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How vulnerable are road networks to shocks? An analysis through accessibility indicators

Angela Stefania Bergantino [a], Gianmarco Troiani [b], Tahseen Bashir [b], Francesca Pagliara [b,*]

[a] Department of Economics, Management and Business Law, University of Bari Aldo Moro, Italy
[b] Department of Civil, Architectural and Environmental Engineering, University of Naples Federico II, Italy

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ABSTRACT

The purpose of the paper is to present an analysis of vulnerability of road networks through an accessibility indicator and a link importance index (LII). Specifically, the objective is to identify which traffic disruptions generate the most significant impacts. This methodology has been applied to three case studies, the medium-sized urban areas in southern Italy. The proposed accessibility indicator represents a measure of the vulnerability of an area, while the LII defines a hierarchy of importance among the roads of the network. The first indicator considers travel time and the distribution of jobs across the territory, while the second indicator depends on traffic flows. The output of the methodology consists of vulnerability maps, which show the most affected urban areas, and a ranking of the most important roads, obtained through the link importance index. This methodology is useful for transportation agencies, administrators, and civil protection, who should manage daily emergency situations following internal or external shocks such as traffic accidents or natural extreme events. Decision-makers can indetify the network's critical areas and develop programs to prioritize infrastructure improvements.

1. Introduction

Transport networks are complex systems necessary for the movement of people and goods as well as for enabling socio-economic activities within a community. Nowadays, they are increasingly challenged by unexpected events such as accidents and technical failures, internal shocks to the transportation system, or external events such as natural phenomena including earthquakes, landslides, and floods.

According to the Intergovernmental Panel On Climate Change (IPCC) (2023), transport systems will need to adapt to and they increase the number of accidents by approximately 75 % (Gossling et al., 2024).

These events physically damage infrastructure, particularly critical elements like bridges and tunnels that may remain closed to traffic for extended periods due to maintenance interventions. Damages to critical infrastructure can vary depending on the type of natural event. For instance, earthquakes might cause cracks and structural collapses in bridges, overpasses, and tunnels, compromising their stability and safety. Floods, usually resulting from heavy rainfall or river overflows, can trigger landslides and damage to construction materials through water infiltration. Landslides can obstruct entire sections of roads and destroy structures located on slopes. There are also indirect damages such as the falling of trees and debris on roads. The direct transportation consequence of these events is a temporary reduction in system performance. These effects, which impact system users, consist of increased travel times, decreased system capacity, and reduced accessibility to urban areas. These emergency situations have additional socio-economic impacts, such as loss of productivity, reduced access to essential services like hospitals and schools, and impacts on local businesses. These latter can fail or experience a temporary reduction in earnings, depending on the severity of the event.

Networks must be able to address disruptions caused by external or internