is the study by Omer et al (2014) who builds a resilience index by comparing the closeness centrality of the network before and after the shock (see also Hosseini et al, 2016), or the work by Knoop et al (2012) who simulate two real world road networks and measure resilience by assessing the robustness of the networks to blocking certain (vulnerable) links.[16]

A more recent strand of research has even sought to operationalize graph theory as a strategy to measure resilience in the case of networks of networks. The importance of modelling network of networks and in general the issue of network interdependence[17] stems from the observation that relatively localized shocks to a particular network (be it an interconnected transport network, or

[16] See the Online Appendix of Reggiani et al (2015) but also Reggiani (2013).
[17] See Section 2.4 below for a more in-depth discussion of the literature on infrastructure interdependence.

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the upstream and downstream networks of buyers and suppliers within a supply chain) may give raise to a successive cascade of shocks along the interconnected network, which in turn might lead to large aggregate effects. In other words, two interdependent networks might be more fragile than each network considered in isolation; however, because isolated networks can be safely considered more an exception than a norm, in recent years the modelling of networks of networks have received increasing attention by scholars in various fields.

A seminal paper in this respect is that by Buldyrev et al (2010), which has been critically reviewed by Vespignani (2010). The main point of this paper is the difference between the resilience of interconnected versus isolated networks.[18] In the latter case, the fragility of a network is assessed by progressively removing nodes from the network: there is a critical threshold beyond which the network becomes completely fragmented. Interestingly, while approaching the critical threshold, there is a progressive loss of efficiency in the operation of the network. By way of contrast, in the case of interconnected networks, the complete breakdown of the network arises at a smaller scale of damage and, perhaps even more strikingly, there is a sudden discontinuity in the operation of the interconnected network at the critical threshold. This in turn makes the control of the breakdown process more difficult than in the case of isolated networks.

While the modelling of interconnected networks and their impact on resilience is rapidly progressing, Reggiani et al (2015) argue that the analysis is, however, in most cases, still purely topological, unless the various nodes are weighted by some metric of importance, be it economic or traffic-related.

We conclude this section by briefly discussing a difference that seems to exist in the literature on the importance played by preparedness to disastrous events in the definition of resilience. Indeed, Reggiani et al (2015) argue that most resilience studies tend to take an ex-post disaster approach; in fact, as noted by Rose (2009), resilience "is the outcome of a post-disaster response" and it is one of the various ways, together with the strategies of adaptation and mitigation, that policymakers can use to address a network's vulnerability. In other words, according to Reggiani et al (2015), there is a dichotomy between vulnerability, which refers to a pre-disaster condition, and reliability, which in turn refers to what happens after the event has occurred.

It is however important to note that in the literature there is not a clear consensus on limiting resilience analysis to what happens after a disaster, at least outside the transportation field.[19] Indeed, some of the general definitions to resilience given above provide a more encompassing view of resilience which nests both the pre and post disaster stages. A clear example has been recently provided by Zobel and Khansa (2014). In their study, authors clearly argue that the definition of resilience "should not only incorporate post-event consequences, but also pre-event preparedness and strategic planning". This suggests that a more extended notion of resilience that includes also planning activities may be important, even if this can make the operationalization of the ensuing resilience concept more difficult.

Moreover, the studies on the resilience in the organizational and social domains suggest that, in order to fully capture the resilience of a community to major shock events to its transportation network, it is also important to adopt a wider definition of resilience which captures its socio-

[18] See also Section 2.4.2 where the literature on infrastructure system interdependencies will be reviewed.
[19] In their study on the measurement of resilience of freight transportation networks, Miller-Hooks et al (2012) refer to resilience as the actions taken in the immediate aftermath of the event, but they also discuss preparedness decisions, which are clear ex-ante ones.

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techno-economic dimensions as well. Of course, also in this case there is a trade-off between adopting the potentially correct concept of resilience and the ability of researchers to operationalize it.

Related to this, the survey of the literature highlights another important point, namely the availability of data, which need to be rich, multifaceted (i.e. they need to encompass the traffic, engineering, economic and social dimensions) and available, which is not always the case, especially in the light of the several stakeholders that manage individual bits of the data.

2.4 Interdependence of critical infrastructures and impact evaluation

This Section will first discuss the important topic of interdependence between critical infrastructures. After briefly introducing the notion of critical infrastructures, we will examine the definitions of infrastructure interdependency that have been proposed in the surveyed literature. Then, the discussion will turn to the analysis of the methods that have been proposed by scholars to study the reaction of interdependent critical infrastructures to various types of shocks: in particular, following Hasan and Foliente (2015), we will distinguish between physical and socioeconomic impacts. Some conclusions from the study of this literature will follow.

2.4.1 Definitions of critical and interdependent infrastructures.

There is not a unique definition of critical infrastructures. The US President's Commission on Critical Infrastructure Protection, mentioned in Ouyang (2014), refers to critical infrastructures as the group of infrastructures "whose capacity or destruction would have a debilitating impact on the defense and economic activity".

Similarly, Chen et al (2009) argues that critical infrastructures are those that, because they constitute the backbone of a modern society, are able to support the economy and contribute to the functioning of "security, safety, and stability of the whole society".

While different countries may include different infrastructures within their lists of critical ones, in most cases those lists include the water, gas, oil and electricity pipelines; the telecommunication and transportation networks; the banking and financial systems.

As noted by Chen et al (2009), not only are critical infrastructures often complex, but they also tend to form interdependent networks. The US President's Commission on Critical Infrastructure Protection defines interdependency as a property of a "network of independent, mostly privately-owned, man-made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services".

A somewhat related but clearly different definition of interdependency is that contained in Chen et al (2009), who define interdependence of (critical) infrastructures in terms of vulnerability (see Section 2.2 above for a definition and a review of the literature): indeed, according to the authors, interdependency of infrastructures is perhaps one of their major sources of vulnerability. In other

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words, two infrastructures are interdependent whenever "the loss of expected service or functions of one infrastructure could be the result of another's unavailability". Chen et al (2009) also argue that two infrastructures are physically interdependent if the state of each depends upon the supply of services that are provided by the other.[20]

The interpretation of interdependency in terms of vulnerability is associated to the different view that scientists have developed over time about the possible pros and cons of interdependency. Indeed, while scientists used to overestimate the benefits of the latter,[21] more recently, the literature has taken a more problematic approach to interdependency, especially after the occurrence of a few major shocks that clearly showed how infrastructure vulnerability might be associated to large degrees of interdependence (Ouyang et al, 2014). Moreover, as noted by Okuyama (2007), among the others, a disruption that involve simultaneously two modes of transport tend to give rise to a total effect which is larger than the sum of the effects when each mode is separately affected (see also the discussion of Vespignani (2010) in Section 2.3 above).

The strict connection between interdependence and infrastructures vulnerability is due to the fact that most interdependent critical infrastructures are generally planned, designed, operated, maintained and owned by different organizations (be they private or publicly-owned firms, government departments, etc.), as noted by Altay and Green (2006). This in turn may give rise to important coordination problems which make it difficult to analyze, forecast and deal with the aggregate consequence of a systemic disaster. This is because the managers in charge of the individual infrastructures tend to take decisions that might be optimal for the single infrastructure but not for the system as a whole. In other words, the decentralized management of individual critical and interdependent infrastructures might not provide the right incentives for managers to internalize the externalities created by the propagation of the effects of a failure in their own infrastructure onto others (cascading failures that can occur over time and across space).[22] This in turn requires some form of coordination and some role for regulation.

More generally, our reading of the literature suggests that, in order to develop a deeper knowledge of the interdependencies among critical infrastructures, it is of paramount importance to develop also a more in depth understanding of the various stakeholders (firms, regulatory agencies, local communities, policy makers), especially as far as it concerns their primary role, set of incentives they face, as well as the geographic scope at which they operate.

[20] In the text we have briefly discussed some general definitions of interdependence. However, in the literature there are also more specific definitions that are summarized in Ouyang (2014). By way of example, Rinaldi et al (2001) distinguish between physical, cyber, geographic and logical interdependence, while Zimmermann (2001) considers functional and spatial interdependence.

[21] Indeed, as noted by Ouyang (2014), scientists used to think that interdependency might improve the joint operating efficiency of the system.

[22] Kivela et al (2014) note that the increasing degree of interconnection among different infrastructure systems might lead to more large-scale events and systemic failures. See also Section 2.3 above, where we discuss the notion of resilience in the case of networks of networks.

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2.4.2 Modeling of interdependent infrastructures.

According to Hasan and Foliente (2015), the effect of a disruptive event, with the associated indirect effects that can percolate through the set of interconnected networks, may cause impacts that can be categorized into physical and socioeconomic ones.

The first group refers to the immediate, direct effects associated to the disruption of an infrastructure; in this case, the customers or users of that infrastructure are those more adversely affected by the event. However, because of the interconnections, users of other related infrastructures might also be adversely affected, so that the total physical effects tend to be larger than the direct ones. In turn, the socioeconomic effects refer to the broader social, demographic, economic, and political impacts, which can unfold both in the short and in the long run. In what follows, we discuss - largely following the categorization proposed by Hasan and Foliente (2015) and Ouyang (2014) - the approaches that have been used by scholars to study infrastructure interdependencies. We conclude this section by briefly analyzing the methods that have been used in the literature to assess the socioeconomic impacts of disruptions.

Turning to the approaches to assess infrastructure interdependencies, one can identify five main categories of approaches, namely empirical approaches, agent-based approaches, system-based approaches, economic theory-based approaches, network-based approaches, plus a residual[23] category (Ouyang, 2014).

The first category, the empirical-based approaches, groups studies whose aim is typically that of assessing the potential vulnerability or resilience of a set of critical infrastructures (Hasan and Foliente, 2015). Ouyang (2014) further decomposes this family into: a) studies that seek to identify frequent and recurrent failure patterns; b) studies that provide a quantification of interdependency related indicators; and c) empirically based risk analysis. Studies in the first sub-category are typically based on time series of past failure events and expert judgment. Although these studies may allow to uncover interdependencies across a set of possibly related infrastructures and may provide useful insights to policymakers and improve preparedness, they have a series of drawbacks. For instance, they may be biased towards the events that have occurred more often in the past, which in turn precludes robust inferences in the case of different future events, or the heterogeneity in the historic data collection procedures (Hasan and Foliente (2015) and Ouyang (2014)).

Studies in the second sub-category tend to develop a set of related indicators on the degree of interdependency, that can then be statistically analyzed to uncover correlations across critical infrastructures, which in turn provide evidence of interdependence.[24]

Finally, the third sub-category groups those papers that provide risk analysis developed on the basis of past failure data and integrated with expert judgments. They typically require a lot of data and might be vulnerable to measurement errors (Ouyang, 2014).

[23] Within this residual category, Ouyang (2014) distinguishes between hierarchical holographic modelling, high level architecture-based methods, Petri-net based methods, dynamic control system theory-based methods and the Bayesian network-based method.
[24] See Ouyang (2014) for some examples.

The second category, the agent-based one, groups studies that model the chains of reactions to a disruptive event in the various layers of the infrastructure system, possibly incorporating the change in behaviour by policymakers as well as individuals. As noted by Ouyang (2014), some agent-based studies are able to model the joint behaviour of the main participants in the set of interdependent networks, as well as to provide scenario-based analysis and to conduct simulations on the effects of different control strategies.[25] Agent-based approaches are relatively easy to be used together with other modelling techniques and to be applied to different situations; however, as noted by both Hasan and Foliente (2015) and Ouyang (2014), they are based on sometimes strong assumptions on the behaviour of agents; moreover rich information is needed to credibly calibrate the model parameters and conduct reliable simulations.

The third set of approaches, the system dynamics one, features top-down studies[26] based on non-linear theory and feedback controls. These studies are based on three concepts: stocks (the accumulated resources in the system), flows (the changes in the system to the accumulated resources) and feedback (which captures the information that influences the values of the flows). As noted by Hasan and Foliente (2015), the simulation of a system of infrastructures using a system dynamics approach "gives important insights on causes and effects leading to a better understanding of the dynamic behaviour of the system". By using causal loops diagrams to capture the causal relationship among the different variables as well as the stock-flow diagram, system dynamics models allow to understand the dynamic behaviour of critical infrastructures under disruptive scenarios and are able to capture the effects of policy makers on the evolution of the system (Ouyang, 2014). However, they require expert knowledge to assess the causal relationship underlying the feedback loops, they are data-intensive techniques and they require extensive calibration (Ouyanga, 2014); moreover, the model parameters can hardly be validated with real data, given the lack of real data information that often plagues this field. Therefore, validation is largely based on conceptual analysis (Ouyanga, 2014).

As far as it concerns the fourth group of studies (the economic-based approaches), it is possible to distinguish between Input-Output models (I-O, thereafter) and Computable General Equilibrium models (CGE, thereafter). IO models are based on the model originally developed in the 1950s by the Nobel Prize winner Leontief, whose extensions have been used in economics to study how a change in supply or demand in any given sector can give rise to a macroeconomic effect through the direct and indirect vertical and downstream relationships (i.e. the input-output structure) with the other sectors of the economy.

A recent extension of the IO model that have been proved to be particularly fruitful in the analysis of the interdependence of critical infrastructure is the Inoperability Input Output Model (IIM) originally due to Haimes and Jiang (2001) and described in Ouyang (2014) and Chen et al (2009) among the others. This approach exploits an IO structure to analyze the contribution to the inoperability of a certain infrastructure that is due to a disruption in a related infrastructure.[27] In a classic IO model, the total output of a certain industry i is the linear combination of the demand

[25] See Ouyang (2014) for a discussion of the main agent-based critical infrastructure models that are available in the literature.
[26] They can be contrasted with the agent-based studies, which take a bottom up approach, i.e. they derive the macro behavior of a system from the micro behavior of the various agents that compose the system.
[27] Inoperability of an infrastructure can be defined along many dimensions, namely geographic, physical, political, temporal, and informational (Rinaldi et al, 2001). Moreover, as noted by Chen et al (2001), inoperability can be demand or supply-driven, depending on the original source of the disruption.

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from other industries j, weighted by technical coefficients (representing the ratio of input of i used by industry j as a fraction of the latter's production requirements), plus final demand from consumers. In the IIM, as noted in Ouyang (2014), the output of industry i is replaced by the overall risk of inoperability of industry i, i.e. the inability of a critical infrastructure to perform its tasks; the technical coefficient in turn represents "the probability of inoperability that the j*th* infrastructure contributes to the i*th* infrastructure due to their interconnectedness" and final demand is replaced by the inherent inoperability risk intrinsic to the complexity of the i*th* infrastructure. The IMM model may thus be used to study the mechanisms of transmission of a disruption along a set of interconnected infrastructures, pretty much as in conventional IO models a disruption in a sector of the economy may have aggregated consequences through its direct and indirect input-output relationship with the other sectors of the economy. Moreover, the IMM model allows modelers to evaluate the vulnerability of various sectors of the economy to the disruptive event, as well as the impact of certain risk mitigation strategies.[28]

The basic version of the IMM models suffer of the typical limitations of IO models, such as linearity[29], price rigidity, no role for import-export substitutions or for the role played by resource constraints, etc. Moreover, in the typical IO models, there is not much role for the representation of the spatial nature of most infrastructures, for the importance of uncertainty as well as for the impact of regulation in the case of emergency events.[30] Various extensions of the model have been developed in the literature to improve the modeling of both inoperability and the transmission mechanisms, i.e. how disruptions to certain infrastructures are transmitted to other interdependent infrastructures and across the economic system.

In turn, CGE models allow researchers to relax some of the critical assumptions of IO models, such as linearity and the lack of behavioural responses to changes in prices, as well as some degrees of flexibility in production techniques (e.g. they incorporate some measures or resilience). Recent extensions include the spatial CGE, which includes transportation networks that can move people and goods across regions (Okuyama (2007) among the others) and that has been further extended to allow the modelling of the infrastructure network, the substitutability between infrastructures, and the policy response by policymakers. However, according to Hasan and Foliente (2015) they are still based on strong assumptions about the functional forms assumed for production and utility functions; moreover, they are data-intensive modeling techniques, which can be a problem given the paucity of data that characterize most real-world situations.[31]

The last category of methods, namely the network-based approaches, groups together those studies that tend to view a certain system of infrastructures as a set of interdependent networks, with the associated nodes (different critical infrastructure components) and links (the physical or virtual connections). Connections among networks are modelled by inter-links. Authors in this strand of literature first model the disruption of one of the (critical) components and then simulate the cascading effects of the failure for the whole network of networks, which in turn

[28] As in conventional IO model, it is possible to consider the demand-side and the supply-side version of the IMM mode. See Chen et al (2009) for an exhaustive discussion.
[29] Non linearities are likely to be dominant during major disruptions, but the model is based on linearity, which is a good approximation only in the case of relatively minor events (Ouyang, 2014).
[30] See Ouyanga (2014) and Chen et al (2009) for a discussion of the limitations of IO models in the context of the analysis of infrastructure interdependence.
[31] See Ouyang (2014) for further discussions on the limitation of CGE models in this area of research.

allows modelers to study the reliability, vulnerability and resilience of the overall system (see Section 2.3.3 above).

Ouyang et al (2014) further distinguish two families of approaches, namely Topology-based or Flow-based methods. Topology-based approaches are based on the topology of the network. In this modeling strategy, links can fail either directly as a consequence of a shock, or indirectly because of failures in other interconnected networks or for other reasons (see Ouyanga, 2014). These models can be solved either analytically of by simulation, depending on the topological complexity, particularly when nodes heterogeneity is allowed for. They are relatively easy to be implemented, they can be applied to various scenarios, they are good in capturing the critical components of the networks and can therefore offer policy suggestions. However, unlike the flow-based approaches, they do not capture the flow features that characterize the interdependent networks. However, the latter need very detailed modelling strategies, with high computational costs and as such are not easily scalable (Hasan and Foliente, 2015).[32]

Ouyang (2014) compares the relative benefits of these various approaches on the basis of five criteria, namely quantity of data that are necessary for the analysis; b) data accessibility;[33] c) type of interdependence (see Section 2.4.1 above); d) computation complexity and e) maturity of the approach. Ouyang (2014) notes that, with the exception of the topology-based analytical methods, all approaches tend to be rather data intensive; moreover, in terms of data accessibility, the economic-based methods score the highest points because they are typically based on freely available data, unlike agent-based models or the flow based methods, which require data that are not often in the public domain. In terms of computational costs, only those methods that require intensive simulations require high computational costs, while most approaches have by now reached a significant level of maturity, with perhaps the exception of the network-based approaches.

Interestingly, Ouyang (2014) also compares the methods in terms of their capacity to improve the resilience of the interconnected critical infrastructures and notes that most methods are able to help policymakers only in certain areas of the overall resilience improvement strategies that could be put in place to address the three key components of resilience, namely the resistant, absorptive and restorative capacities.

Before drawing conclusions, it might be worth spending a few words on the socioeconomic effects of major disruptions - which often involve more than one critical and interdependent infrastructure -, even if the latter are not the central part of this research project. Indeed, there is also an important literature that investigates the socioeconomic impacts of shock events and that can provide useful indications to policymakers that seek to increase the resilience of their local communities.

While we refer to Hasan and Foliente (2015) for a recent short overview of this literature, in this place we just note two issues. First, in the case of the studies that address the purely economic consequences of major emergency events, the literature is by now well-established and largely based on the application of IO and CGE models. These are similar to those we have already described above: we therefore refer to the above discussion for a description of their relative

[32] See Ouyang (2014) for a more detailed description of flow-based methods.

[33] Researchers and policymakers alike are likely to experience problems in this regard, in the light of issues of confidentiality and privacy that might arise, as well as the fact that relevant data are dispersed across a possibly large set of data owners.

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major advantages and limitations. By way of contrast, the social impacts of major emergency events are still a relatively unexplored research area (Hasan and Foliente, 2015), with a few contributions that attempt to provide a conceptual framework and others that have explored the use of the Social Accounting Matrices framework. The latter method shares most features of IO models, but it allows researchers to analyze in some detail the distributional effects of shocks and therefore can provide some useful insights on the social consequences of emergency events.[34]

2.4.3 Some concluding remarks.

Turning to the literature on the modeling and evaluation of emergency events in the case of interdependent critical infrastructures, the studies by Ouyang (2014) and Hasan and Foliente (2015) offers useful insights on the gaps that still exist in the literature as well as on the likely future challenges and directions.

First, both Ouyang (2014) and Hasan and Foliente (2015) highlight the wealth of data that are necessary to conduct the analysis (e.g. datasets of past disruptive events, network topological features, procedures to manage the emergencies, the nature of interdependencies, information on traffic flows, etc.) which is matched by the lack of data availability that characterizes the field. The poor availability of data is clearly associated to the fact that critical infrastructures are owned and operated by different organizations. This suggests that these organizations (some publicly, some privately owned) may not be willing to share their data and, in some instances, they may not even collect some categories of data if that is not a mandatory requirement; moreover, even if data exist, they may not be standardized, complicating their joint analysis by researchers or by a regulatory agency. In the light of this, issues of proprietary data become central, as well as confidentiality and privacy regulations do. Some coordination at government level is typically required in order to make data collection mandatory as well as some form of data sharing with regulatory agencies compulsory. Moreover, some coordination at international level as far as data collection, data sharing and standardization is concerned might be crucial, in order to develop useful benchmarks (Hasan and Foliente, 2015).

Second, the different methods that have been used to model infrastructure interdependency might provide conflicting results. Indeed, Ouyang (2014) clearly argues that some methods score better than others in terms of the different criteria that we have described above; moreover, the various methods can be fruitfully applied only to some of the resilience improvement strategies that could be put in place to increase the resilience of the system. This in turn suggests that policymakers might consider the idea of having different tools to address specific needs but also the necessity to include these tools within an integrated framework, which is clearly the most promising but also most challenging avenue of research and development.

Finally, Hasan and Foliente (2015) note that, so far, the methods that describe in good detail the interdependencies of infrastructure systems have rarely been applied to evaluate the impacts of disasters. In particular, the incorporation of reasonably detailed topological features of infrastructures into the models that assess the socioeconomic impacts of disasters is still in its

[34] See Okuyama (2007) for a short description of the use of Social Accounting Matrices in the field of disaster impact analysis.

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infancy and should be developed. The existence of such a (group of) tool(s) would help policymakers, in the aftermath of a disaster, to understand the likely geographic scale of the impact, the sectors and local communities more likely to be affected as well as to conduct impact assessments of the consequences of different types of interventions.

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3 Taxonomy of emergency events

As emerged in the previous section, scientific literature proposes several classifications of emergencies in consideration of the different possible approaches to this topic.

The dimensions according to which emergencies involving transport infrastructure can be classified are as follows:

- The natural or anthropogenic cause of the emergency events; in this context it is not so much the cause that is relevant as the effect in terms of a significant drop in the service levels of a transport infrastructure. Therefore, this definition of an emergency event includes both the complete unavailability of an edge or a node of the network (or a set of edges and nodes), as in the case of the fall of the Morandi bridge, or the accident that occurred in Ranstatt in 2017, but also important maintenance works on the network that drastically reduce the conditions of use of (a part of) the transport infrastructure network.
- The possibility to foresee the emergency event; thus distinguishing between *predictable* (as natural events like floods or snowfalls) and *unpredictable* events (as earthquakes of terrorist attacks);
- The impact of the emergency; either in terms of the volume of people or firms impacted (and not only involved) by the event and also in terms of the economic impact of the damages due to the event. Moreover, also the spillover effects (or cascading effects) on other modal infrastructure should be taken into consideration;
- The duration of the effects due to the emergency; in fact, the kind of emergencies considered in this project must not be resolved in a matter of hours or a few days, as this would make any form of intermodal regulation rather difficult, if not impossible, to introduce.

In accordance with the aims of the present project we define an emergency event as any event that:

- *Severely reduces the service levels of a transport network* and hence has a relevant impact on the other (if any) available transport networks,
- *Cannot be solved in less than a week* (in order to reconfigure alternative transport services or alternative transport routes, also with the involvement of the other transport modes available),
- *Has a relevant economic, social and transport impact,* beyond the infrastructure users and the infrastructure manager
- *Happens in an urban context*, thus determining a confusion between different traffic flows on the same transport infrastructure (and possibly resulting in a congestion increase and other negative externalities).

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4 Construction of the network graph

The graph of the infrastructure network has been mapped using Mapinfo software, which allows for a geo-referenced visualization of the North-Western Italian networks. The source of both road and rail infrastructure data is Openstreet Map. Both short and long-distance road infrastructure data, i.e. motorways and urban roads, are included. The long-distance network is here used to identify critical points in the infrastructure network, while shorter-distance urban roads will be used in performing the actions within the Output 3 of the Project. The railway network refers to fundamental, secondary, and high-speed lines. Figure 6 shows the motorways network (red lines) and rail network (yellow lines) considered for the purpose of the Project.

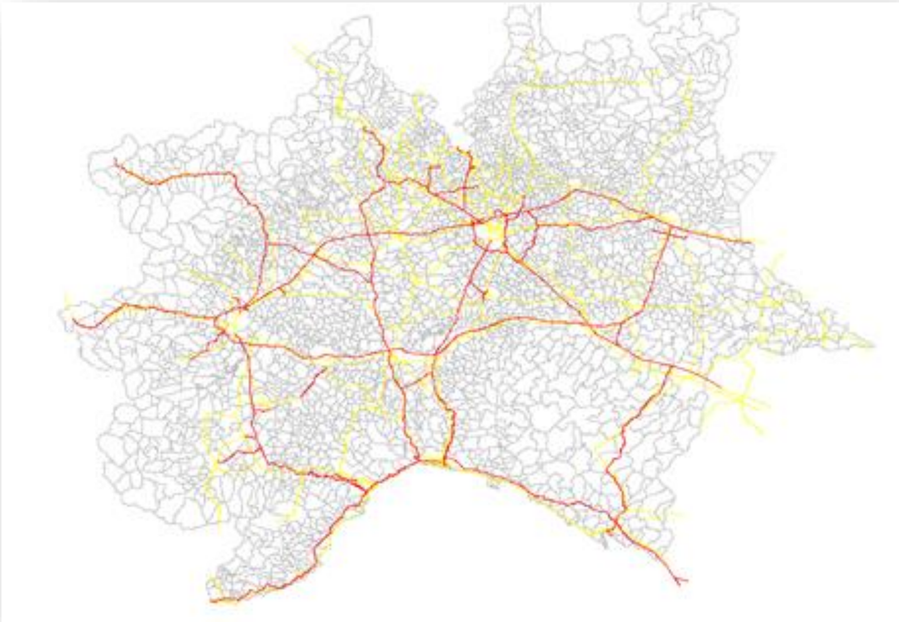

Figure 6. Road and Rail Infrastructure visualization in MapInfo.

Since the focus is on metropolitan areas which generally coincide with provincial (NUTS-3) and regional (NUTS-2) capitals, Figure 7 shows railway lines, motorways and also urban roads for the three regional capitals included in the analysis, i.e. Milan, Turin and Genoa.

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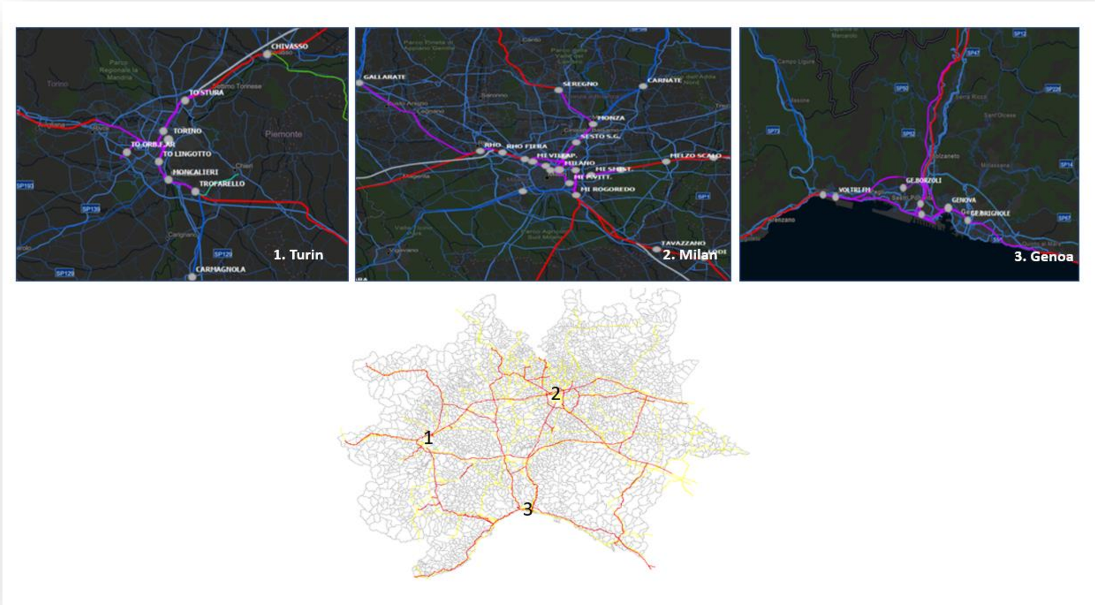

Figure 7. Road and Rail Infrastructure and NUTS-2 Capital Cities.

Thanks to the georeferenced approach, it is possible to handle different regional scales and then to conduct an in-depth analysis of certain aspects that are relevant for the purposes of the Project. In this phase, the aim is to map the infrastructure networks and even to analyze some of their main features. This in order to simulate a case study like the emergency event that involved the metropolitan city of Genoa when the Morandi bridge collapsed. In this perspective, all the motorways bridges overpassing the railway network and the railways bridges overpassing a motorway have been mapped. The analysis returned 66 points of overpass in the north-western Italy, as shown in Figure 8.

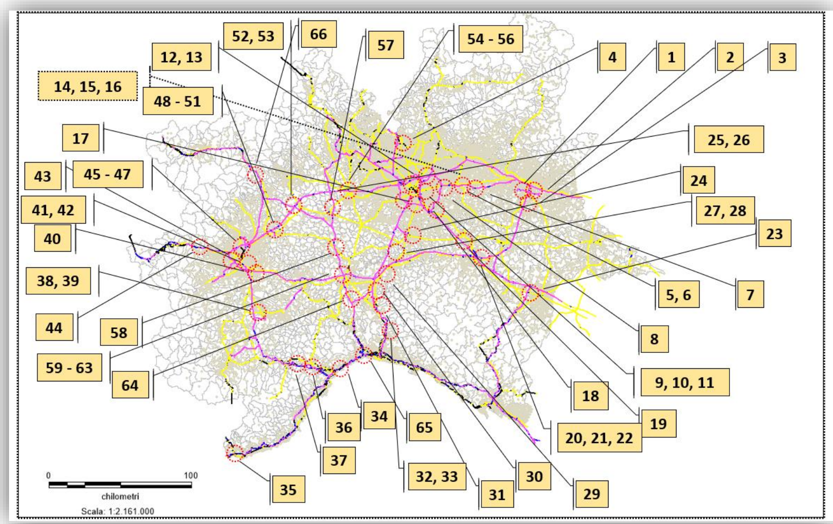

Figure 8. Overpassing Points between motorways and railways.

In addition, considering only the most densely populated locations and overpass points affecting only fundamental railway lines (or relevant urban rail junctions), it is possible to identify ten overlap points considered most relevant for the purposes of the Project (Figure 9 and Table 3).

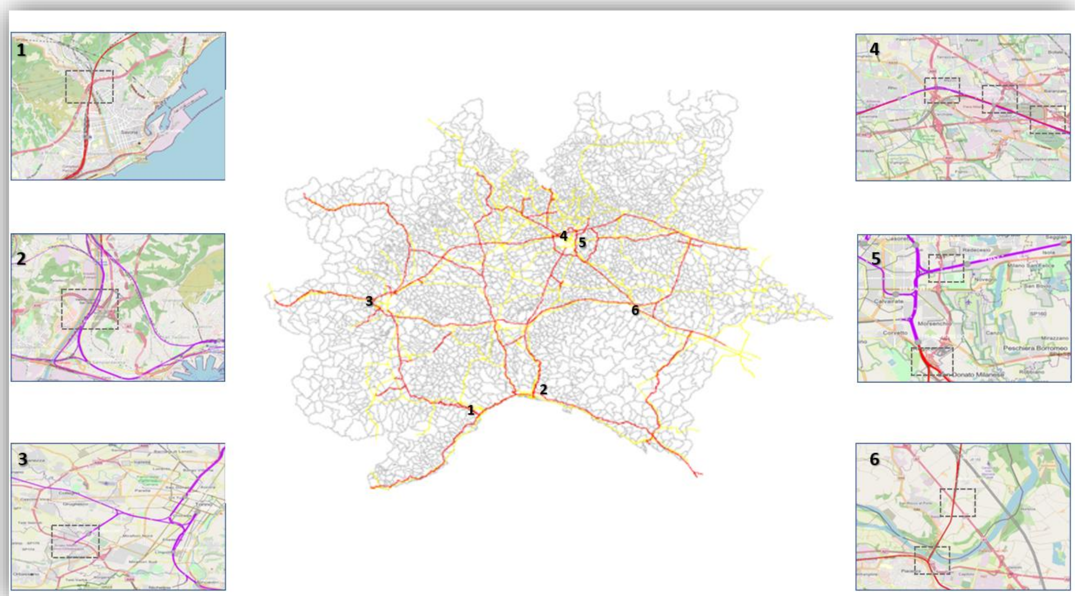

Figure 9. Overpass points between motorways and fundamental railways.

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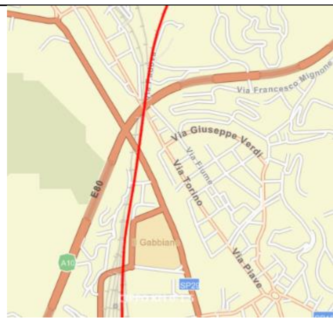
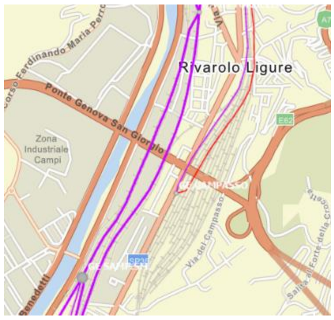
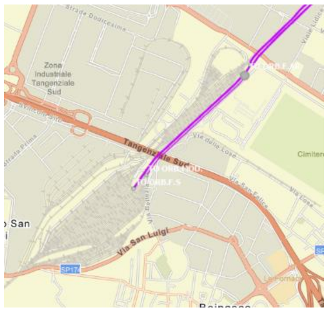
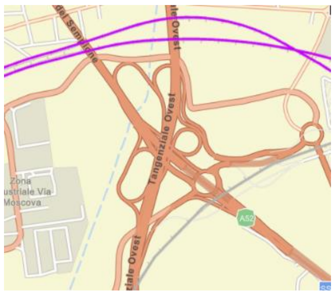
City	***ID***	***Railway***	***Motorway***	
Savona (1)	*Intersection 1*	Fundamental Line (Savona-Genova Voltri)	A10	
Genoa (2)	*Intersection 2* (Morandi Bridge Collapse)	Urban Junction	A10	
Turin (3)	*Intersection 3*	Urban Junction	A55 (ring road)	
Milan (4)	*Intersection 4*	Urban Junction (Milano Certosa-Rho)	A50 and A52 (ring roads)	

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Milan (4)	*Intersection 5*	Urban Junction (Milano Certosa-Rho)	A52 (ring road)	
Milan (4)	*Intersection 6*	Urban Junction (Milano Certosa-Rho)	A4	
Milan (5)	*Intersection 7*	Urban Junction (Milano centrale-Pioltello)	A51 (ring road)	
Milan (5)	*Intersection 8*	Fundamental Line (Milano Rogoredo – Lavino Bologna)	A1	

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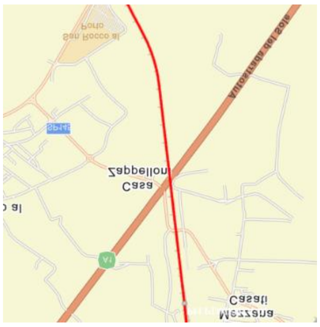
Piacenza (6)	*Intersection 9*	Fundamental Line (Milano Rogoredo – Lavino Bologna)	A1	
Piacenza (6)	*Intersection 10*	Fundamental Line (Milano Rogoredo – Lavino Bologna)	A21	

Table 3. Most important overpass points

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5 NETWORK INDICATORS

5.1 Transport infrastructure network under the Complex Network Theory perspective

Transportation systems are commonly represented using networks. Transport networks belong to the wider category of spatial networks because their design and evolution are physically constrained. The term network refers to the framework of routes within a system of locations, identified as nodes. A route is a single link between two nodes that are part of a larger network that can refer to tangible routes such as roads and rails (Rodrigue, 2020).

Complex Network Theory (CNT) is the chosen approach to elaborate some useful indicators for the identification of the critical elements of the motorways and railways network. The analysis is conducted using the R software, well suited for the study of multiplex networks, i.e. networks in which different connections – or types of connection - between the same pair of nodes are allowed for.

The analysis conducted is developed in three phases:

- the first step consists in the construction of the motorway and railway network (Section 5.1.2 and Section 5.1.3),
- the second step consists in defining the characteristics of the networks relevant for the Project, outlining some key indicators to understand the structure of the two networks separately (Section 5.2), and
- lastly, multi-layers network is taken into account for geographic and functional interdependencies between rail and motorway infrastructures (Section 5.3).

The purpose of the analysis is first to provide a clear description of the networks and to derive an assessment of the most critical and central nodes in both the rail and the highway networks. Then, relying on a multi-layers network, we perform a vulnerability and resilience analysis on a large-scale network. Using different interconnection criteria, different types of analysis can be conducted. In this study, in particular, we observe what happens to the efficiency of a network when a node representing a point where the motorway network passes over the railway network, or vice versa, is removed. In addition, by simulating a situation in which an intermodal shift can take place in all major cities in the North-West of Italy, we observe how the robustness of the network changes with respect to the corresponding uni-modal networks.

5.1.1. Nodes, Arcs and Weights

In this section the graphs of the motorway and railway networks are presented. A graph is a symbolic representation of a network and its connectivity. It involves an abstraction of reality so that it can be simplified as a set of connected nodes or vertices.

A *Graph* is defined as follows:

$$G = (v, e)$$

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where v are the vertices (or nodes) and e the edges (or links) connecting them. 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) 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 terminal extremity j. Each link is the abstraction of a transport infrastructure supporting movements between nodes; in this study the edges represent the existing highways or railways. Moreover, a weight (or a set of weights) may be assigned to each link, i.e. a numerical value to each connection, the graph is said weighted, otherwise the graph is not weighted. We rely to both unweighted and weighted graphs; in the latter case the weight used is the geodesic distance (expressed in kilometres).

Finally, a graph is symmetrical if each link is bidirectional, i.e. links are undirected, otherwise it is asymmetrical. Most transport systems are symmetrical, but when we consider one-way routes we deal with asymmetry. In this study both networks are symmetrical. In particular, the highway network is symmetrical because each connection between two motorway exits is always bidirectional. In the case of the rail network, most connections between two stations consist of two tracks, corresponding to the two directions of travel, and only in some cases a single track serves the two directions simultaneously. Also in this case, however, the graph is considered symmetrical, since at this stage of the analysis the characteristics related to the number of tracks are not taken into account.

5.1.2. Motorways

The graph used to study the motorway network, $Graph_m = (v_{m,} e_m)$, is a symmetric graph, in which each node, v_m, represents a motorway exit or an intersection[35], with $v_{m,} = 1, \ldots, 26$, and each link, e_m, represents a highway connection, with $e_m = 1, \ldots, 36$.[36]

In order to calculate the motorway network indicators, a numerical value corresponding to the distance (expressed in kilometres) is assigned to each link. A complete list of motorway exits is provided in Table 4, while Figure 10 shows a representation of the network.

Motorway Exit	***NUTS-2 region***
Piacenza	Emilia-Romagna
Parma	Emilia-Romagna
Ventimiglia	Liguria
Savona	Liguria
Genova Prà	Liguria

[35] For the sake of clarity, it should be pointed out that motorway nodes are referred to by the term "Exit" even when they represent intersections and that the name associated with the latter refers to the nearest municipality. Examples are Bettole di Tortona and Predosa, to indicate the start and end points of the A26-A7 junction motorway, respectively.
[36] At this stage of the study, we consider the motorway network both before and after the collapse of the Morandi bridge, consequently the graph has an extra link, namely the motorway section between Genova Aeroporto and Genova Ovest, when we consider the network before August 14, 2018. This point will be made clearer in Section 5.2.

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Genova Ovest	Liguria
Genova Aeroporto	Liguria
La Spezia	Liguria
Sestri Levante	Liguria
Milano	Lombardy
Brescia	Lombardy
Bergamo	Lombardy
Predosa	Piedmont
Alessandria	Piedmont
Tortona	Piedmont
Bettole di Tortona	Piedmont
Vercelli	Piedmont
Novara	Piedmont
Asti	Piedmont
Santhià	Piedmont
Ivrea	Piedmont
Torino	Piedmont
Carrù	Piedmont
Cuneo	Piedmont
Gravellona Toce	Piedmont
Aosta	Valle d'Aosta

Table 4. List of Nodes of the Motorway Network

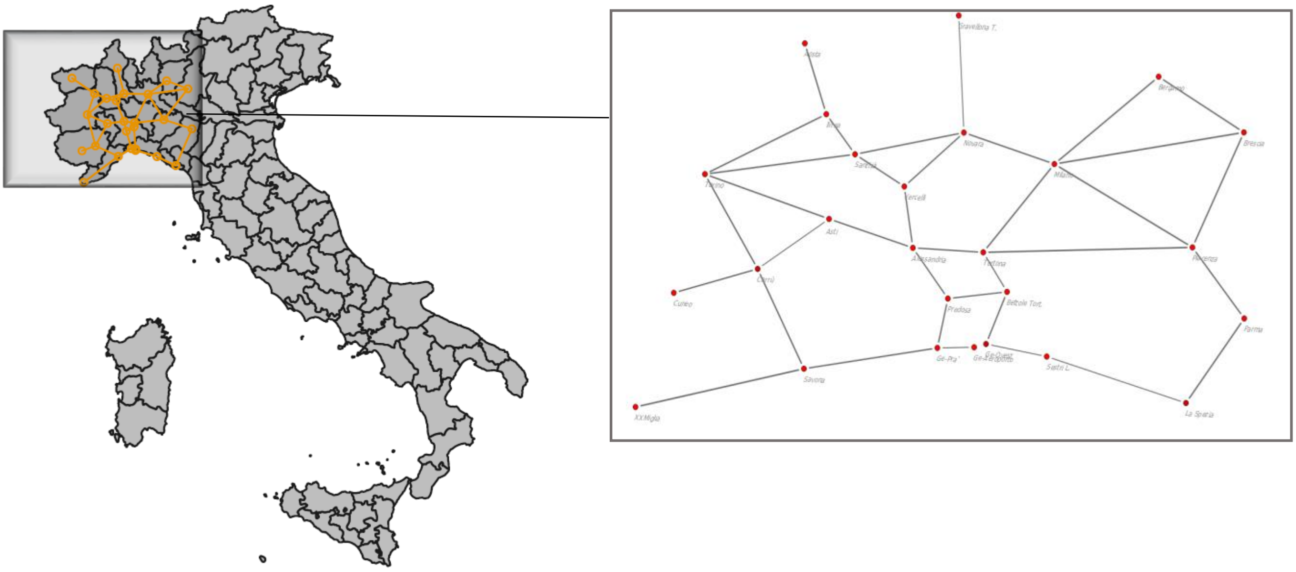

Figure 10. Highway Network after the collapse of the Morandi bridge

5.1.3. Railways

The graph used to study the railway network, $Graph_r = (v_r, e_r)$, is a symmetric graph with $v_{h,} = 1, \dots, 196$, and each link, e_r, represents a railway connection, with $e_h = 1, \dots, 276$.[37]

Figure 6 shows a representation of the network used in this analysis. Railway lines have been selected starting from the full list provided by RFI, the company managing the railway infrastructure in Italy, in its Online Network Statement.[38]

The analysis focuses on the North-West of Italy, and on the railway lines classified as fundamental (red lines in Fig. 11), complementary - secondary - (in blue), and high-speed (in red). The urban junctions within the three metropolitan areas of Genoa, Milan and Turin have also been considered (purple lines). It is worth noting that, while in the motorway network each node represents a motorway exit or an important intersection, in the railway network nodes are selected in accordance with the technical division used in the RFI Online Network Statement. Consequently, the nodes are not only representative of railway stations or intersections, but also of interchange points (the full list of nodes is presented in Annex A).

As in the case of the motorway graph, a weight is assigned to the rail links according to their distance (expressed in kilometres).

[37] As already mentioned, at this stage of the analysis, single-track and double-track routes are treated in the same way, and both are represented with a bi-directional arc.
[38] Available at https://epir.rfi.it/arcgis/apps/sites/#/epir-en

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Figure 11. Railway Network. Source: Authors' elaboration from the RFI Online Network Statement

5.2. Network Indicators – Centrality Analysis

In describing the two networks separately, both a "micro" level analysis, i.e. at the level of a single node, and a "macro" level study, aimed at providing a description of the properties of the entire network, are proposed. Regarding the analysis of node importance, measures of centrality are of considerable relevance. The concept of node centrality relates, in general, to the importance of a node within the network. The word "importance" has many meanings, and this leads to the definition of different measures of centrality.

If by importance we mean the number of connections, then we refer to *Degree Centrality*. The most basic structural property of a vertex is given by the number of its adjacent edges, i.e. its degree. In this study we refer to undirected graphs, hence we do not need to distinguish between out-degree and in-degree, and we calculate the total value of undirected adjacent links.

When for importance we mean the proximity of a node regarding all the nodes of the network, then we refer to *Closeness Centrality*. It measures how many steps are required to access every other vertex from a given vertex. Moreover, if the graph has also a weight edge attribute, then

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weights are used for calculating weighted shortest paths, so they are interpreted as distances. More formally, in the R software, the closeness centrality of a vertex is defined by the inverse of the average length of the shortest paths to/from all the other vertices in the graph.

If by importance we mean the ability of a node to connect all other nodes, we refer to *Betweenness Centrality*; the vertex betweenness is defined by the number of geodesics (shortest paths) going through a vertex. In this case, a node is more central the more it is on geodetic paths between each pair of nodes in the network.

Finally, some measures of centrality consider not only the importance of a node but also the importance of its connections, thus considering the quality of the connections. In this sense, it is not only relevant how well a node is connected to other nodes, but also the importance of its neighbouring nodes. In this spirit, in this analysis we calculate *Eigenvector Centrality*. In this case, the index scores correspond to the values of the first eigenvector of the graph adjacency matrix. These scores may, in turn, be interpreted as arising from a reciprocal process in which the centrality of each node is proportional to the sum of the centralities of those nodes to whom it is connected. In general, vertices with high eigenvector centralities are those which are connected to many other vertices which are, in turn, connected to many others (and so on). We report only a non-weighted measure of Eigenvector Centrality, because using weights would imply assuming that higher weights can spread the centrality better, and this is not the case when weights are based on distances as it is in this study.

Regarding the macroscopic characteristics of the network, important considerations can be made through the *Shortest Path* matrices, i.e. matrices based on the shortest paths between pairs of vertices. Shortest paths have been calculated using Dijkstra's algorithm. Furthermore, this analysis provides two measures of connectivity and two measures of accessibility. To the latter category belong *Diameter* and *Efficiency*, while to the former category belong the *Alpha index* and the *Gamma index*. In particular:

- the *Diameter* is the length of the shortest path between the most distanced nodes of a graph.
- *Efficiency* is calculated as follows: $E = \frac{1}{v(v-1)} \sum_{hj \in V,\, h \neq j} \frac{1}{d_{hj}}$, where d_{hj} represents the length of shortest path between nodes h and j.
- The *Alpha index* is a measure of connectivity of the network. It evaluates the number of cycles in a graph in comparison with the maximum number of cycles (as it would be fully connected). The higher the *Alpha index*, the more a network is connected. Since *Alpha index* ranges from 0 to 1, this means that a value of 1 indicates a completely connected network.
- The *Gamma index* is a measure of connectivity that considers the ratio between the number of observed links and the maximum number of links (as it would be a network fully connected). It ranges from 0 to 1 and it takes value of 1 when the network is fully connected.

Finally, in accordance with Milanović and Zhu (2017), the importance of a node is assessed by calculating the drop of global efficiency after removing that node from the network:

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

The larger is the efficiency drop, the more critical the node is in the network. Moreover, this analysis is replicated by observing the efficiency drop when removing one link at a time.

5.2.1. Motorways

First, the *Degree Centrality* of each node of the motorway graph is calculated. In Figure 12, where the motorway graph after the collapse of the Morandi bridge is represented, the size of the nodes is proportional to the degree of each vertex, while the width of the links is proportional to the distance between two nodes.

In particular, the “Milano” node has the highest degree, with 5 adjacent links. Then there are seven nodes, namely Alessandria, Turin, Piacenza, Novara, Tortona, Santhià, and Carrù, which have a degree equal to 4. Moreover, as Figure 13 shows, in the graph there also are: five nodes with degree 1, other five nodes with degree 2, and eight nodes with degree 3.

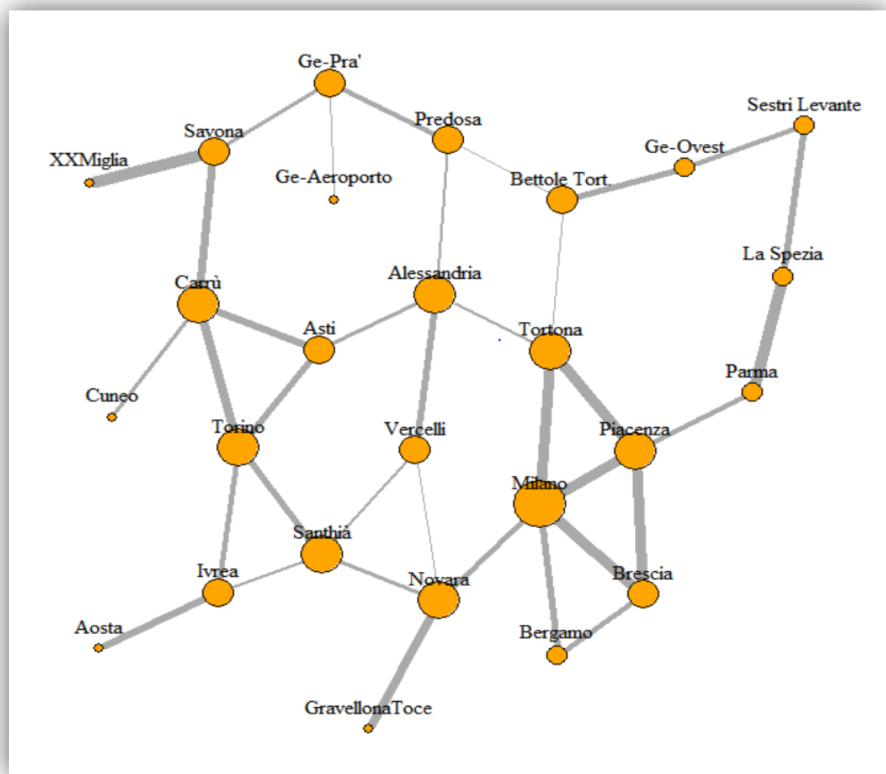

Figure 12. Degree Centrality

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It is worth noting that, analyzing the graph before the bridge collapse, all nodes show the same degree, with the only exception of Genova Ovest and Genova Aeroporto, which have one additional adjacent link, namely the Morandi bridge, and then have a higher value (+ 1) of the index.

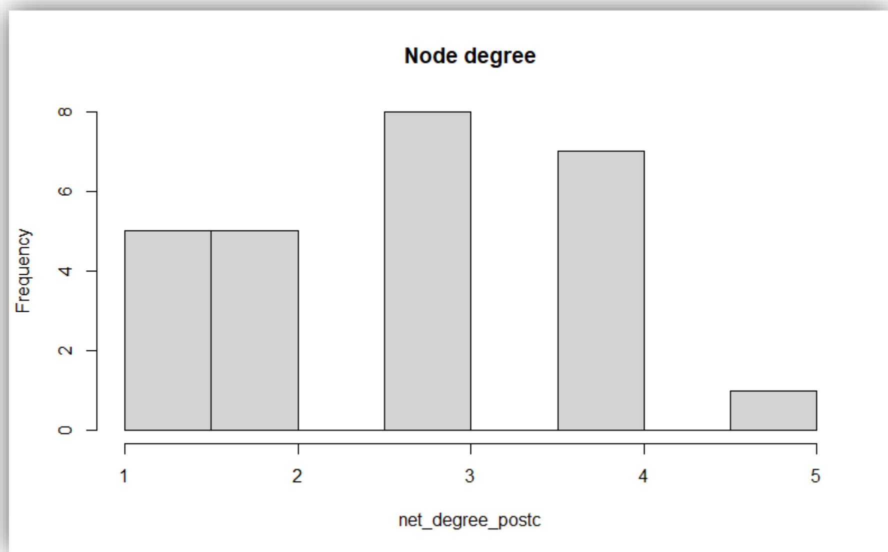

Figure 13. Degree Centrality

Turning to *Closeness Centrality*, Table 5 presents the percentage variation in the value of this measure after the collapse of the Morandi bridge. We calculate the index of closeness both before and after the collapse, and either with and without weights. When weights are not used, only the number of nodes that need to be crossed to reach the other vertices of the network is considered. When edges are weighted for distance, in the calculation of this measure the weighted shortest paths are considered. The values shown in Table 5 emphasize that the motorway exits that experienced the greatest percentage increase in minimum paths are those in the Liguria NUTS-2 region.[39] From Figure 14 it is clear that in Liguria the variation undergone, both with and without weights, is greater than the average value (red bar), which is equal to just over -3 % in the case of the unweighted measure, and almost -4 % in the case of the weighted closeness centrality.

[39] Note that the indicator is constructed as the inverse of the average of the minimum paths, and when it results in a negative percentage change, this means that the average of the minimum paths has increased.

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Motorway Exit	**Percentage variation in Closeness Centrality (*not weighted*)**	**Motorway Exit**	**Percentage variation in Closeness Centrality (*weighted*)**
Ge-Aeroporto	-15,9	Ge-Ovest	-17,3
Ge-Ovest	-8,4	SestriLevante	-14,0
SestriLevante	-7,1	Ge-Aeroporto	-12,5
LaSpezia	-5,5	LaSpezia	-11,5
Ge-Pra'	-3,6	Ge-Pra’	-9,5
Savona	-3,4	Savona	-8,4
XXMiglia	-2,7	Carrù	-5,8
Carrù	-2,5	XXMiglia	-5,0
Parma	-2,1	Cuneo	-4,9
Cuneo	-1,9	Predosa	-1,4
Tortona	-1,5	Alessandria	-0,7
Milano	-1,4	Vercelli	-0,6
Bettole Tort.	-1,3	Asti	-0,6
Piacenza	-1,3	Novara	-0,6
Brescia	-1,1	Santhià	-0,5
Bergamo	-1,1	Torino	-0,5
Predosa	0,0	Ivrea	-0,5
Alessandria	0,0	Tortona	-0,4
Vercelli	0,0	Bettole Tort.	-0,4
Novara	0,0	GravellonaToce	-0,4
Asti	0,0	Aosta	-0,3
Santhià	0,0	Milano	-0,3
Ivrea	0,0	Piacenza	-0,3
Aosta	0,0	Bergamo	-0,2
Torino	0,0	Parma	-0,2
GravellonaToce	0,0	Brescia	-0,2

Table 5. Closeness Centrality Variations (%)

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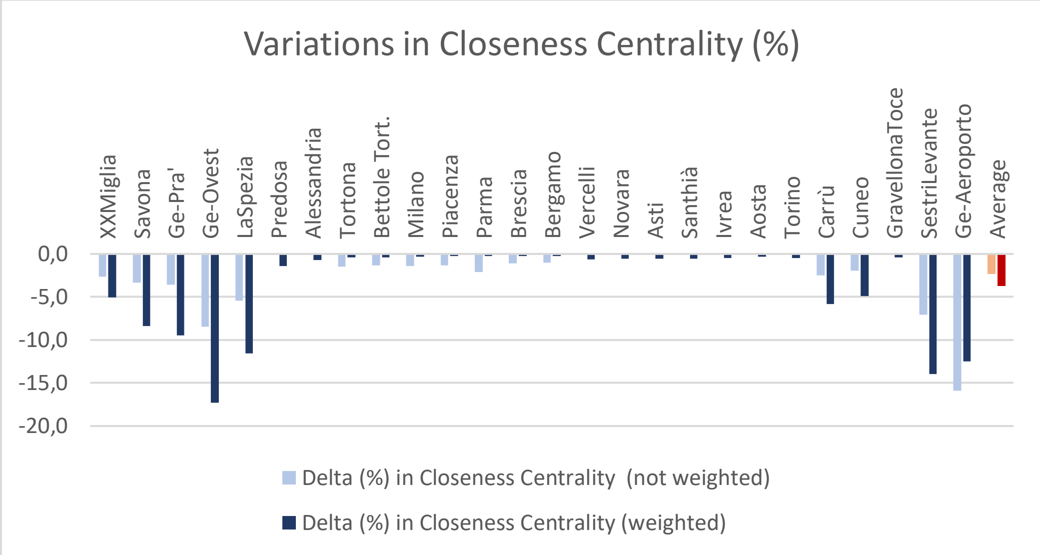

Figure 14. Closeness Centrality Delta (%)

Variations in *Betweenness Centrality* are calculated excluding the pendent nodes which, by definition, never occur on a minimum path as well as the "Bergamo" node that, although not pendent, presents an index equal to zero, either before and after the collapse of the bridge. In addition, the Genova-Aeroporto node is not shown since, due to the collapse of the Bridge, it has itself become pendant (thus, presenting a negative variation of 100%). Figure 15 shows, for example, the minimum path between the motorway exits of Ventimiglia and La Spezia, respectively the westernmost and easternmost in Liguria. In panel a), which represents the configuration before the collapse of the Bridge, the minimum path passes through the Genova-Aeroporto node. After the collapse of the Morandi bridge, instead, the latter becomes pendent and is no longer part of the shortest path (panel b). The minimum path increases from 257 km (panel a) to 366 km after the collapse of the Morandi bridge (panel b). This represents a relevant increase in the distance between the eastern and the western part of the Liguria region in case vehicles remain on the highways instead leaving the motorway at Genova-Aeroporto exit, cross the municipal territory (or part of it) along the municipal road system and then enter the motorway again. This route deviation is particularly cost- and time-consuming for vehicles and in particular for heavy traffic. In fact, as shown in Annex E, the number of heavy vehicles entering the motorways network at the National border of Ventimiglia and exiting in Genova-Ovest or other eastern exits recorded in the second week of June 2019 dramatically dropped in comparison with the figures recorded in the same week in the previous year (2018).

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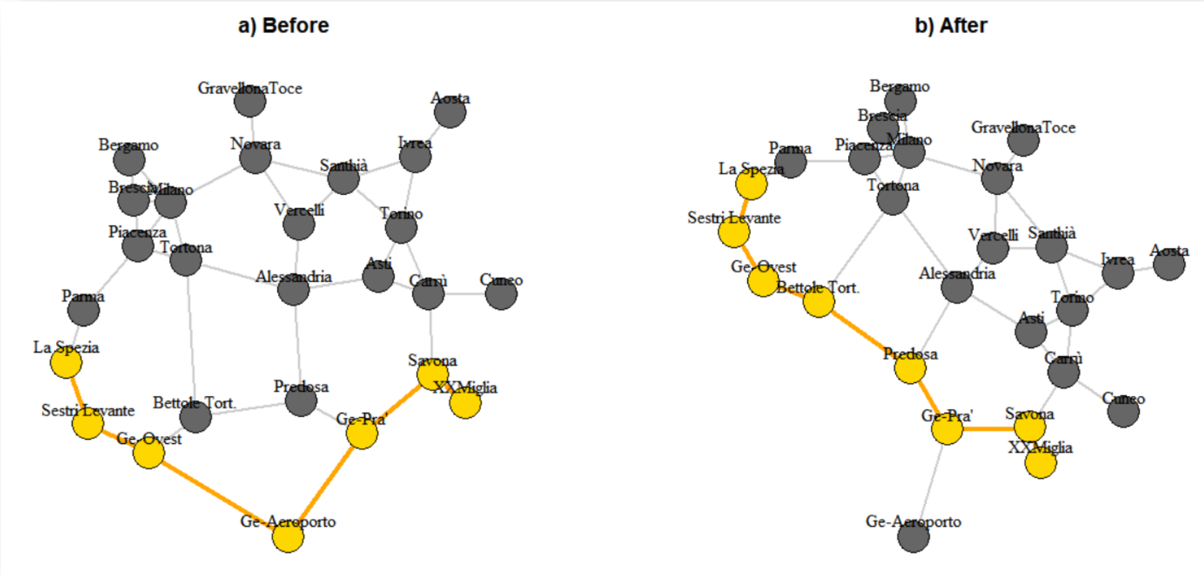

Figure 15. Shortest-path Ventimiglia-La Spezia, before and after the collapse of the Morandi Bridge

Clearly, the effect of the unavailability of the link from Genova-Aeroporto to Genova-Ovest is also observed on other shortest paths. Table 6 reports the percentage variation of the betweenness index before and after the collapse of the Bridge, both with and without weights. A graphical representation is also given in Figure 16, where the average percentage variation is also indicated.

The variation of betweenness centrality measures (weighted) of the nodes of the network highlights how the collapse of the Morandi bridge has increased the centrality of the nodes behind Genoa – i.e. the motorway nodes of Alessandria, Asti, Tortona and Bettole - as they connect (i.e. are on the shortest paths) the nodes located in the far western part of Liguria with the eastern nodes of the network.

Motorway Exit	**Variations (%) in Betweenness Centrality (*not weighted*)**	**Motorway Exit**	**Variations (%) in Betweenness Centrality (*weighted*)**
Ge-Ovest	-29,8	Ge-Pra’	-31,7
Sestri Levante	-26,2	Savona	-17,6
La Spezia	-20,9	Ge-Ovest	-14,9
Savona	-11,3	Predosa	-10,5
Carrù	-2,1	La Spezia	0,0
Milano	-1,3	Milano	0,0

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Torino	-1,0	Piacenza	0,0
Brescia	0,0	Parma	0,0
Ivrea	0,0	Brescia	0,0
Novara	0,3	Vercelli	0,0
Santhià	0,8	Novara	0,0
Parma	5,3	Santhià	0,0
Tortona	5,3	Ivrea	0,0
Piacenza	6,8	Torino	0,0
Vercelli	6,8	Carrù	0,0
Alessandria	12,8	Sestri Levante	0,0
Asti	14,7	Alessandria	6,0
Ge-Pra’	14,7	Asti	19,4
Bettole Tort.	36,2	Tortona	45,8
Predosa	66,2	Bettole Tort.	114,3

Table 6. Variations in Betweenness Centrality (%)

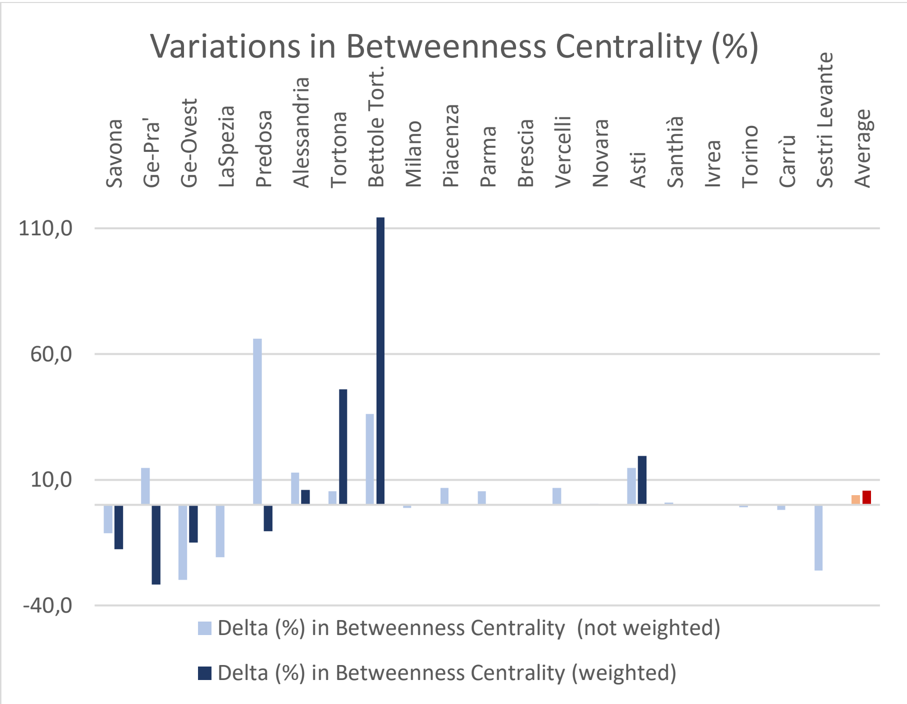

Figure 16. Betweenness Centrality Variations (%)

To conclude the microscopic analysis, Table 7 proposes the percentage changes of *the Eigenvector Centrality* after the collapse of the Bridge. Results are quite intuitive: the nodes most affected by the unavailability of the edge linking Genova Aeroporto to Genova Ovest are these same two nodes, and then the effect expands along the network in successive waves of increasingly smaller size.

Motorway Exit	**Variations (%) in Eigenvector Centrality (*not weighted*)**
Ge-Aeroporto	-53,7
Ge-Ovest	-22,3
SestriLevante	-15,2
Ge-Pra'	-11,6
Savona	-4,2
XXMiglia	-4,1
Bettole Tort.	-3,9
LaSpezia	-3,6
Predosa	-3,3
Alessandria	-0,7
Carrù	-0,7
Tortona	-0,6
Cuneo	-0,6
Asti	-0,4
Parma	-0,4
Piacenza	-0,1
Torino	0,0
Vercelli	0,0
Milano	0,0
Brescia	0,1
Bergamo	0,1
Novara	0,2
Santhià	0,2
Ivrea	0,2
GravellonaToce	0,3
Aosta	0,3

Table 7. Eigenvector Centrality Delta (%)

Turning to explore some macroscopic characteristics of the network considered, Figure 17 presents the diameter of the motorway network. The total length of the longest geodesic path is 377 kilometres, and goes from Ventimiglia to Brescia, passing through the vertices yellow coloured in Figure 17.

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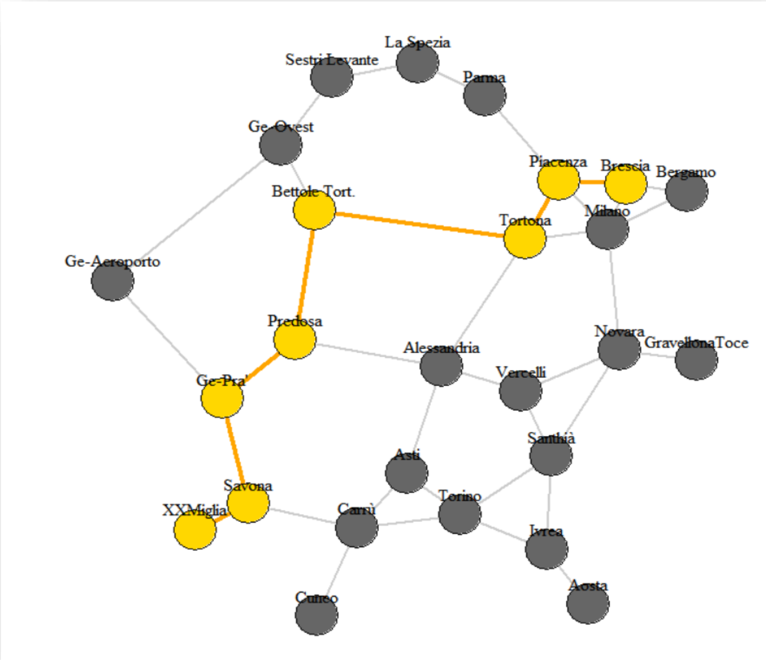

Figure 17. Diameter of Motorway Graph

Moreover, Figure 18 presents the percentage changes in the total length of the shortest paths for each node. That is, the minimum path length between each node and every other node in the network is calculated, thus obtaining the sum of the minimum path lengths of each node. Doing this computation on the network before and after the Morandi Bridge collapse, the percentage change of the minimum lengths is calculated. The nodes in the Liguria NUTS-2 region show the highest percentages increase in minimum paths. The first is the Genova-Ovest node recording a 21% increase, followed by Sestri Levante (+16%), Genova-Aeroporto (+14%), La Spezia (+13%), Genova-Pra' (+10%), Savona (+9%), and Ventimiglia (+5%). Interestingly, two nodes located in the Piedmont NUTS-2 region also record a substantial increase in the sum of the shortest paths: Carrù +6% and Cuneo +5%.

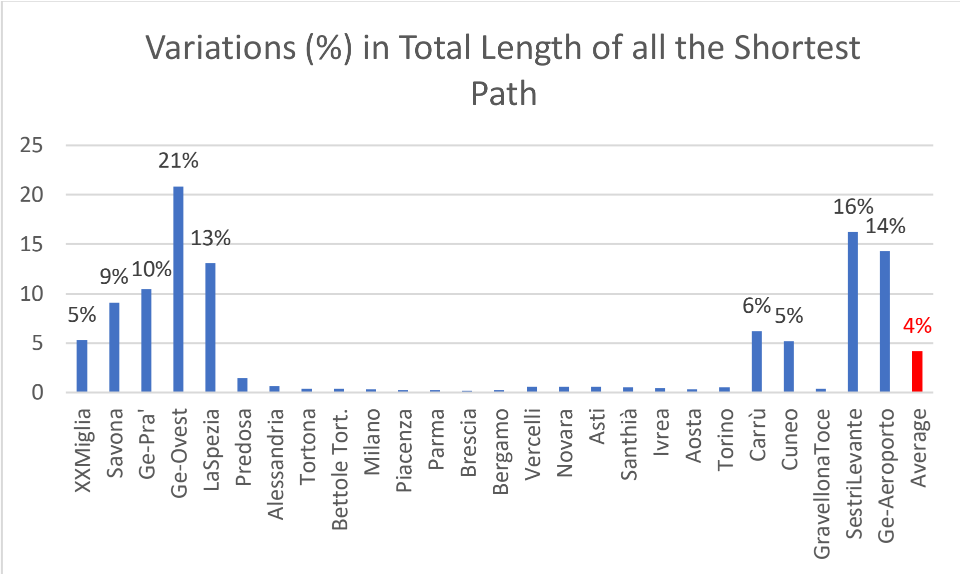

Figure 18. Variations (%) in Total Length of all the Shortest Path

Finally, the proportion of edges in the network over all possible edges that could exist, i.e. the *Gamma Index*, is about 11% both before and after the collapse of the Bridge, and *Alpha Index* is equal to about 0.255 before the collapse while it slightly decreases to 0.234 afterwards.

To conclude the study of the motorway network, a network efficiency analysis is conducted with the aim of detecting the most critical nodes and links in terms of efficiency loss. By removing one vertex at a time, it is possible to compare the efficiency of the network before and after removal. Recalling that our efficiency loss measure is constructed in such a way that higher values are associated with greater efficiency loss, Figure 19 shows results from this analysis. Interestingly, the first two nodes in order of loss of efficiency are those affected by the collapse of the Morandi bridge, followed by another node in the city of Genova, i.e. Pra' motorway exit. It is worth noting that when, following the removal of a node from the network, another node remains pendant, the distance between the latter and all the other nodes of the network is in principle infinite.[40] Then, when interpreting the results in Figure 19 it is worth bearing in mind that the loss of efficiency caused by the removal of Savona, Novara, Ivrea, and Carrù is somewhat underestimated since by definition, all nodes connected to a pendant node would lead to a total loss of efficiency when removed, since the pendant node is then separated from the main cluster. This is because whenever one of these nodes is removed at least one other node in the network remains isolated.

[40] Taking for example the drop of the Savona motorway exit, the direct consequence is the disconnection of the network of the Ventimiglia node. Then, in the shortest paths matrix the distance between Ventimiglia and all other nodes in the network is considered to be infinite, but for computational reasons the value is replaced by a 0.

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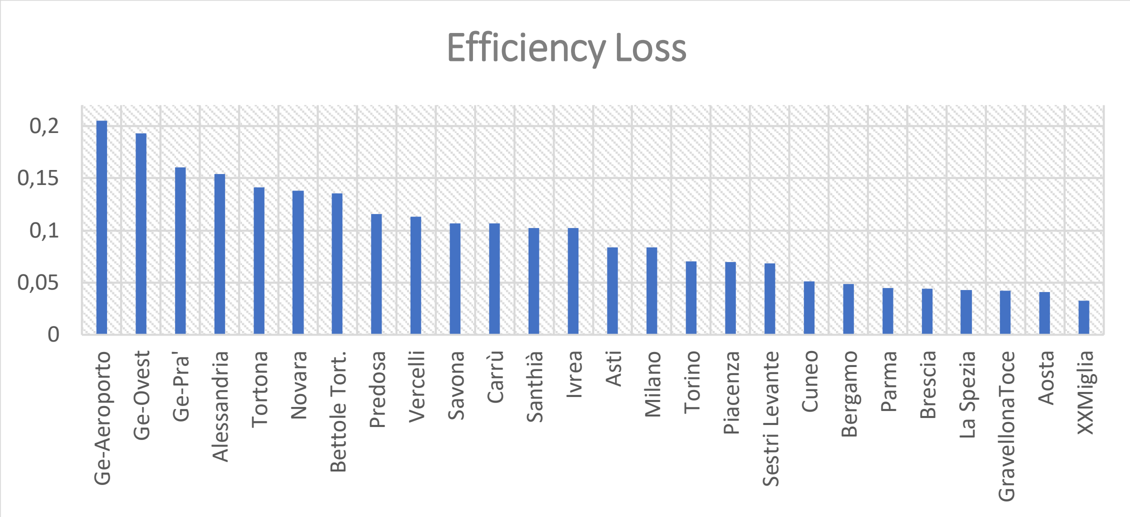

Figure 19. Efficiency Analysis – Removal of Nodes

Then the analysis has been replicated removing one link at a time. Results are shown in Table 8, and a graphical representation is given in Figure 20. In Table 8, we list all links belonging to the motorway network in order of efficiency loss. Two sections of the Ligurian motorways, namely the link between the Genova Aeroporto and Genova Ovest exits (A10), and the link between the Genova Pra' and Genova Aeroporto exits (A10) determine the highest loss of efficiency of the highways network. Notice one of the two is precisely the link that collapsed when the Morandi bridge emergency occurred. By removing these links separately, the network loses about 12% and 8% of its efficiency, respectively. Among the links leading to a loss of efficiency between 4% and 5% there are two other links in Liguria, namely the motorway section between the exits of Genova Pra' and Savona, and between Genova Ovest and Sestri Levante.

Table 8. Loss of Efficiency - Link Removal

Removed Link	Loss of Efficiency %
Ge-Aeroporto-Ge-Ovest	11,64
Ge-Pra'-Ge-Aeroporto	8,00
Carrù-Cuneo	5,14
Tortona-Bettole Tort.	5,08
Savona-Ge-Pra'	4,58
Ge-Ovest-Sestri Levante	4,26
Novara-GravellonaToce	4,24
Ivrea-Aosta	4,06
Alessandria-Asti	3,54
Alessandria-Vercelli	3,52

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XXMiglia-Savona	3,24
Vercelli-Novara	2,90
Milano-Novara	2,58
Santhià-Ivrea	2,34
Predosa-Bettole Tort.	2,14
Predosa-Alessandria	1,99
Piacenza-Parma	1,90
Alessandria-Tortona	1,82
Ge-Pra'-Predosa	1,74
Vercelli-Santhià	1,59
Tortona-Piacenza	1,58
Sestri Levante-La Spezia	1,56
Savona-Carrù	1,47
Milano-Bergamo	1,28
Asti-Carrù	0,93
Asti-Torino	0,88
Tortona-Milano	0,74
Torino-Carrù	0,62
Ge-Ovest-Bettole Tort.	0,60
Ivrea-Torino	0,58
Brescia-Bergamo	0,52
Santhià-Torino	0,52
Piacenza-Brescia	0,50
Milano-Piacenza	0,47
La Spezia-Parma	0,40
Novara-Santhià	0,22
Milano-Brescia	0,03

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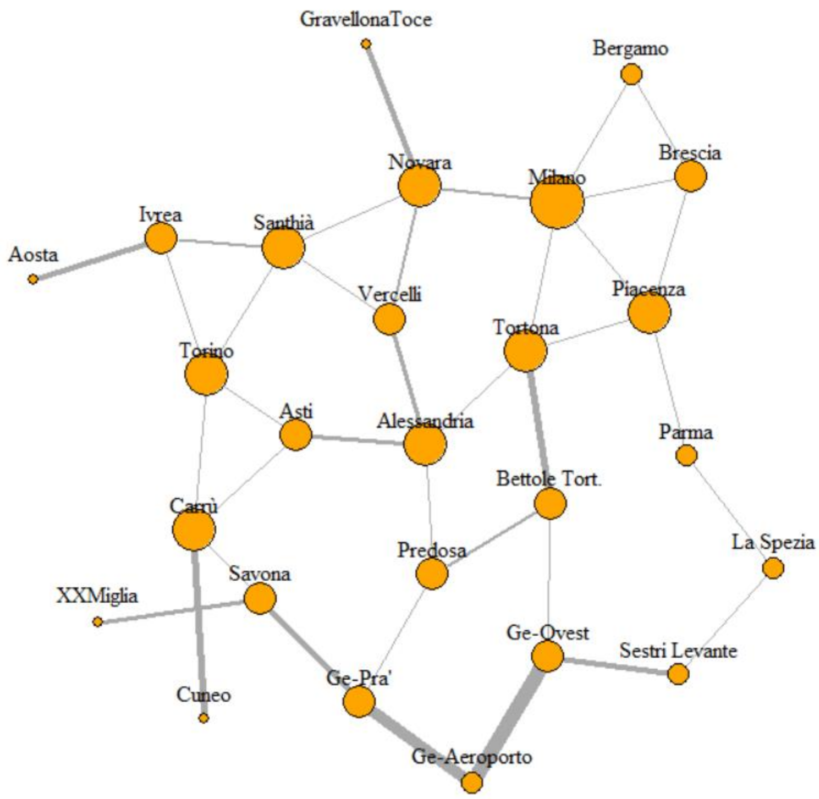

Figure 20. Link Removal - Edge Width proportional to Efficiency Loss

5.2.2. Railways

In this section the same structure of the analysis made on motorways is proposed. At first the node centrality indicators are presented and then an analysis at macroscopic level. For the sake of clarity, since the number of nodes for the railway network is much higher than that of the motorway graph, results are proposed through a graphical analysis, while the relevant tables appear in the Annex B.

Figure 21 shows the degree distribution of the railway graph. The higher relative frequency of *Degree centrality* equals to 2 (43% of the total), followed by nodes with a degree of 3, representing about the 30% of the nodes. Only 10% of the nodes has a degree of 4, while nodes with a degree higher than 4 represent 9% of all nodes included in the network. Figure 22 shows a graph of all the railway lines considered, highlighting nodes with a degree greater than 4. Their size and colour reflect graphically their centrality. The node with the highest degree is Milano Lambrate, followed by Milano Rogoredo, with *Degree Centrality* equal to 10 and 9, respectively. Moreover, the three nodes with 7 adjacent links also belong to the Milan metropolitan area. The remaining thirteen nodes, in orange, are those with a grade of 5.

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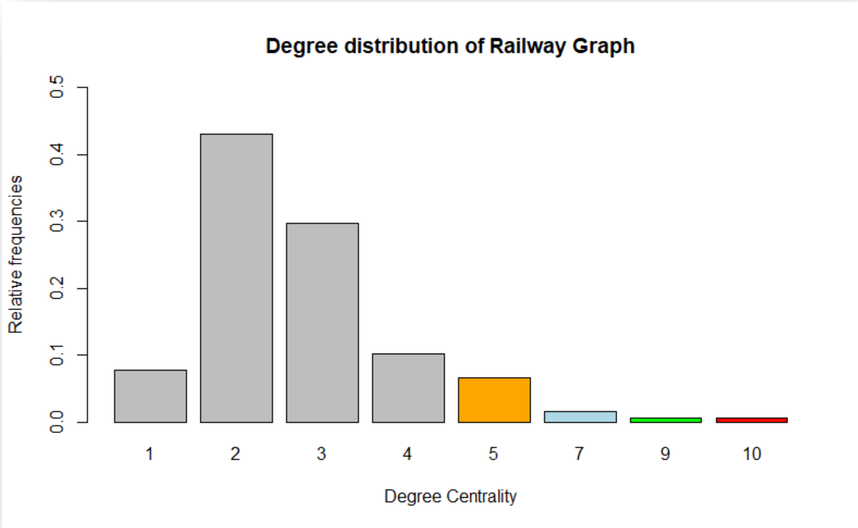

Figure 21. Degree Distribution Railway Network

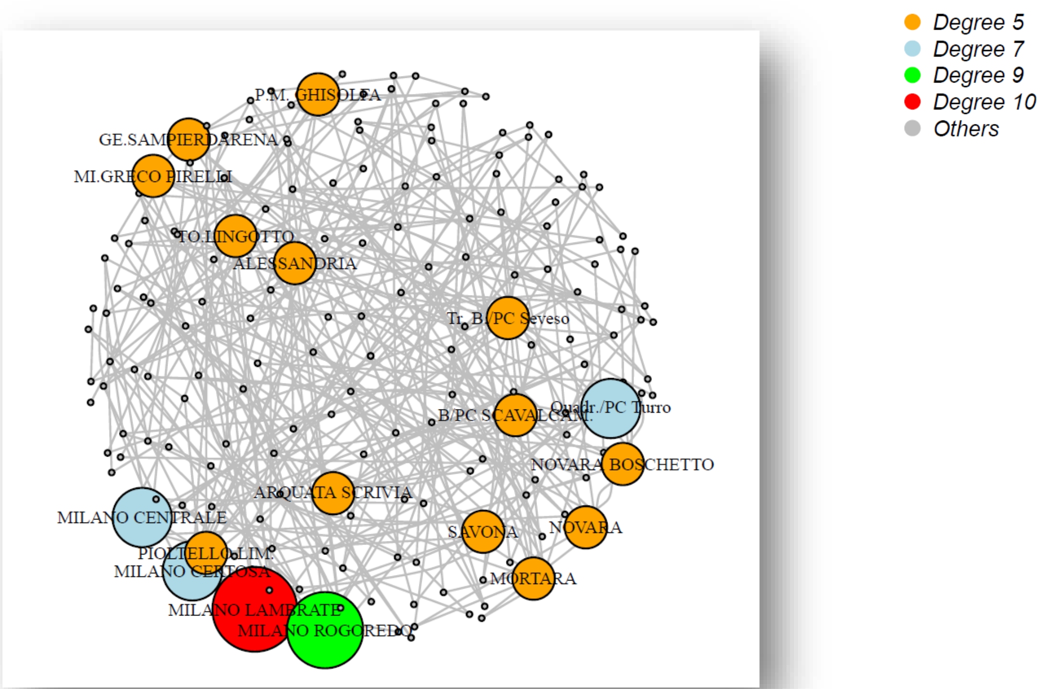

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Figure 22. Most central railways nodes

As abovementioned, the railway network is made of several railway lines with different characteristics. Figure 23 shows four "subgraphs", corresponding to the four types of lines considered in this analysis (fundamental, secondary, high speed and urban junctions). The size and the colour of nodes reflect the *Degree Centrality* of each vertex in that specific subgraph.

In the network of fundamental lines (panel a Figure 23) there are two nodes (B.Po Scavalcamento and Arquata Scrivia) with degree 5 (in orange), 6 nodes with degree 4 (in pink), while nodes with degree 3 (in yellow) represent about 18% of the total, and those with degree 2 (in violet) about 57%.

Panel b represents the network of secondary lines. The only node with grade 5 is highlighted in orange (Mortara), and the two nodes with grade 4 in pink (S. Giuseppe D.C. and Cremona). About 30% of the distribution is characterized by nodes with grade 1, about 50% by nodes with grade 2, and about 15% by nodes with three adjacent links.

The high-speed rail network is represented in panel c. This type of lines characterizes the connection between Turin and Milan, including the junction towards Novara, and the connection from Milan to Parma. In this network half of the nodes have a degree of 1, while the remaining half is equally divided between nodes with degree 2 and nodes with degree 3.

Finally, the subgraph of urban lines (panel d) is characterized by the largest range of *Degree Centrality*; it goes from nodes with degree 1 (about 20%) to nodes with degree 10 (Milano Lambrate, the node colored in red). Milan Rogoredo, in brown, has 9 adjacent links, followed by three other nodes belonging to the metropolitan city of Milan that have a degree equal to 7 (in light blue). Finally, five nodes have a degree of 5, 13% of nodes have degree 4, 34% degree 3, and 16% degree 2.

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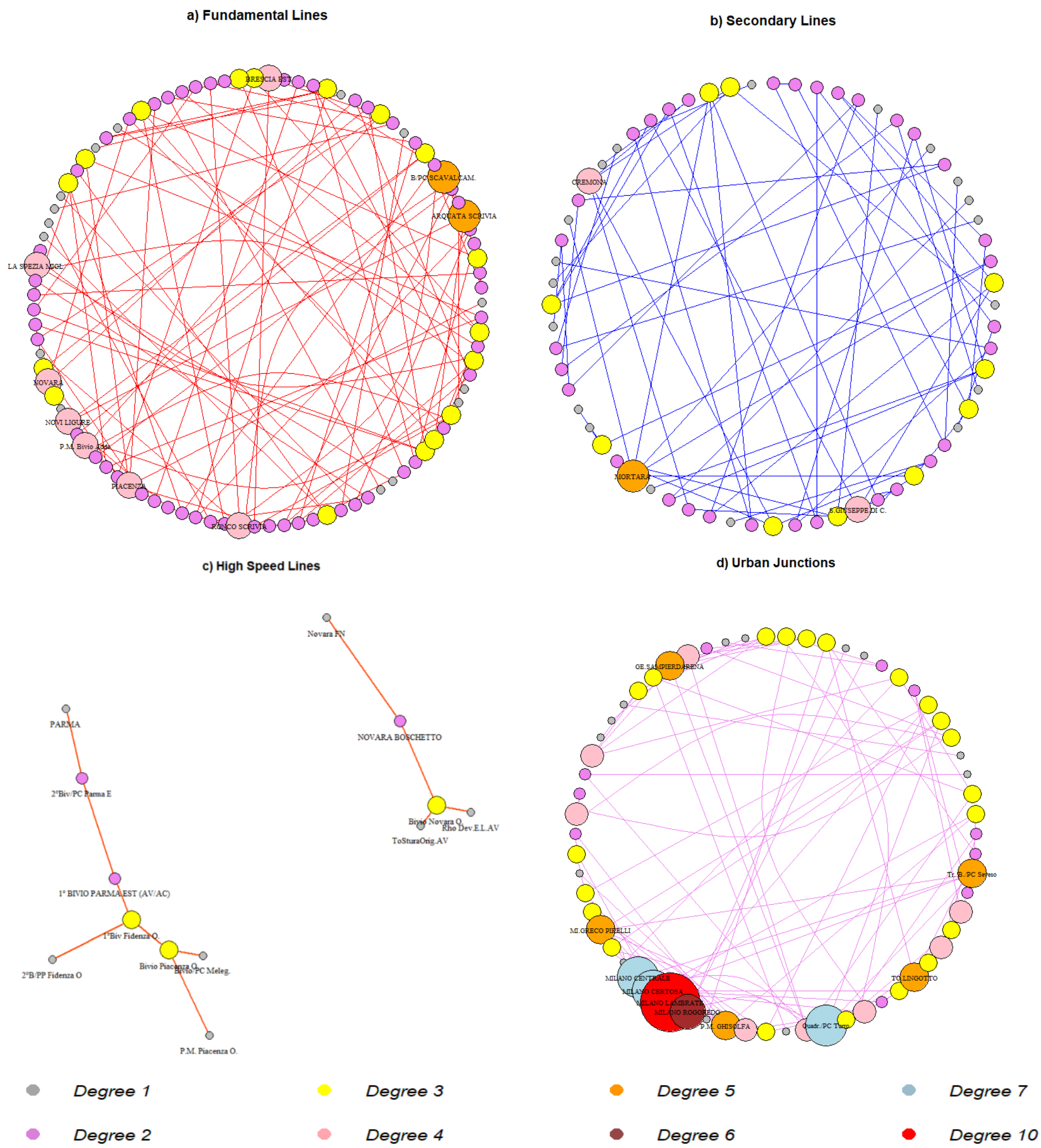

Figure 23. Degree Centrality of Nodes in Four Subgraphs

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Regarding the *Closeness Centrality*, Figure 24 shows the ten nodes with the highest value of closeness index, in orange, and the ten nodes with the lowest value, in red.[41] Panels a) and b) depict the results for the weighted and the unweighted graph respectively, where the weights are the kilometric distances.

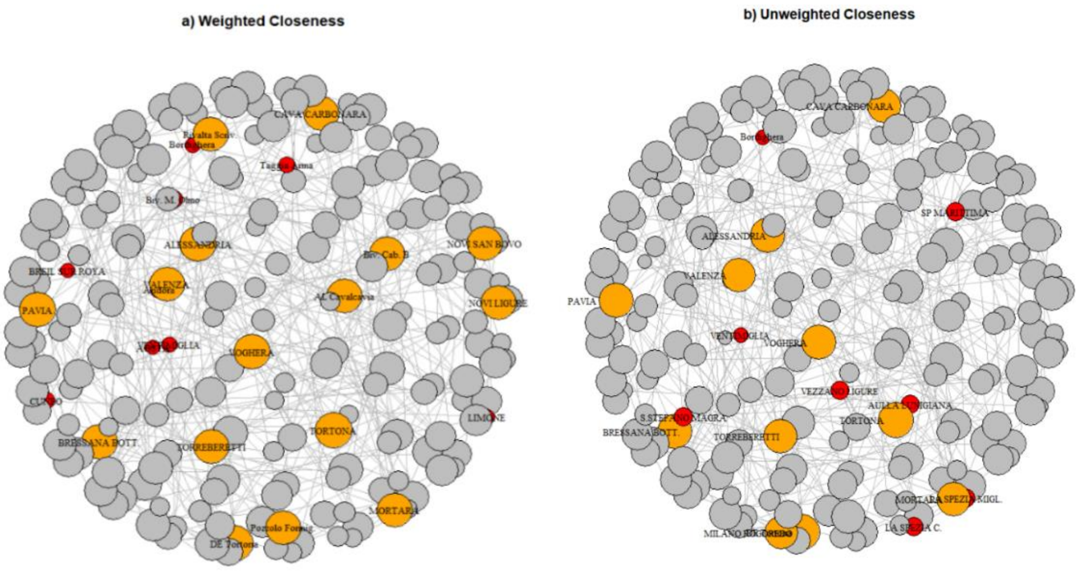

Figure 24. Closeness Centrality

Turning to *Betweenness Centrality*, Figure 25 shows the ten nodes with the highest index value (in orange) and the nodes with a value of the index equal to 0 (in red). Panels a) and b) show the index weighted for the distance between nodes and the un-weighted index, respectively. Six are the orange coloured nodes in both panels of the figure: Arquata Scrivia, Milano Rogoredo, Alessandria, Voghera, Tortona, and Pavia.

[41] Note that the indicator is constructed as the inverse of the average of the minimum paths; higher index values indicate a smaller total shortest path, and therefore indicate a higher *Closeness Centrality* of the node.

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Figure 25. Betweenness Centrality

To conclude the microscopic analysis, Table 9 reports the top thirty nodes for the value of the *Eigenvector Centrality* index, and it is interesting to note that most of these are located in the Milan metropolitan area.

Rank	Railway Node	*Eigenvector Centrality*
1	Milano Lambrate	1,00000
2	Milano Centrale	0,94440
3	Quadr./Pc Turro	0,90144
4	Mi.Greco Pirelli	0,60765
5	Milano Rogoredo	0,50051
6	Tr. B./Pc Seveso	0,46650
7	P.M. Trecca	0,31535
8	Pioltello Lim.	0,28060
9	Mi. Smistamento	0,27481
10	Biv/Pc Mirabello	0,27222
11	Bivio Lambro	0,24410
12	Milano Certosa	0,13902
13	Mi. P. Vittoria	0,13703
14	Biv. Musocco	0,11674
15	Pavia	0,09519
16	Bivio/Pc Meleg.	0,09491
17	Melegnano	0,09191

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18	D.E.Rog.L.MI PR	0,08618
19	D.E.Rog.L.Trecca	0,08618
20	P.M. Ghisolfa	0,07244
21	Mi.P.Garibaldi	0,07182
22	P.M. Bivio Adda	0,05899
23	Mi Rog.Bin.Ester	0,05609
24	Melzo Scalo	0,05173
25	Mi Lancetti	0,05120
26	Rho Dev.E.L.No	0,03519
27	Rho	0,03434
28	Tavazzano	0,03328
29	Rho Dev.E.L.Av	0,03099
30	Mi Bovisa P.	0,02129

Table 9. Eigenvector Centrality

Finally, some macroscopic characteristics of the railway network are observed. The *Diameter* is 377.6 km., the *Gamma* index is equal to 0.014, a low value (lower than the corresponding value of the motorways network) due to the large number of nodes considered in the railways network. *Alpha* index is about 0.21.

5.3 Multi-layer Network Analysis

The last part of this study is devoted to analyzing the two networks jointly, thus considering a multi-layer network, to allow a more comprehensive framework. In multi-layer networks, nodes are organized into layers, and edges can connect nodes in the same layer (*intralayer edges*) or nodes located in different layers (*interlayer edges*).

Fundamental starting point is to define the way motorways and railways networks are interconnected. In this study, two different definitions of interconnection are used, serving to different purposes. Indeed, depending on how two infrastructures are connected, different aspects of the multi-layer network arise. A first interesting analysis is aimed at highlighting the geographic interdependence of critical infrastructures, observing how a damage that initially affects only one infrastructure can also propagate to another one that is closely connected to it, for example by geographical proximity. Section 5.3.1 is devoted to this aspect. The second analysis aims at observing how the robustness of a network can change if all the main nodes allow an intermodal shift. Section 5.3.2 proposes a robustness analysis assuming that in every major city in the North West of Italy there is an infrastructure junction that allows switching from the main motorway exit to the main railway station, and vice versa.

5.3.1. Joint Network based on Overlapping Points

Scientific literature on networks identifies four principal classes of interdependencies: physical, cyber, geographic, and logical (Rinaldi et al, 2001).[42] 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. Assuming, for example, the collapse of a bridge, one can imagine that the event may damage another underlying infrastructure. This is what happened 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, consisting of nodes representing motorway exits, and the railway network, consisting of nodes corresponding to railway stations, are interconnected through overpassing points.[43] In this case, the two infrastructures are directly connected, i.e. there is a first-order interdependence or first-order effect. Suppose a motorway bridge crosses over a railway line: if the bridge collapses this would have a direct effect on the railway infrastructure.

Following Havlin et al (2015), the interconnected system can be transformed into a complex-valued $n \times n$ adjacency matrix Ω. Each row and column represents a node. The connection between two nodes, i and j, is (h, j). There exist three types of links: motorways, railways, or connections. Each entry, ω_{hj}, can take values as follows:

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

Let's consider the following scenario: 3 motorway exits, 3 railway stations, and an overpassing point, suggesting the presence of a bridge where one of the two infrastructures cross over the other (Figure 26).

[42] See Section 2.4.1 on the different definitions of interdependent infrastructures.
[43] See Section 4 for a detailed description of the methodology used to select overpassing points.

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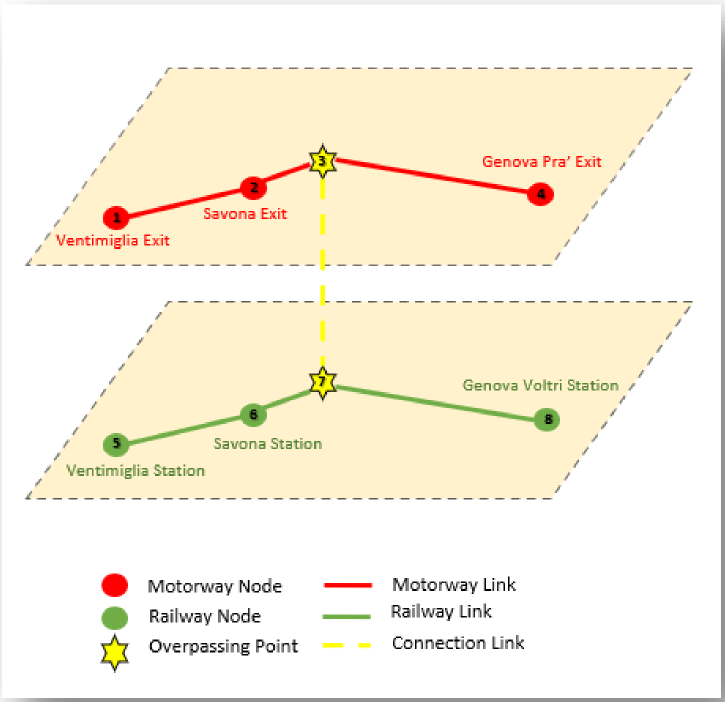

Figure 26. Example of multi-layer network creation using overpassing points

The resulting adjacency matrix is:

$$\Omega = \begin{bmatrix} 0 & m & 0 & 0 & 0 & 0 & 0 & 0 \\ m & 0 & m & 0 & 0 & 0 & 0 & 0 \\ 0 & m & 0 & m & 0 & 0 & m+r & 0 \\ 0 & 0 & m & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & r & 0 & 0 \\ 0 & 0 & 0 & 0 & r & 0 & r & 0 \\ 0 & 0 & m+r & 0 & 0 & r & 0 & r \\ 0 & 0 & 0 & 0 & 0 & 0 & r & 0 \end{bmatrix}$$

Since the connection link has a weight (namely distance) of 0, indicating perfect overlap, it is possible to consider a final interconnected graph as shown in Figure 27.

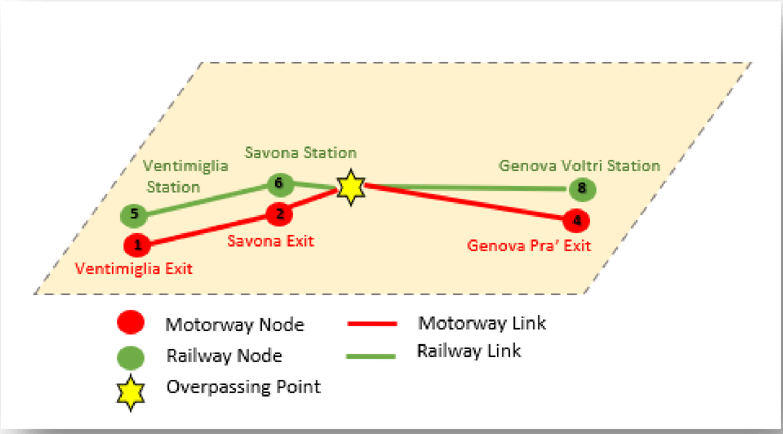

Figure 27. Example of resulting multi-layer network using overpassing points

Figure 28 shows how the two networks are joined using the overpassing points. The graph considered are:

- $Graph_m = (v_{m,} e_m)$, a symmetric graph, with $v_{m,} = 1, \ldots, 46$, and 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 each link, e_r, represents a fundamental railway connection, with $e_h = 1, \ldots, 76$.[44]

[44] Even in this section, for the sake of simplicity, the term "exit" is also used to indicate important motorway intersections, using the name of the nearest municipality to these intersections. While for railways a simplified network consisting of fundamental lines and most important nodes is considered. In some cases, urban junction lines are also considered to allow fundamental lines to be connected.

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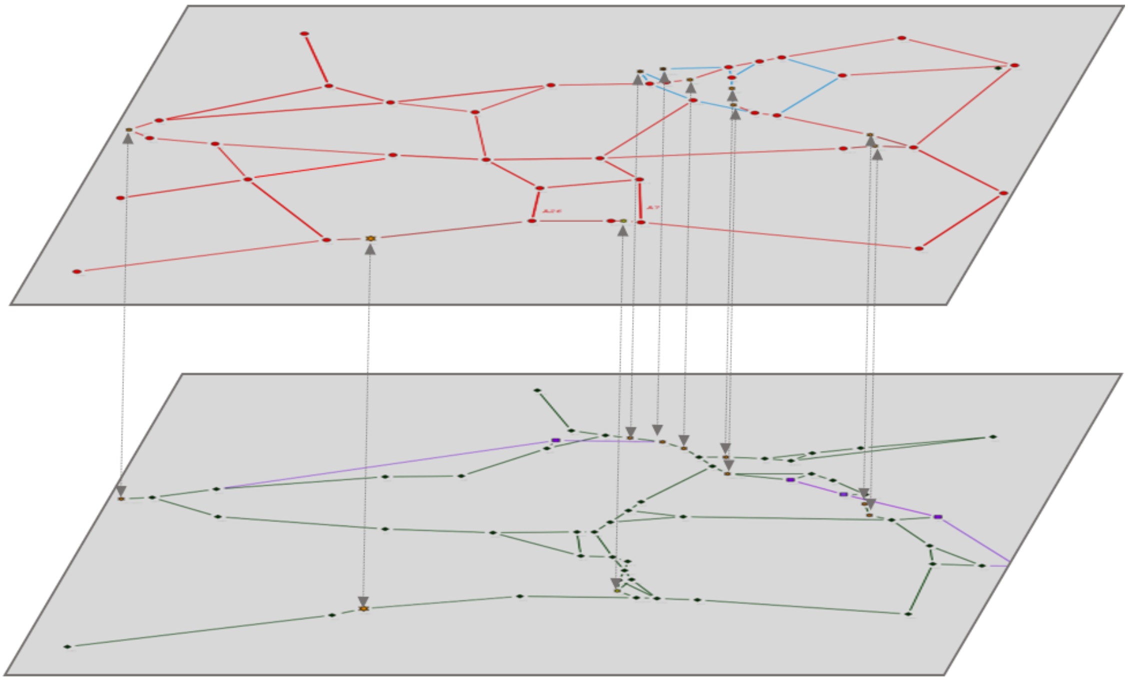

Figure 28. Multi-layer Network - Overpassing Points

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 overpassing point, with $v_{e,} = 1, \dots, 94$, and each link, e_z, represents a motorway or a railway connection, with $e_z = 1, \dots, 138$. Figure 29 shows a graphical representation of the graph where motorways link are colored in red, railway lines in green, and high-speed railways are in purple. Overpassing points are indicated with yellow stars.[45] Edges are weighted according to distance expressed in kilometres.

[45] The full list of nodes is provided in Annex C.

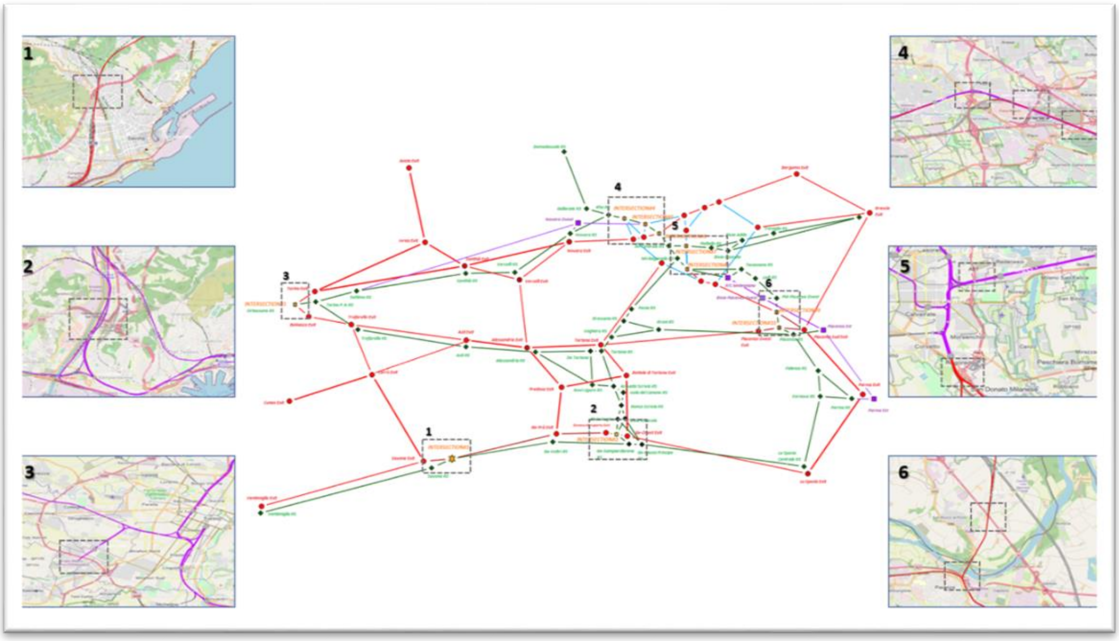

Figure 29. *Overpass Multi-Layer Network*

Using the multi-modal network in Figure 29 it is possible to assess the vulnerability of the network using two different metrics.

A first measure that quantify the vulnerability of a network is efficiency. Indeed, a drop in efficiency, associated to the removal of a node, is directly related to the vulnerability of the network.

Recalling that efficiency can be measured as follows:

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

and that the efficiency loss can be calculated in the following way:

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

First, the drop of efficiency by removing one node at a time is computed. Moreover, vulnerability can also be calculated by considering the largest connected component remaining after the removal. In general, if removing a few nodes significantly decreases the size of the largest connected component, then the network is considered vulnerable. In this analysis, we focus on how the size of the largest component changes by removing one overpassing node at a time, to observe which of these nodes is most likely to cause the vulnerability of the connected networks.

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Results from the vulnerability analysis are shown in Figures 30 and 31. In particular, Figure 30 reports the efficiency loss caused by each removed node.[46] As expected, the intersections are the points that generally make the network most vulnerable. For this reason, the second analysis focuses on these points.

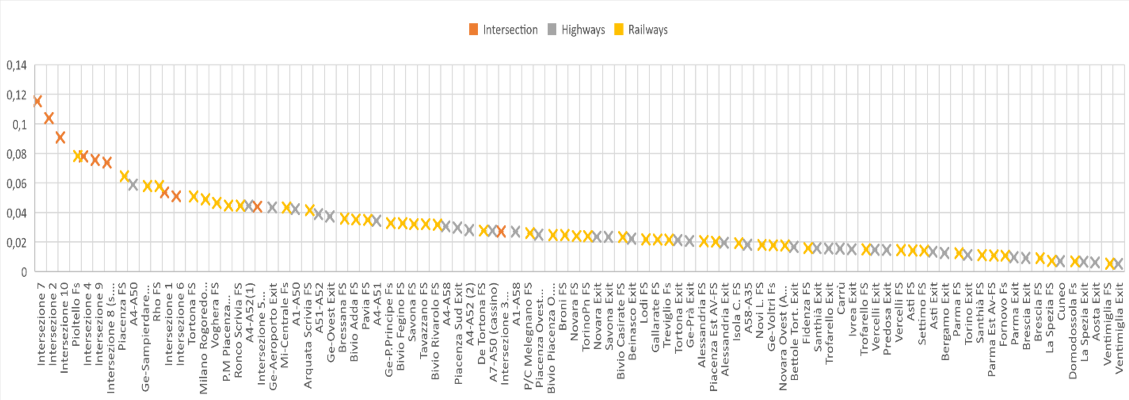

Figure 30. Efficiency loss – Overpassing points Removal

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. Figure 31 shows how the largest cluster changes each time a node corresponding to an overpassing point is removed. In all cases where a node other than *Intersection 1* or *7* is removed, the giant component contains 93 nodes, indicating that all nodes remain in the main cluster. As expected, as a consequence of removing a node, the number of links also changes. The size of the largest connected cluster has the most pronounced decrease when *Intersection 7* is removed, leading to a loss of about 6% of nodes and 7% of links. An in-depth analysis on this issue is presented in Annex F in which it is discussed the change in the structure of the network caused by the collapse of each overpassing point.

[46] Notice that also in this case the removal of some nodes leads to a part of the network no longer having any connection with the initial network. As already pointed out in Section 5.2.1, the efficiency loss associated to the removal of one of these nodes can be underestimated because in principle can be considered as 100%. Due to the large number of nodes in the network, we do not search here for all nodes with this characteristic, but below we propose an in-depth analysis of overpassing nodes.

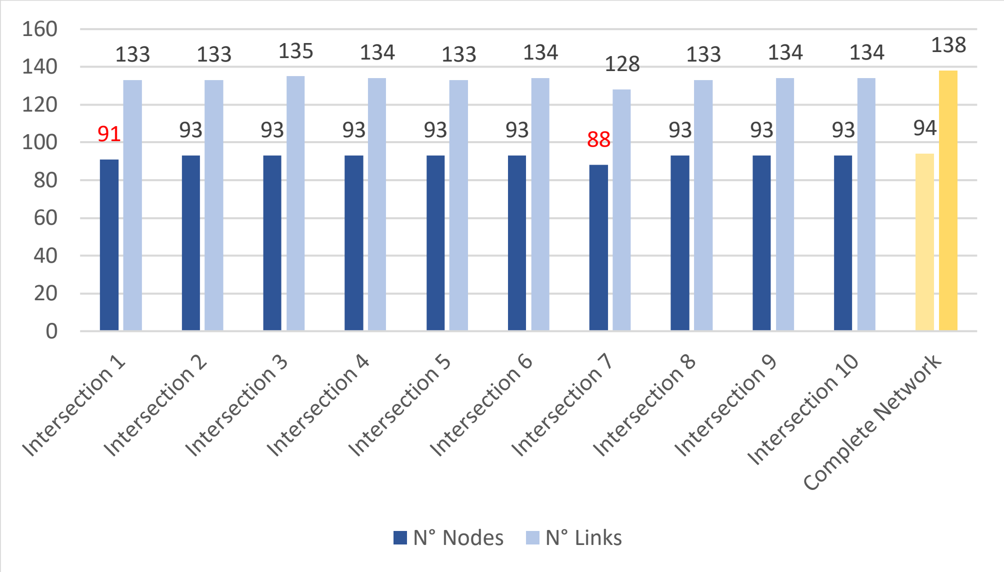

Figure 31. Variation in the size of the giant component after the removal of Overpassing Point

5.3.2. Multi-layer Network based on Artificial Points of Interchange

The second multi-layer network is built with the aim of studying the robustness of a multi-modal network compared to the respective single-modal networks. In the previous section, the collapse of a bridge has been simulated by removing the overpassing points, thus affecting the two types of infrastructure irrespective of those that generated the emergency event; whereas this section addresses the question on how the functionality of a network changes as the percentage of the removed node increases.

The literature recognises as a measure of the robustness of a network the size of the giant component during all possible "attacks" on the system (Schneider et al, 2011). Therefore, in this analysis both a “targeted attack” and a “random failure” of the network are simulated, calculating the size of the largest component after vertex or edge removal.

This analysis in based on a network in which in each main city the intermodal shift can take place and the motorway exit and the railway station are 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.

To make the railway stations and motorway exits intermodal, new and artificial infrastructures are inserted in the network, i.e. interchange points. In each of the aforementioned cities, nodes of the main motorway exit and the main railway station are connected to the corresponding interchange node. Figure 32 shows the three layers used to construct the multi-layer graph. The layers considered are:

- $Graph_m = (v_{m,} e_m)$, a symmetric graph, with $v_{m,} = 1, \dots ,39$, and each link, e_m, represents a highway connection or a ring road, with $e_m = 1, \dots , 55$

- $Graph_r = (v_r, e_r)$, a symmetric graph with $v_{h,} = 1, \dots, 50$, and each link, e_r, represents a fundamental railway connection, with $e_h = 1, \dots, 68$.[47]
- 20 artificial interchange points where the modal shift can take place.

The usual distance weight is applied. As far as the link between a motorway exit and an interchange station and between the latter to the corresponding railway station, weights consist in road distance.

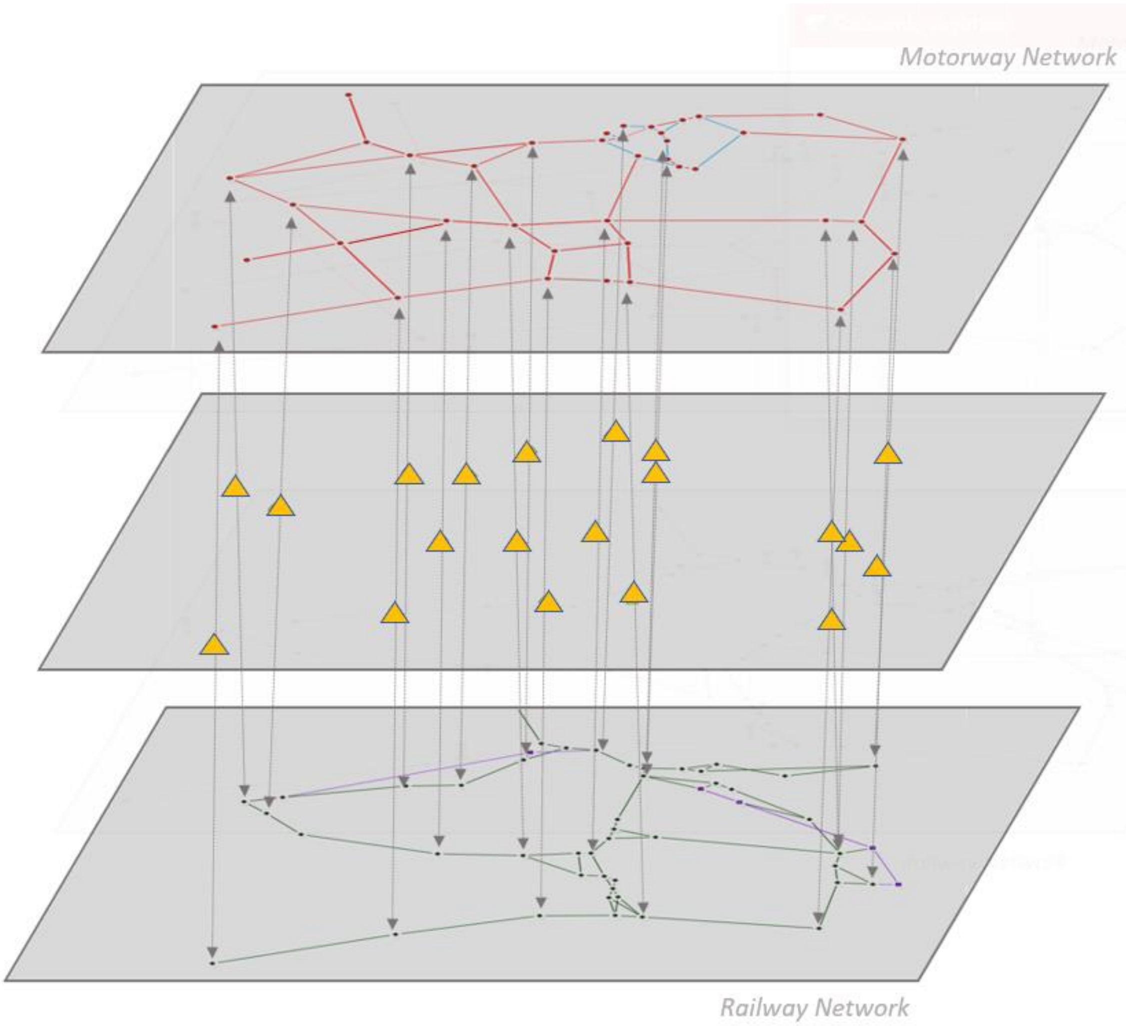

Figure 32. Multi-layer network using railways, motorways, and artificial interchange infrastructures

[47] Also in this section for the sake of simplicity the term "exit" is also used to indicate important motorway intersections, using the name of the nearest municipality to these intersections. While for railways a simplified network consisting of fundamental lines and most important nodes is considered. In some cases urban junction lines are also considered to allow fundamental lines to be connected.

This second multi-layer graph therefore considers a functional connection between the two transport networks rather than a geographical one. It could be argued that intermodal shift is not always possible or easy to realize and therefore the assumptions of the model are challenged. We are aware that this is a simplification that may in some cases depart from the real feasibility of a modal shift, but it is also necessary given the extent of the network we are considering. Moreover, because of the size of the network and the granularity of the analysis, the simple assumption that a modal shift can take place in the major cities, without going into more restrictive assumptions, is still realistic. In fact, considering as intermodal nodes only the major cities implies that no distinction should be made between different rail services for passengers.

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 $v_{e,} = 1, \dots, 109$, and each link,e_z, represents a motorway or a railway connection, with $e_z = 1, \dots, 163$. The number of nodes is the sum of motorway, railway, and interchange nodes. The number of edges is the sum of the motorway and railway links plus the (road) links connecting each artificial interchange station with the corresponding railway and motorway stations (2 edges for each interchange node, for a total of 40 links).[48]

Figure 33 shows a graphical representation of the multi-layer graph: motorways are the red lines, railways are the green one (high speed railways are in violet), interchange points are indicated with yellow triangles, and roads connecting the latter to the corresponding railway stations and motorway exits are grey.

[48] The full list of nodes is reported in Annex D

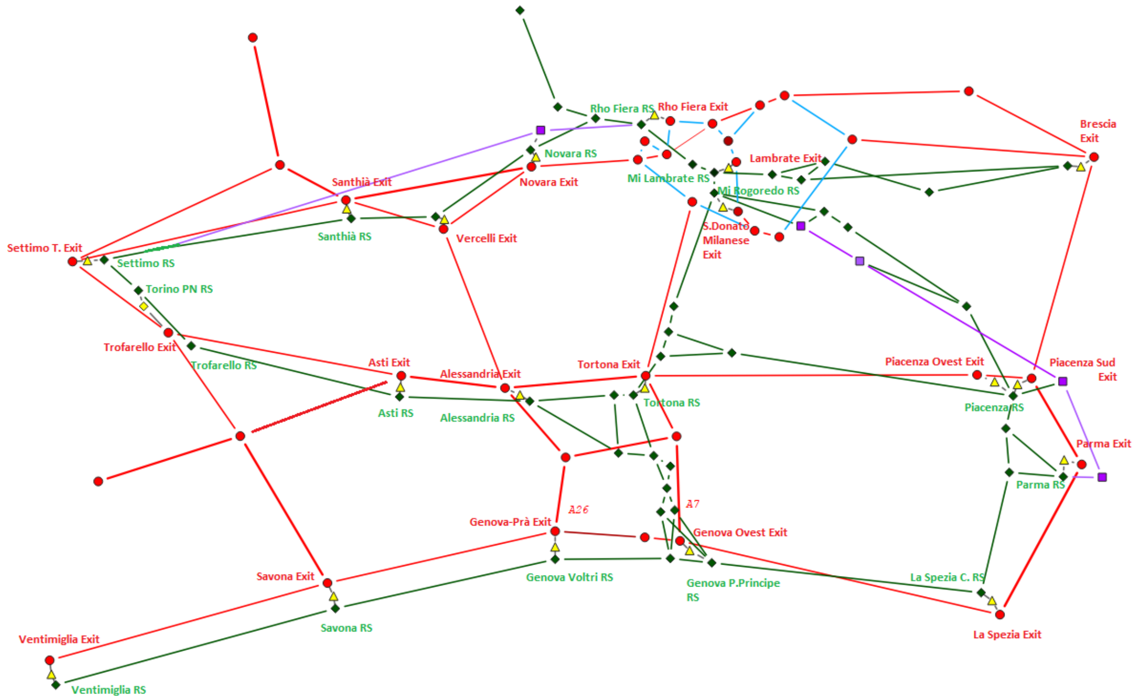

Figure 33. Multi-layer graph – Artificial interchange stations

Once the multi-layer graph is constructed, a vertex targeted attack 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 multi-layer network $Graph_z = (v_z,\ e_z)$. In 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. They are successively removed, and the maximal component size is calculated. Results are shown in Figure 34 and Figure 35, respectively, where the ratio of the remaining maximal component size to the initial maximal component size (*comp.pct*) is related to the ratio of vertices removed (*remved.pct*). The red line refers to the motorway network, the green line to the railway network and the blue line to the multimodal network. The dotted line corresponds to the limiting case of a fully connected network. Figure 34 and Figure 35 show the results using the degree of centrality and betweenness centrality, respectively, as criteria for ordering and then removing vertices. Evidence from the analysis is mixed.

In Figure 34, 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 Figure 35, the behaviour 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 shows greater robustness than the two unimodal networks when more than 10% of the nodes have been 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 until the share of nodes removals remains below a 10%.

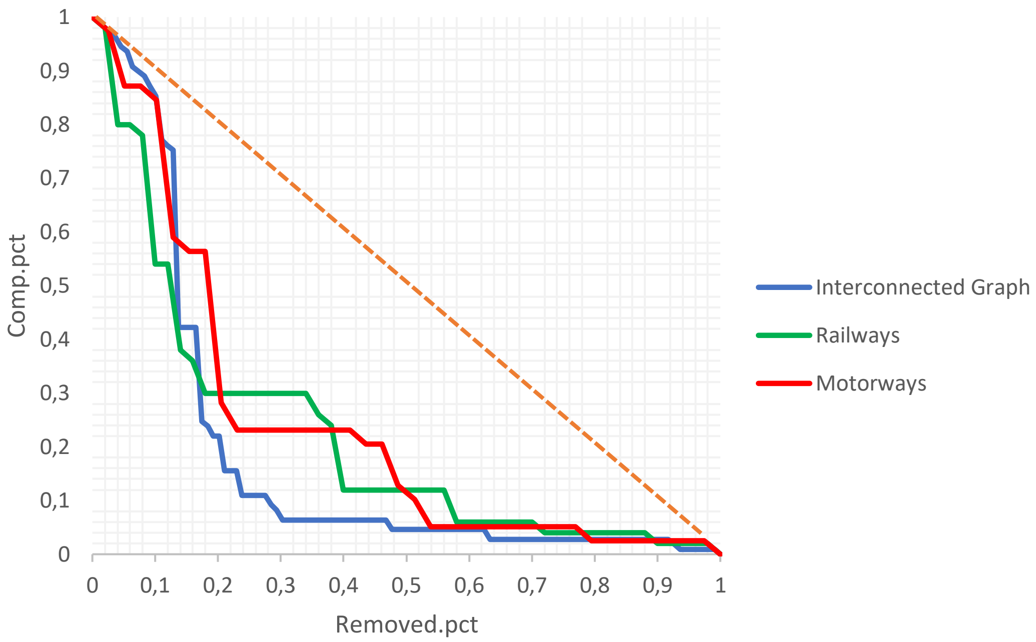

Figure 34. "Targeted" attack to vertices, by degree centrality. Comparison between motorway network, railway network, and multi-layer network with interchange stations.

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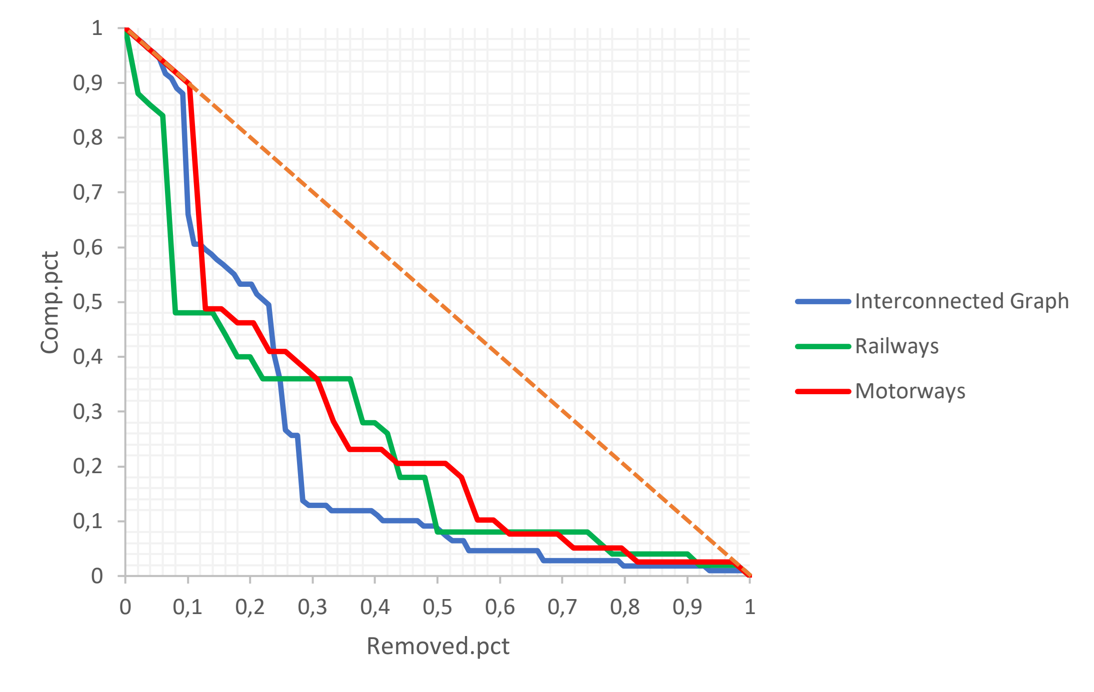

Figure 35. "Targeted" attack to vertices, by betweenness centrality. Comparison between motorway network, railway network, and multi-layer network with interchange stations.

The last analysis concerns the random removal of edges, independently of the measures of centrality of the nodes associated with them. In this random failure analysis, edge is randomly chosen and then removed, at each step calculating the maximum component size until all elements have been removed. The process is repeated for one thousand iterations. Results are shown in Figure 36. They highlight that the motorway infrastructure network seems more resilient than the railways one. In this case, the interconnected graph appears less vulnerable up to the loss of 40% of the edges, but afterwards it becomes less resilient than networks related to individual transport modes as the attacks progress.

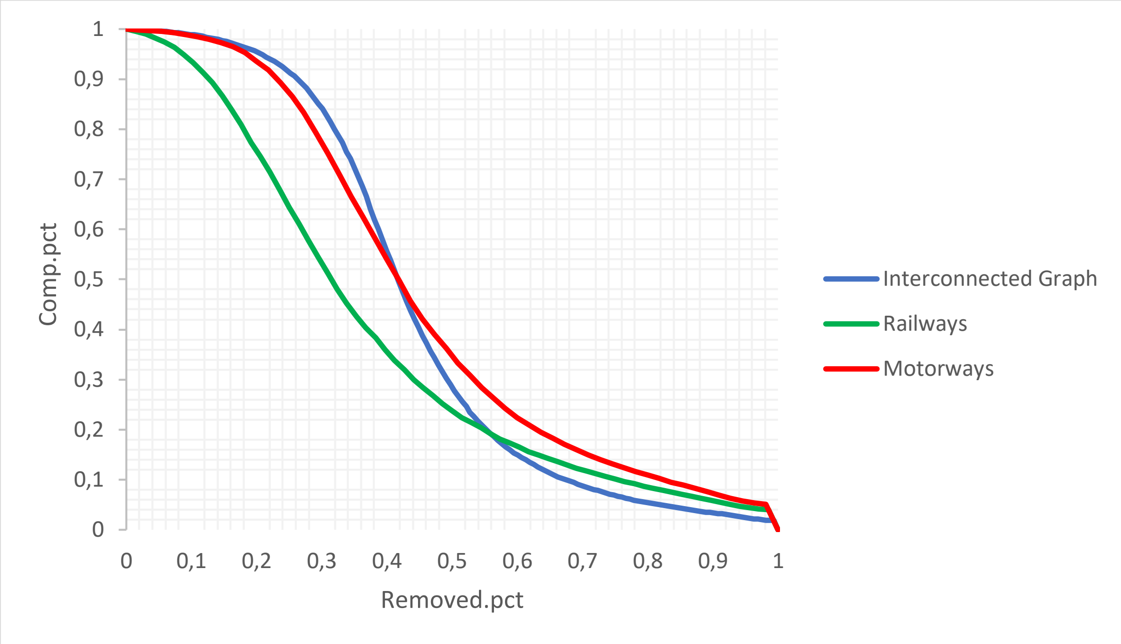

Figure 36. Random failure of edges. Comparison between motorway network, railway network, and multi-layer network with interchange stations.

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.
The resulting graph, $Graph_w = (v_w,\ e_w)$, is a bidirectional graph, in which each node, v_w, represents alternatively a motorway exit or a railway station, with $v_{w,} = 1, \dots, 89$, and each link, e_w, represents a motorway or a railway connection, with $e_z = 1, \dots, 143$. The number of nodes is the sum of motorway and railway nodes. The number of edges is the sum of the motorway and railway links plus the urban road links connecting each main railway and motorway stations (1 edges for each place where the modal shift is allowed, for a total of 20 links).

Considering the same motorway network, $Graph_m = (v_{m,}e_m)$ and railway network, $Graph_r = (v_{r,}e_r)$, as described above, together with and the multi-layer network $Graph_w = (v_w,\ e_w)$, the robustness analysis is replicated. In particular, we show results either for the “targeted” attack to vertex (Figures 37 and 38) and for the random failure of edges (Figure 39).

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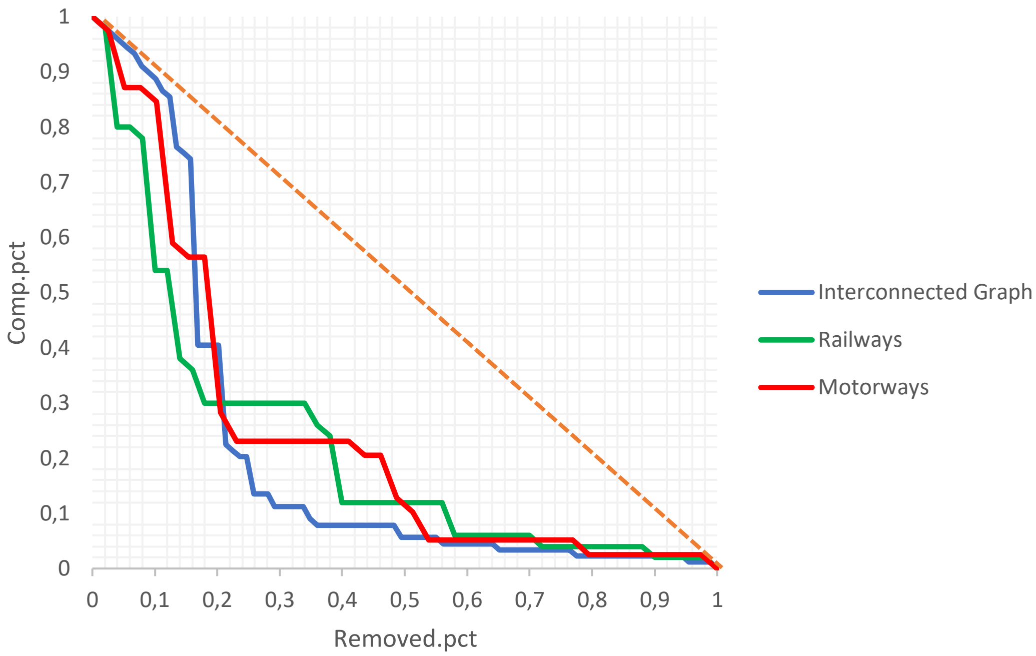

Figure 37. "Targeted" attack to vertices, by degree centrality. Comparison between motorway network, railway network, and multi-layer network without interchange stations.

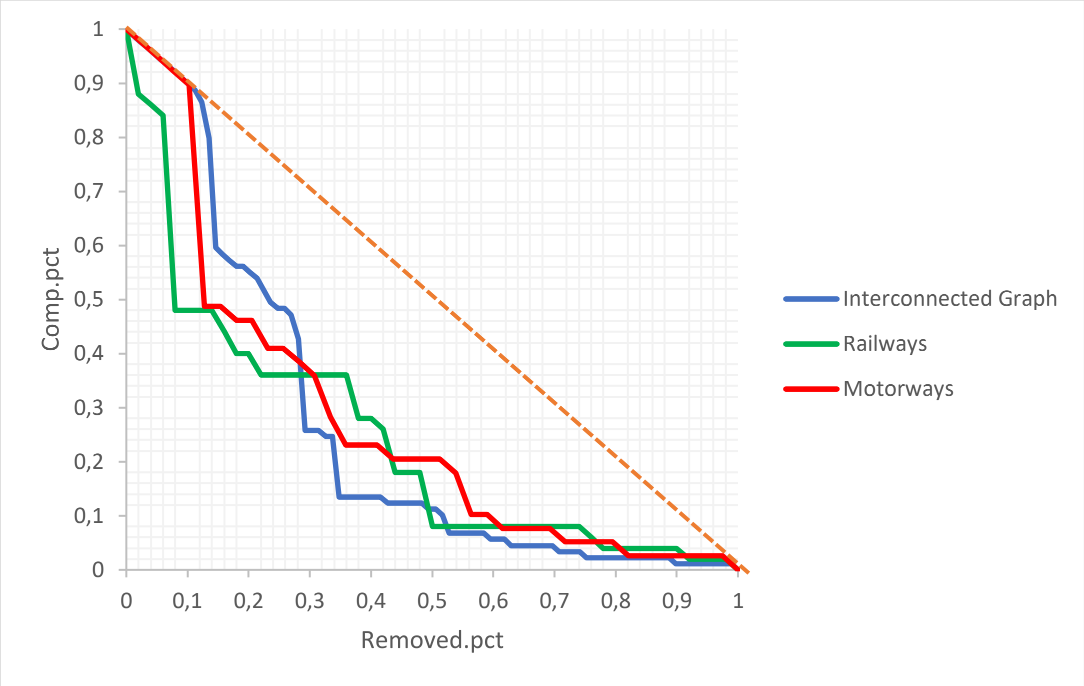

Figure 38. "Targeted" attack to vertices, by betweenness centrality. Comparison between motorway network, railway network, and multi-layer network without interchange stations.

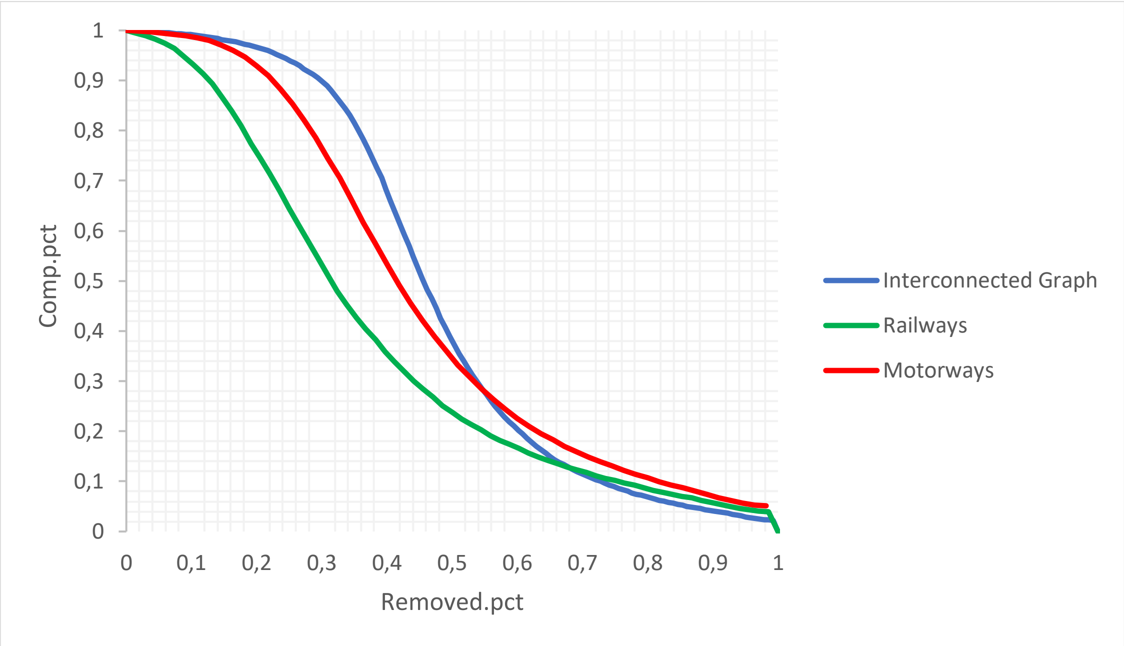

Figure 39. Random failure of edges. Comparison between motorway network, railway network, and multi-layer network with interchange stations.

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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 tend to consider more realistic the robustness results for a 3-layer network (railways, motorways, and interchange stations).

Overall, this robustness analysis leads to some interesting evaluations. First, the multi-modal network is more robust than the corresponding uni-modal networks until a 20% of the network is damaged. Indeed, assuming that passengers and cargoes may use different transport modes in performing their journeys, either combining different transport modes or changing their choices in accordance with the state of the transport services and infrastructure, means that any problem that occurs on one transport infrastructure also affects all the other infrastructures in the network (i.e. the "percolation effect"). Moreover, the multimodal network is more robust when the failure of edges is assessed until the number of edges is halved.
This result leads to an interesting consideration. 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.

To conclude, it is also important to note that adding or removing an intermodal station leads to a change in the robustness of the network: as interchange possibilities increase, we expect the intermodal network to become more robust. In this sense, an intermodal network with few interchanges is likely to be less robust than a unimodal network, and on the contrary, an intermodal network with more interchanges is likely to be more robust than a unimodal one.

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ANNEX A: List of Railway Nodes

ID	*Railway Node*	*ID*	*Railway Node*	*ID*	*Railway Node*	*ID*	*Railway Node*
1	1° Bivio Parma Est (AV/AC)	51	Campoligure M.	101	Loano	151	Rho
2	1°Biv Fidenza O.	52	Cantalupo	102	Lodi	152	Rho Dev.E.L.Av
3	2°B/Pp Fidenza O	53	Carmagnola	103	Mele	153	Rho Dev.E.L.No
4	2°Biv.Piacenza E	54	Casale Monferr.	104	Melegnano	154	Rivalta Scriv.
5	2°Biv/Pc Parma E	55	Casale Popolo	105	Melzo Scalo	155	Ronco Scrivia
6	Acqui Terme	56	Casalpusterlengo	106	Mi Bovisa P.	156	Rovato
7	Al Cavalcavia	57	Casteggio	107	Mi Lancetti	157	S. Zeno Folzano
8	Albairate-Verme.	58	Castelvetro	108	Mi Rog.Bin.Ester	158	S.Giuseppe Di C.
9	Albenga	59	Cava Carbonara	109	Mi. P. Vittoria	159	S.Nicolo
10	Alessandria	60	Cava Tigozzi	110	Mi. Smistamento	160	S.Stefano Magra
11	Andora	61	Cavallermaggiore	111	Mi.Greco Pirelli	161	Sannazzaro
12	Aosta	62	Ceva	112	Mi.P.Garibaldi	162	Santhia`
13	Arona	63	Chignolo Po	113	Mi.P.Genova	163	Sarmato
14	Arquata Scrivia	64	Chivasso	114	Mi.S.Cristoforo	164	Savona
15	Asti	65	Codogno	115	Mignanego	165	Savona P.Doria
16	Aulla Lunigiana	66	Cremona	116	Milano Centrale	166	Sesto Calende
17	B/Pc Scavalcam.	67	Cuneo	117	Milano Certosa	167	Sestri Levante
18	Berceto	68	D.E.Rog.L.Mi Pr	118	Milano Lambrate	168	Settimo
19	Biv. Cab. B	69	D.E.Rog.L.Trecca	119	Milano Rogoredo	169	Sp Marittima
20	Biv. Cast.Rosso	70	D.Estr.Monc.Sang	120	Monc. Sangone	170	Stradella
21	Biv. Crocetta	71	De Tortona	121	Montirone	171	Taggia Arma
22	Biv. Doria	72	Dev No Latomi	122	Mortara	172	Tavazzano
23	Biv. M. Olmo	73	Dev.Binar. Curva	123	Novara	173	To.Lingotto
24	Biv. Musocco	74	Dev.E Rho	124	Novara Boschetto	174	To.Sm.Nord
25	Biv. Polcevera	75	Dev.E.Lato Ge Pp	125	Novara Fn	175	Torino P. Susa
26	Biv. Rivarolo	76	Dev.Estr.Borzoli	126	Novi Ligure	176	Torino P.Nuova
27	Biv. Succursale	77	Domo Ii	127	Novi San Bovo	177	Torino Stura
28	Biv.Castelluccio	78	Domodossola	128	Oleggio	178	Torreberetti
29	Biv/Pc Mirabello	79	Fidenza	129	Olmeneta	179	Torrile S. Polo
30	Bivio Casirate	80	Finale Ligure M.	130	Ovada	180	Tortona
31	Bivio Lambro	81	Fornovo	131	P.M. Bivio Adda	181	Tosturaorig.AV
32	Bivio Novara O.	82	Fossano	132	P.M. Ghisolfa	182	Tr. B./Pc Seveso
33	Bivio Piacenza O	83	Gallarate	133	P.M. Piacenza O.	183	Trecate
34	Bivio Settimotse	84	Ge Sestri P. Aer	134	P.M. Trecca	184	Treviglio
35	Bivio/P.C.Fegino	85	Ge.Samp.Smist.	135	P.P. Chiesaccia	185	Trino Verc.
36	Bivio/Pc Meleg.	86	Ge.Sampierdarena	136	Parma	186	Trofarello
37	Bivio/Pc Sesia	87	Genova Borzoli	137	Pavia	187	Valenza
38	Bivio/Pc Toce	88	Genova Brignole	138	Piacenza	188	Ventimiglia
39	Bivio/Pc Valle	89	Genova Campasso	139	Piadena	189	Vercelli
40	Bordighera	90	Genova Marittima	140	Pioltello Lim.	190	Vezzano Ligure
41	Borgo Val Taro	91	Genova Nervi	141	Pontremoli	191	Vignale
42	Borgomanero	92	Genova P.Princ.	142	Posto Pss. Corvi	192	Villadossola
43	Breil Sur Roya	93	Genova Rivarolo	143	Pozzolo Formig.	193	Villastellone
44	Brescia	94	Genova Voltri	144	Pp Osteriazza	194	Vittuone Arluno
45	Brescia Est	95	Gr.Sc.Ge.Voltri	145	Premosello Ch.	195	Voghera
46	Bressana Bott.	96	Ivrea	146	Q.Vio Torbella	196	Castelguelfo
47	Broni	97	La Spezia C.	147	Quadr./Pc Turro		
48	Bs Est F. Merci	98	La Spezia Migl.	148	Quadriv. Zappata		
49	Busalla	99	Levanto	149	Racconigi		
50	Busto Arsizio	100	Limone	150	Recco		

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ANNEX B: Betweenness and Closeness Centrality Railway Network

Table B.1: Closeness Centrality, Weighted (Left Panel) and Unweighted (Right Panel) for Railway Network.

Rank	Railway Node	*Clsoeness Centrality Weighted*	Rank	Railway Node	*Closeness Centrality Not Weighted*
1	Tortona	0,010363	1	Pavia	0,000741
2	De Tortona	0,010302	2	Cava Carbonara	0,000728
3	Bressana Bott.	0,010257	3	Bressana Bott.	0,000726
4	Voghera	0,010248	4	Mortara	0,000725
5	Pavia	0,010246	5	Voghera	0,000713
6	Alessandria	0,010056	6	Torreberetti	0,000710
7	Al Cavalcavia	0,010028	7	Tortona	0,000708
8	Torreberetti	0,010017	8	Valenza	0,000703
9	Valenza	0,010014	9	De Tortona	0,000698
10	Rivalta Scriv.	0,010008	10	Milano Rogoredo	0,000697
187	Domodossola	0,005416	187	Levanto	0,000355
188	Andora	0,005261	188	Breil Sur Roya	0,000355
189	Biv. M. Olmo	0,005213	189	Aulla Lunigiana	0,000349
190	Cuneo	0,005130	190	S. Stefano Magra	0,000343
191	Taggia Arma	0,004676	191	La Spezia C.	0,000342
192	Limone	0,004521	192	Vezzano Ligure	0,000339
193	Bordighera	0,004420	193	Bordighera	0,000338
194	Ventimiglia	0,004357	194	La Spezia Migl.	0,000337
196	Aosta	0,004292	196	Ventimiglia	0,000337
196	Breil Sur Roya	0,004155	196	Sp Marittima	0,000316

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Table B.2: Betweenness Centrality, Weighted (Left Panel) and Unweighted (Right Panel) for Railway Network

Rank	Railway Node	Betweenness Centrality Weighted
1	Arquata Scrivia	5236,00
2	B/Pc Scavalcam.	5156,00
3	Ronco Scrivia	5077,00
4	Milano Rogoredo	4968,00
5	Mignanego	4388,75
6	Bivio/P.C.Fegino	4310,75
7	Tortona	4291,00
8	Voghera	4290,00
9	Alessandria	4004,00
10	Pavia	3701,00
	2°B/Pp Fidenza O	0
	Aosta	0
	Biv. Doria	0
	Biv. Succursale	0
	Bivio/Pc Toce	0
	Brescia	0
	D.E.Rog.L.MI PR	0
	D.E.Rog.L.Trecca	0
	Dev.E.Lato GE PP	0
	Genova Marittima	0
	Mi.Greco Pirelli	0
	Mi.P.Genova	0
	Milano Centrale	0
	Monc. Sangone	0
	Novara FN	0
	P.M. Piacenza O.	0
	Posto Pss. Corvi	0
	Sp Marittima	0
	Torino P.Nuova	0
	Villadossola	0

Rank	Railway Node	Betweenness Centrality Not Weighted
1	Pavia	6924,712235
2	Alessandria	5931,27242
3	Milano Rogoredo	4884,118988
4	Tortona	4814,54065
5	MORTARA	4595,762558
6	Valenza	3837,917092
7	Voghera	3734,733835
8	Bressana Bott.	3656,457552
9	Cava Carbonara	3611,048856
10	Arquata Scrivia	3568,519158
	Novi San Bovo	0
	2°B/Pp Fidenza O	0
	AOSTA	0
	Biv. Doria	0
	Biv. Succursale	0
	Bivio/Pc Toce	0
	BRESCIA	0
	D.E.Rog.L.MI PR	0
	D.E.Rog.L.Trecca	0
	Genova Marittima	0
	Mi.P.Genova	0
	Monc. Sangone	0
	Novara Fn	0
	P.M. Piacenza O.	0
	Posto Pss. Corvi	0
	Sp Marittima	0

ANNEX C: List of Nodes in Multi-layer Network with overpassing points

ID	*Node*	*Type*
1	Savona Exit	Highway
2	Ge-Prà Exit	Highway
3	Ge-Ovest Exit	Highway
4	La Spezia Exit	Highway
5	Predosa Exit	Highway
6	Alessandria Exit	Highway
7	Tortona Exit	Highway
8	Bettole Tort. Exit	Highway
9	Piacenza Sud Exit	Highway
10	Parma Exit	Highway
11	Novara Exit	Highway
12	Asti Exit	Highway
13	Santhià Exit	Highway
14	Ivrea Exit	Highway
15	Aosta Exit	Highway
16	Torino Exit	Highway
17	Carrù	Highway
18	Cuneo	Highway
19	Ventimiglia FS	Railway
20	Savona FS	Railway
21	Intersezione 1	Intersection
22	Ge-Voltri Fs	Railway
23	Ge-Aeroporto Exit	Highway
24	Ge-Sampierdarena FS	Railway
25	La Spezia FS	Railway
26	Fornovo Fs	Railway
27	Parma FS	Railway
28	Piacenza Ovest Exit	Highway
29	P.M Piacenza Ovest Fs	Railway
30	Intersezione 9	Intersection
31	Intersezione 10	Intersection
32	Piacenza FS	Railway
33	Lodi FS	Railway

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34	Tavazzano FS	Railway
35	Intersezione 8 (s. Donato)	Intersection
36	Milano Rogoredo FS	Railway
37	Brescia FS	Railway
38	Mi-Centrale Fs	Railway
39	Intersezione 7	Intersection
40	Pioltello Fs	Railway
41	Bivio Casirate FS	Railway
42	Bivio Adda FS	Railway
43	Treviglio Fs	Railway
44	Bergamo Exit	Highway
45	Rho FS	Railway
46	Gallarate FS	Railway
47	Domodossola Fs	Railway
48	Novara FS	Railway
49	Vercelli FS	Railway
50	Ventimiglia Exit	Highway
51	Santhià FS	Railway
52	Settimo FS	Railway
53	Trofarello Exit	Highway
54	Beinasco Exit	Highway
55	Intersezione 3 (orbassano fs)	Intersection
56	TorinoPn FS	Railway
58	Ronco Scrivia FS	Railway
59	Isola C. FS	Railway
60	Arquata Scrivia FS	Railway
61	Tortona FS	Railway
62	Novi L. FS	Railway
63	De Tortona FS	Railway
64	Alessandria FS	Railway
65	Asti FS	Railway
66	Trofarello FS	Railway
67	Pavia FS	Railway
68	Voghera FS	Railway
69	Bressana FS	Railway
70	Broni FS	Railway
71	A7-A50 (cassino)	Highway
72	Intersezione 6	Intersection
73	A4-A52 (2)	Highway

74	Intersezione 5 (Rho Fiera)	Intersection
75	Intersezione 4	Intersection
76	Fidenza FS	Railway
77	Brescia Exit	Highway
78	A4-A51	Highway
79	A51-A52	Highway
80	A58-A35	Highway
81	Parma Est Av-FS	Railway
82	Piacenza Est AV-FS	Railway
83	Bivio Piacenza O. Av FS	Railway
84	P/C Melegnano FS	Railway
85	Novara Ovest (AV FS)	Railway
86	A1-A50	Highway
87	A1-A58	Highway
88	A4-A52(1)	Highway
89	A4-A50	Highway
90	A4-A58	Highway
91	Ge-P.Principe Fs	Railway
92	Bivio Fegino FS	Railway
93	Bivio Rivarolo FS	Railway
94	Intersezione 2	Intersection
95	Vercelli Exit	Highway

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ANNEX D: List of Nodes in Multi-layer Network with Artificial Interchange Points

ID	*Node*	*Type*
1	A1-A50	Highway
2	A1-A58	Highway
3	A4-A50	Highway
4	A4-A51	Highway
5	A4-A52 (2)	Highway
6	A4-A52(1)	Highway
7	A4-A58	Highway
8	A51_8	Highway
9	A51-A52	Highway
10	A58-A35	Highway
11	A7-A50 (cassino)	Highway
12	Alessandria Exit	Highway
13	Alessandria Artificial	Artificial Interchange
14	Alessandria Fs	Railway
15	Aosta Exit	Highway
16	Arquata Scrivia FS	Railway
17	Asti Exit	Highway
18	Asti Artificial	Artificial Interchange
19	Asti FS	Railway
20	Bergamo Exit	Highway
21	Bettole Tort. Exit	Highway
22	Bivio Adda FS	Railway
23	Bivio Casirate FS	Railway
24	Bivio Fegino FS	Railway
25	Bivio Piacenza O. Av FS	Railway
26	Bivio Rivarolo FS	Railway
27	Brescia Exit	Highway
28	Brescia Artificial	Artificial Interchange
29	Brescia Fs	Railway
30	Bressana FS	Railway
31	Broni FS	Railway
32	Carrù Exit	Highway
33	Cuneo Exit	Highway
34	De Tortona FS	Railway

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35	Domodossola Fs	Railway
36	Fidenza FS	Railway
37	Fornovo Fs	Railway
38	Gallarate FS	Railway
39	Ge-Aeroporto Exit	Highway
40	Genova Artificial	Artificial Interchange
41	Genova P.Principe FS	Railway
42	Genova-Ovest Exit	Highway
43	Ge-Prà Exit	Highway
44	Ge-Sampierdarena FS	Railway
45	Ge-Voltri Fs	Railway
46	Isola C. FS	Railway
47	Ivrea Exit	Highway
48	La Spezia Exit	Highway
49	La Spezia Artificial	Artificial Interchange
50	La Spezia FS	Railway
51	Lodi FS	Railway
52	Mi-Centrale Fs	Railway
53	Mi-Lambrate Fs	Railway
54	Milano Lambrate Artificial	Artificial Interchange
55	Milano Rogoredo Artificial	Artificial Interchange
56	Milano Rogoredo FS	Railway
57	Novara Exit	Highway
58	Novara Artificial	Artificial Interchange
59	Novara FS	Railway
60	Novara Ovest (AV FS)	Railway
61	Novi L. FS	Railway
62	P.M Piacenza Ovest Fs	Railway
63	P/C Melegnano FS	Railway
64	Pantanedo Exit	Highway
65	Parma Est Av-FS	Railway
66	Parma Exit	Highway
67	Parma Artificial	Artificial Interchange
68	Parma FS	Railway
69	Pavia FS	Railway
70	Piacenza Est AV-FS	Railway
71	Piacenza FS	Railway
72	Piacenza O Artificial	Artificial Interchange
73	Piacenza Ovest Exit	Highway

74	Piacenza S Artificial	Artificial Interchange
75	Piacenza Sud Exit	Highway
76	Pioltello Fs	Railway
77	Predosa Exit	Highway
78	Rho Fiera Exit	Highway
79	Rho Fiera FS	Railway
80	Rho FS	Railway
81	Ronco Scrivia FS	Railway
82	S. Donato Exit	Highway
83	Santhià Exit	Highway
84	Santhià Artificial	Artificial Interchange
85	Santhià FS	Railway
86	Savona Exit	Highway
87	Savona Artificial	Artificial Interchange
88	Savona FS	Railway
89	Settimo Artificial	Artificial Interchange
90	Settimo FS	Railway
91	Settimo Torinese Exit	Highway
92	Tavazzano FS	Railway
93	Torino Artificial	Artificial Interchange
94	TorinoPn FS	Railway
95	Tortona Exit	Highway
96	Tortona Artificial	Artificial Interchange
97	Tortona FS	Railway
98	Treviglio Fs	Railway
99	Trofarello Exit	Highway
100	Trofarello FS	Railway
101	Ventimiglia Exit	Highway
102	Ventimiglia Artificial	Artificial Interchange
103	Ventimiglia FS	Railway
104	Vercelli Exit	Highway
105	Vercelli Artificial	Artificial Interchange
106	Vercelli FS	Railway
107	Voghera FS	Railway
108	Voltri Artificial	Artificial Interchange
109	Rho Fiera Artificial	Artificial Interchange

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ANNEX E: Focus on Heavy Traffic on the Ligurian Motorways Network

The map in Figure E.1 shows the motorway network that crosses Liguria longitudinally. Data made available by the “Autostrada dei Fiori” concessionaire on heavy goods traffic coming from the French border and exiting at one of the Ligurian toll stations (referring to the same week in June) show that in 2019 - i.e. after the fall of the Morandi bridge - heavy goods vehicles directed to Genoa or to the other toll stations on the eastern Ligurian Riviera preferred to leave the motorway network rather than take the recommended route involving a diversion of more than 100 km.

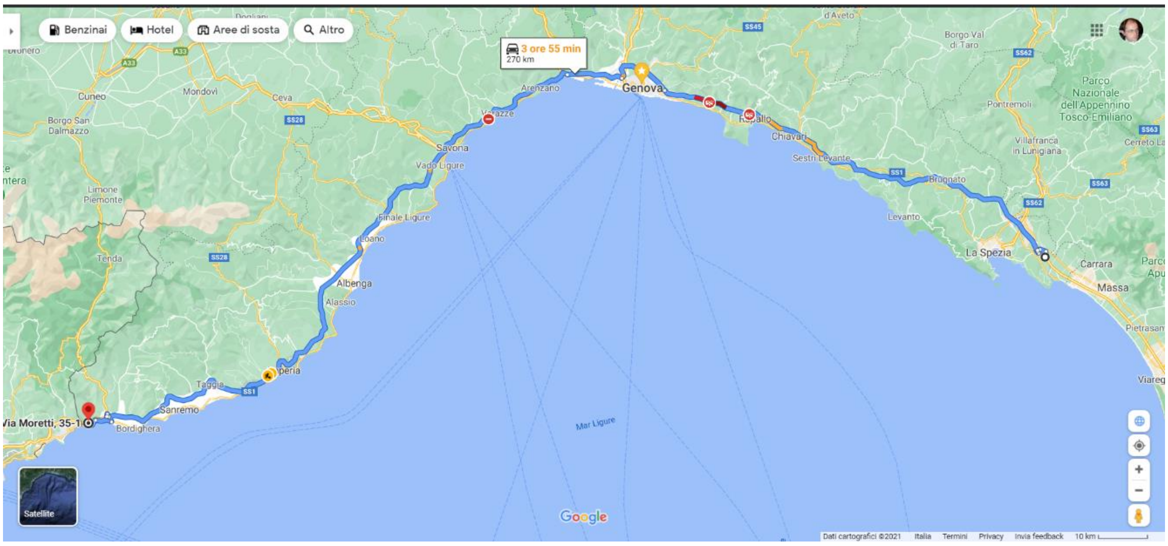

Figure E.1: The motorway network that crosses Liguria longitudinally.

In fact, the graph in Figure E.2 shows that in 2019 the weekly number of heavy vehicles coming from the French border and leaving the motorway to the east of the airport - i.e. over the collapsed bridge – drops to almost zero in comparison to the figures recorded in the same week of 2018.

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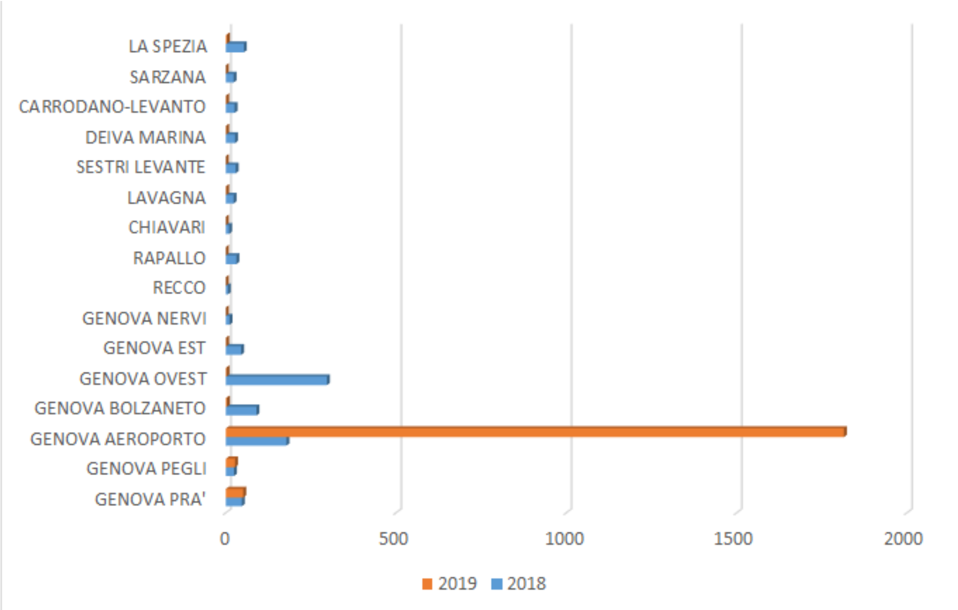

Figure E.2: Heavy traffic from the French border directed to Liguria.

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ANNEX F: Focus on Changes in Giant Component (Figure 31 in Main Text)

In this section, we propose an in-depth analysis of the changes in the giant component due to the fall of one of the overpassing points (see Figure 31 in main text).

By removing intersection 1, as shown in Figure F.1, there is no longer a direct connection between Genova Prà and Savona exits, and between Voltri and Savona railway stations. Moreover, whereas the Savona exit and, consequently, Ventimiglia exit remain connected to the network (via the direct link between the former and the Carrù exit), Savona and Ventimiglia railway nodes remain isolated, forming a new cluster, separated from the giant component.

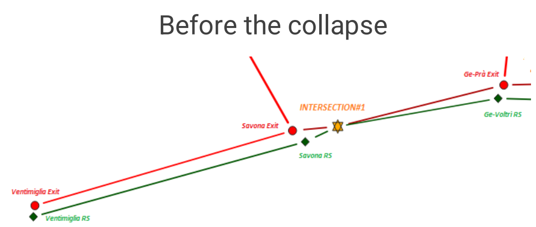

Figure F.1: Effect of Removing Intersection 1.

When intersection 2 is removed (Figure F.2), the motorway link between Genova Aeroporto and Genova Ovest, i.e. the Morandi bridge, ceases to exist. As regards the railway network, the Sampierdarena station no longer has a direct connection with Bivio Fegino and Bivio Rivarolo. Despite this, all nodes continue to be part of the giant component.

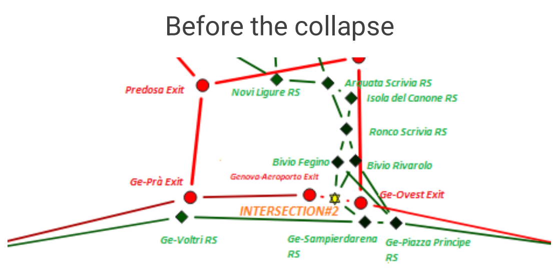

Figure F.2: Effect of Removing Intersection 2.

The collapse of intersection 3 causes the link between Torino and Beinasco exits to fall. In addition, since intersection 3 coincides with the Orbassano railway node, the latter is no longer connected to Torino Porta Nuova station (Figure F.3).

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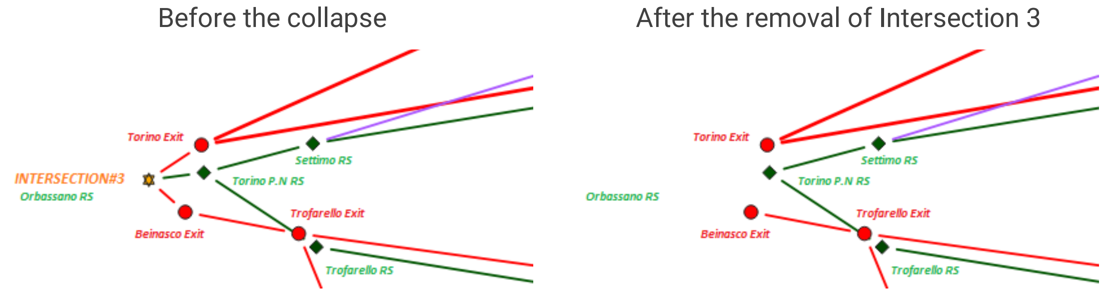

Figure F.3: Effect of Removing Intersection 3.

The drop of intersection 4 (Figure F.4) leads to the collapse of some links on the Milan ring road and a rail link from Rho Fiera towards the centre of Milan, and vice versa.

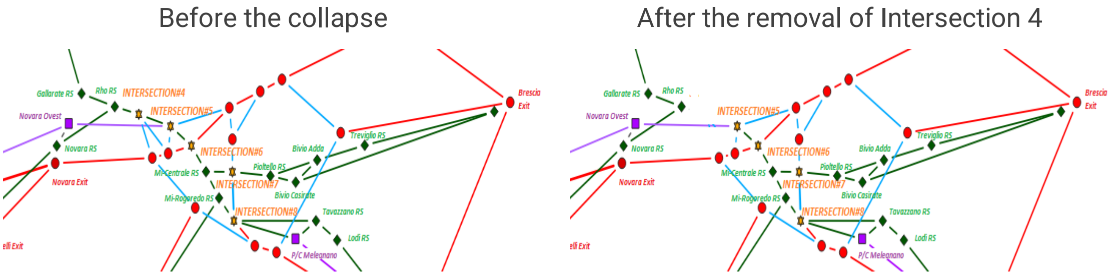

Figure F.4: Effect of Removing Intersection 4.

When intersection 5 is removed as in Figure F.5, the Milano ring road is again affected and also the railway line connecting the centre of Milan to Rho. In addition, the high-speed railway line may also be affected in the direction of Novara Ovest.

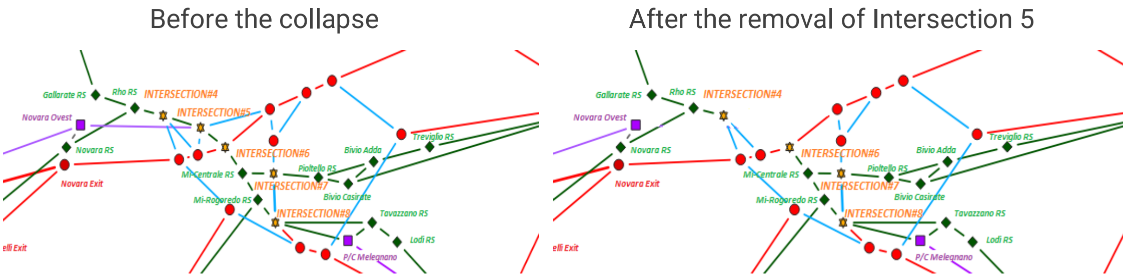

Figure F.5: Effect of Removing Intersection 5.

Intersection 6 removal (Figure F.6) compromises a section of the A4 motorway and again the railway line connecting Milano Centrale and Rho.

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Before the collapse | After the removal of Intersection 6

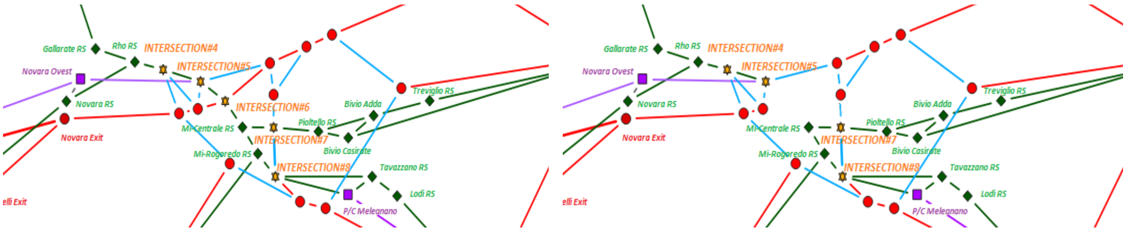

Figure F.6: Effect of Removing Intersection 6.

When intersection 7 is removed, the Milan ring road is again compromised, but more importantly, the Pioltello railway station is no longer connected to the Milano Centrale station. This results in a new unconnected cluster of the railway network comprising 5 nodes, including Brescia station, as shown in Figure F.7.

Before the collapse | After the removal of Intersection 7

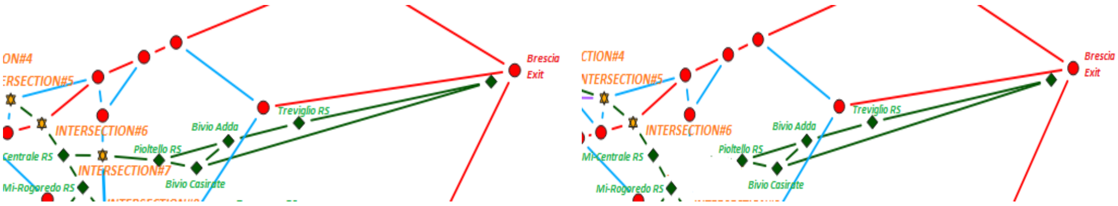

Figure F.7: Effect of Removing Intersection 7.

The collapse of intersection 8 (Figure F.8) compromises the final section of the A1 motorway and also a section of the Milano ring road. The railway is also damaged as the network is interrupted in the segment between Milano Rogoredo and Tavazzano station and between the former and approximately the PC/Melegnano node (high-speed network is then also involved).

Before the collapse | After the removal of Intersection 8

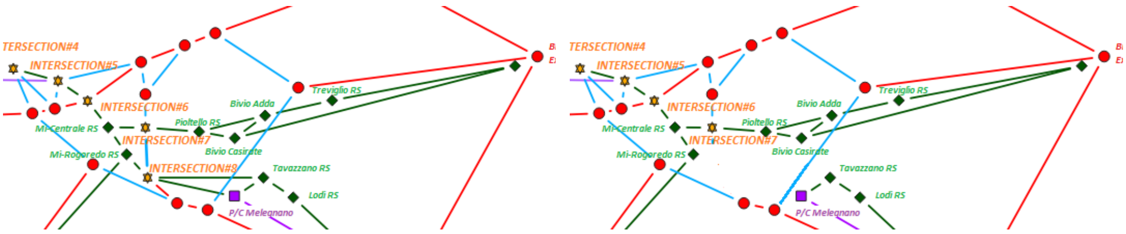

Figure F.8 Effect of Removing Intersection 8.

The collapse of intersection 9 implies the interruption of a section of the A1 motorway between Piacenza Sud and Milano, as well as a railway segment between Piacenza and Lodi (Figure F.9).

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Figure F.9 Effect of Removing Intersection 9.

Finally, Figure F.10 shows that the motorway section of the A21 between the Piacenza Ovest and Piacenza Est exits will be interrupted if intersection 10 falls, as will the railway line connecting Piacenza to Lodi (and vice versa).

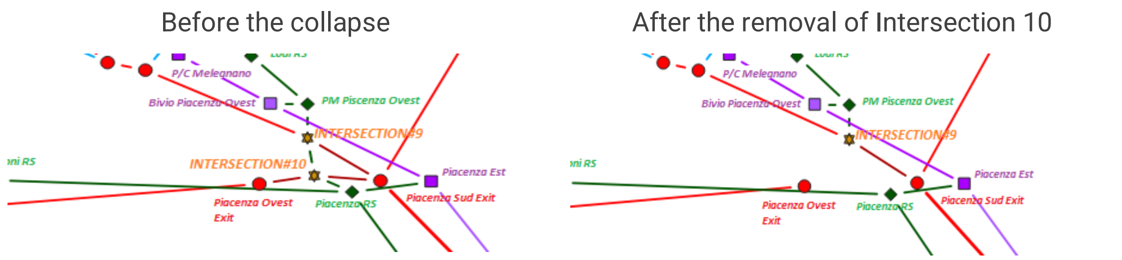

Figure F.10 Effect of Removing Intersection 10.

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ANNEX G: Focus on changes in Shortest Paths After Simulating a Damage in the Network

In this section we propose an in-depth analysis of the minimum path matrices. Specifically, we look at what happens to the minimum paths between each possible pair of nodes in the given network when one of the nodes is eliminated.
Let's take the following example in Figure G.1 where a weighted graph Z with 5 nodes and 7 links is considered. The weights assigned to each link correspond to Euclidean distance.

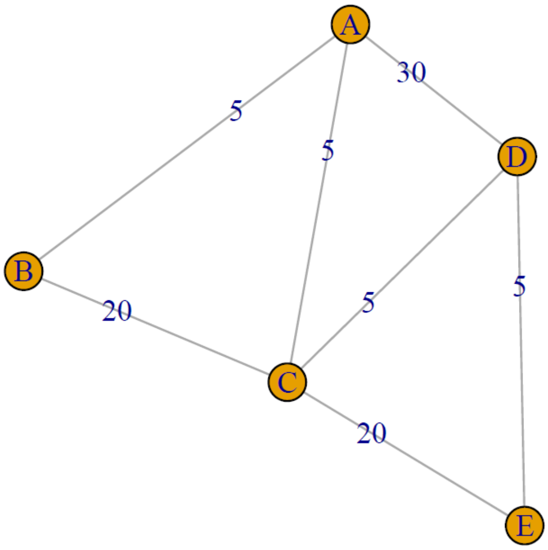

Figure G.1: Example of a weighted network with 5 nodes and 7 links.

The shortest path matrix is shown in Table G.1.

Table G.1: Shortest Path Matrix of Graph Z

	A	B	C	D	E
A	0	5	5	10	15
B	5	0	10	15	20
C	5	10	0	5	10
D	10	15	5	0	5
E	15	20	10	5	0

Simulating the fall of one node at a time and recalculating the matrix of minimum paths at each step, we obtain the results reported in Tables from G.2 to G.6. For computational reasons that will be made clear below, we add a column and a row of 0 at the removed node.

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Table 1: Scenario 1 - node A is removed.

	A	B	C	D	E
A	0	0	0	0	0
B	0	0	20	25	30
C	0	20	0	5	10
D	0	25	5	0	5
E	0	30	10	5	0

Table G.3: Scenario 2 - node B is removed.

	A	B	C	D	E
A	0	0	5	10	15
B	0	0	0	0	0
C	5	0	0	5	10
D	10	0	5	0	5
E	15	0	10	5	0

Table G.4: Scenario 3 - node C is removed.

	A	B	C	D	E
A	0	5	0	30	35
B	5	0	0	35	40
C	0	0	0	0	0
D	30	35	0	0	5
E	35	40	0	5	0

Table G.5: Scenario 4 - node D is removed.

	A	B	C	D	E
A	0	5	5	0	25
B	5	0	10	0	30
C	5	10	0	0	20
D	0	0	0	0	0
E	25	30	20	0	0

Table G.6: Scenario 5: - node E is removed.

	A	B	C	D	E
A	0	5	5	10	0

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B	5	0	10	15	0
C	5	10	0	5	0
D	10	15	5	0	0
E	0	0	0	0	0

We then calculate the average minimum distance between each pair of nodes in the 5 possible scenarios and thus the average percentage deviation from the initial values. On average, when a node in the network falls, the minimum paths vary in the percentage expressed in Table G.7.

Table G.7: Average variation (%) in minimum paths after a damage to the network occurs.

	A	**B**	**C**	**D**	**E**
A	0,0				
B	0,0	0,0			
C	0,0	33,3	0,0		
D	66,7	66,7	0,0	0,0	
E	66,7	66,7	33,3	0,0	0,0

We perform this analysis both for motorways and railways. In particular, for motorways, we rely on $Graph_m = (v_{m,} e_m)$ as described in Section 5.1.2. As already mentioned, it is a symmetric graph, with $v_{m,} = 1, \dots, 26$, and each link, e_m, represents a highway connection, with $e_m = 1, \dots, 36$. Results from this analysis are presented in Figure G.2.
As in the example shown in Table G.7, also in this case the values in each cell represent the average increase in the minimum path between each pair of nodes following the dropping of a node in the network. The gradation of colour, from yellow to red, reflects the smaller or larger variation. The motorway sections most sensitive to variation are those between Genova Ovest and Genova Pra', Genova Ovest and Savona, Sestri Levante and Savona, Sestri Levante and Genova Pra', Genova Aeroporto and Savona, Genova Aeroporto and Sestri Levante.
It is worth noting that, as can be seen, the nodes corresponding to Ventimiglia, Aosta, Cuneo and Gravellona Toce motorway exits are not listed. This is because these nodes are subject to being disconnected from the entire network due to the fall of another node. Specifically, the Ventimiglia node would be isolated in the event of a collapse of the Savona node. The other three nodes would be disconnected following the collapse of Ivrea, Carrù, and Novara, respectively.

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Node	Savona	Ge-Pra'	Ge-Ovest	La Spezia	Predosa	Alessandria	Tortona	Bettole Tort.	Milano	Piacenza	Parma	Brescia	Bergamo	Vercelli	Novara	Asti	Santhià	Ivrea	Torino	Carrù	Sestri Levante
Savona																					
Ge-Pra'	0,0																				
Ge-Ovest	29,3	34,9																			
La Spezia	19,2	17,1	7,7																		
Predosa	5,5	0,0	1,8	5,2																	
Alessandria	3,7	1,9	0,9	3,3	0,0																
Tortona	4,3	1,6	2,5	3,8	3,5	0,0															
Bettole Tort.	4,6	0,5	0,0	4,0	0,0	0,9	0,0														
Milano	3,0	1,5	2,4	0,7	1,9	0,2	0,0	2,7													
Piacenza	4,9	3,7	4,0	3,0	5,2	3,7	0,0	6,6	0,0												
Parma	2,2	0,9	0,3	0,0	6,3	6,1	4,4	7,2	6,7	0,0											
Brescia	2,6	1,6	2,2	4,1	1,8	0,9	0,4	2,2	0,0	0,0	10,2										
Bergamo	3,5	2,4	3,1	1,4	2,9	1,9	2,0	3,6	0,0	0,6	6,0	0,0									
Vercelli	4,0	4,1	2,7	3,0	4,9	0,0	3,5	3,5	7,2	0,8	3,8	4,4	9,6								
Novara	4,8	4,3	2,6	1,5	5,2	4,7	2,9	2,9	0,0	1,5	5,3	3,4	8,3	0,0							
Asti	0,3	3,5	2,6	3,8	11,0	0,0	12,9	10,4	1,6	6,7	7,9	2,0	2,6	2,2	3,3						
Santhià	0,5	4,4	3,6	3,2	5,8	3,1	4,8	4,7	5,3	0,9	3,6	4,0	8,3	0,0	0,0	0,4					
Ivrea	1,2	2,8	2,3	2,8	4,3	2,0	3,5	3,5	8,9	1,7	3,9	5,7	10,1	9,8	8,3	1,7	0,0				
Torino	1,6	0,9	1,0	2,6	5,8	2,2	5,7	5,5	3,7	1,8	3,7	2,3	5,3	3,2	3,0	0,0	0,0	0,0			
Carrù	0,0	3,0	8,5	9,7	1,7	3,0	3,5	2,3	0,2	3,9	3,7	1,1	1,2	0,1	0,2	0,0	1,8	3,0	0,0		
Sestri Levante	28,3	29,0	0,0	0,0	9,0	6,4	7,9	7,7	3,9	0,7	2,3	0,8	3,8	5,8	4,8	6,5	6,1	4,7	4,2	12,7	
Ge-Aeroporto	21,8	0,0	0,0	15,3	1,5	1,5	2,5	0,7	2,2	4,0	0,5	2,0	2,9	3,3	3,4	3,0	4,1	2,6	1,2	6,1	26,7

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Turning to the railways network we use $Graph_r = (v_r, e_r)$, a symmetric graph with $v_r = 1, \dots, 50$, and where each link, e_r, represents a fundamental railway connection, with $e_r = 1, \dots, 68$, as described in Section 5.3.2.
Each cell identifies the average change in the minimum path between two nodes following damage to the network, and the gradation of colour reflects the magnitude of this change.
The railway segments that show the greatest sensitivity are those involving nodes around the metropolitan city of Milan, such as Milano Rogoredo, Milano Centrale, and Rho.
Some nodes do not appear in the list as these are the ones that may become disconnected if other nodes fall. For example, Bivio Adda, Bivio Casirate, Brescia, Treviglio, and Pioltello, in the event of a node failure at Milano Lambrate, remain isolated from the network.
Likewise, Domodossola and Gallarate may also remain disconnected following the collapse of the Rho Fiera node. Ventimiglia, Savona and Voltri may form a separate cluster in case the Sampierdarena node collapse.

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Node	Alessandria Fs	Arquata Scrivia FS	Asti FS	Bivio Fegino FS	Bivio Piacenza O. Av FS	Bivio Rivarolo FS	Bressana FS	Broni FS	De Tortona FS	Fidenza FS	Fornovo Fs	Genova P.Principe FS	Ge-Sampierdarena FS	Isola C. FS	La Spezia FS	Lodi FS	Mi-Centrale Fs	Mi-Lambrate Fs	Milano Rogoredo FS	Novara FS
Arquata Scrivia FS	0,9																			
Asti FS	0,0	8,0																		
Bivio Fegino FS	18,7	21,2	17,4																	
Bivio Piacenza O. Av FS	11,3	9,2	8,6	8,8																
Bivio Rivarolo FS	17,9	19,8	16,9	0,3	8,5															
Bressana FS	21,1	20,8	13,5	20,9	3,7	20,1														
Broni FS	18,6	17,1	12,7	17,2	3,9	16,6	0,0													
De Tortona FS	0,0	0,1	9,0	19,1	14,3	18,3	37,6	30,4												
Fidenza FS	8,1	6,0	8,3	3,6	3,5	3,4	4,2	4,2	9,5											
Fornovo Fs	5,6	3,6	6,2	0,0	2,6	0,1	3,5	3,4	6,4	0,0										
Genova P.Principe FS	16,8	17,8	16,2	0,0	8,0	0,0	18,8	15,5	17,0	2,8	0,1									
Ge-Sampierdarena FS	17,3	18,6	16,5	0,0	8,3	0,0	19,4	16,0	17,6	3,1	0,2	0,0								
Isola C. FS	16,4	0,0	15,8	28,9	10,7	26,4	25,2	20,6	17,6	6,2	3,1	23,3	24,5							
La Spezia FS	4,0	4,5	6,0	4,4	1,9	4,5	1,7	0,5	3,4	2,3	0,0	0,0	4,6	5,4						
Lodi FS	7,2	7,4	5,0	8,0	1,7	7,7	1,8	0,4	9,6	3,5	2,8	7,2	7,5	9,3	2,0					
Mi-Centrale Fs	15,3	16,6	8,4	18,5	16,8	18,1	23,8	19,1	22,4	13,0	10,7	17,5	17,8	19,3	3,2	45,5				
Mi-Lambrate Fs	13,4	14,1	7,9	16,7	9,3	16,3	15,0	12,1	19,2	8,1	6,7	15,6	16,0	17,2	1,7	29,4	0,0			
Milano Rogoredo FS	11,0	11,1	7,2	14,4	0,4	13,9	3,6	3,5	15,3	2,5	2,2	13,2	13,6	14,6	0,0	6,1	84,9	0,0		
Novara FS	4,4	7,0	1,4	9,9	11,6	9,8	12,6	11,2	9,2	10,0	8,8	9,5	9,6	9,5	2,0	23,0	9,1	16,4	22,2	
Novara Ovest (AV FS)	4,9	7,5	1,1	10,4	12,2	10,2	13,3	11,8	9,7	10,4	9,1	9,9	10,0	9,9	2,1	24,2	9,8	17,6	23,7	0,0
Novi L. FS	0,0	0,0	9,3	29,7	10,8	28,0	23,7	20,7	0,0	7,4	4,7	25,7	26,6	34,1	5,4	8,0	17,5	15,1	12,1	7,0
P.M Piacenza Ovest Fs	11,5	9,3	8,6	8,9	0,0	8,6	3,5	3,6	14,6	3,6	2,6	8,0	8,3	10,9	1,9	0,0	18,2	10,3	0,9	12,2
P/C Melegnano FS	9,2	9,4	6,3	11,1	0,4	10,8	3,3	1,7	12,4	2,8	2,4	10,1	10,5	12,2	1,3	12,0	65,4	43,2	0,0	25,2
Parma Est Av-FS	5,2	3,8	5,9	1,6	0,0	1,4	2,1	1,8	5,9	4,9	6,4	0,9	1,2	4,0	4,2	0,9	8,9	5,1	0,7	7,6
Parma FS	5,9	4,4	6,5	1,8	1,4	1,6	2,8	2,6	6,7	0,0	0,0	1,1	1,4	4,4	2,8	2,0	10,3	6,2	1,6	8,5
Pavia FS	19,6	19,4	13,0	21,0	2,3	20,3	0,0	8,6	30,8	3,3	2,9	19,1	19,7	24,0	2,2	3,3	30,2	17,4	0,0	14,9
Piacenza Est AV-FS	11,8	9,4	9,1	9,0	0,0	8,7	4,0	3,9	14,5	2,2	1,3	8,1	8,4	10,9	1,4	1,9	15,3	8,8	1,1	10,8
Piacenza FS	11,4	8,8	8,6	8,5	3,6	8,2	2,2	0,0	14,2	0,0	1,3	7,6	7,9	10,5	1,4	3,0	17,4	10,3	1,7	11,7
Rho Fiera FS	13,8	15,5	6,0	17,4	19,1	17,1	24,4	20,3	20,4	14,9	12,5	16,6	16,8	18,0	3,8	43,9	0,0	37,7	59,5	0,0
Rho FS	14,8	16,9	5,7	18,5	23,7	18,2	29,0	24,2	22,2	18,1	15,2	17,7	17,9	19,3	4,8	51,7	38,0	60,0	73,6	0,0
Ronco Scrivia FS	15,8	0,0	15,4	0,0	10,4	0,0	24,3	19,9	16,8	5,9	2,8	0,1	0,2	0,0	2,9	9,0	19,1	17,0	14,4	9,3
Santhià FS	2,6	1,1	6,2	4,8	6,7	4,7	5,7	5,3	0,4	6,2	5,7	4,5	4,6	3,7	1,0	13,0	7,0	9,6	11,7	4,5
Settimo FS	7,5	6,0	11,2	11,8	0,4	11,6	2,4	2,7	5,8	0,7	0,8	11,2	11,4	10,2	5,5	3,8	1,1	2,0	2,5	0,2
Tavazzano FS	8,4	8,6	5,7	9,9	1,2	9,6	2,5	0,8	11,3	3,2	2,7	9,0	9,3	11,2	1,7	0,0	54,6	34,5	0,0	23,7
TorinoPn FS	7,5	6,9	8,6	13,1	2,6	12,9	5,0	5,0	6,9	3,3	3,1	12,5	12,7	11,5	5,9	1,8	1,1	1,2	1,2	3,1
Tortona FS	3,4	0,0	9,9	19,8	8,7	18,9	20,4	16,3	0,0	6,6	4,8	17,5	18,1	18,5	3,5	5,6	18,4	14,6	9,9	8,4
Trofarello FS	5,1	6,3	0,0	13,2	4,2	12,9	6,2	6,1	6,4	4,7	4,2	12,4	12,6	11,4	5,5	0,6	0,5	0,2	0,3	4,5
Vercelli FS	0,5	2,3	4,3	5,6	9,1	5,5	9,0	8,1	3,9	8,1	7,3	5,3	5,4	4,7	0,8	17,3	8,6	12,7	16,1	0,0
Voghera FS	16,6	15,0	12,5	20,3	3,6	19,5	0,0	0,0	35,4	4,1	3,5	18,2	18,8	22,8	2,6	1,5	19,1	12,9	5,1	10,4

Node	Novara Ovest (AV FS)	Novi L. FS	P.M Piacenza Ovest Fs	P/C Melegnano FS	rma Est Av	Parma FS	Pavia FS	enza Est A	Piacenza FS	ho Fiera F	Rho FS	nco Scrivia	Santhià FS	Settimo FS	avazzano	TorinoPn F.	Tortona FS	rofarello F	Vercelli
Novi L. FS	7,6																		
P.M Piacenza Ovest Fs	12,8	11,0																	
P/C Melegnano FS	26,7	10,1	1,0																
Parma Est Av-FS	7,9	4,6	0,3	0,7															
Parma FS	8,8	5,3	1,4	1,7	0,0														
Pavia FS	15,7	21,6	2,0	3,3	1,6	2,2													
Piacenza Est AV-FS	11,3	11,0	1,0	1,2	0,0	0,1	2,8												
Piacenza FS	12,3	10,5	0,0	2,0	0,1	0,6	1,9	0,0											
Rho Fiera FS	0,0	16,2	20,4	55,9	10,8	12,1	30,3	17,4	19,5										
Rho FS	0,1	17,5	25,1	64,9	13,5	15,0	36,5	21,5	23,8	0,0									
Ronco Scrivia FS	9,8	32,1	10,5	12,0	3,8	4,1	23,5	10,5	10,1	17,8	19,0								
Santhià FS	7,8	1,3	7,0	13,5	4,7	5,4	7,6	6,2	6,7	4,2	4,8	3,6							
Settimo FS	0,0	6,7	0,4	3,5	0,2	0,5	0,2	0,2	0,2	0,0	0,2	10,0	0,0						
Tavazzano FS	25,1	9,2	1,1	0,0	0,9	2,0	2,6	1,8	2,7	49,7	58,5	11,0	12,9	3,3					
TorinoPn FS	2,9	7,6	2,5	1,8	2,5	2,8	3,4	3,2	2,8	1,0	1,3	11,3	7,9	0,0	1,7				
Tortona FS	8,9	1,9	8,8	7,9	3,9	4,6	19,5	8,9	8,1	17,7	19,8	17,7	0,1	6,0	6,9	7,3			
Trofarello FS	4,2	6,9	4,1	0,8	3,6	4,0	5,1	4,7	4,1	1,1	1,4	11,2	11,5	19,6	0,6	0,0	6,8		
Vercelli FS	10,0	2,1	9,5	18,4	6,3	7,0	10,9	8,5	9,1	4,0	4,5	4,6	0,0	1,6	17,5	6,3	3,9	8,5	
Voghera FS	11,0	18,3	3,4	3,6	2,1	2,8	10,3	3,9	2,1	19,7	23,1	22,0	3,2	4,3	2,6	6,2	0,0	6,7	7,1

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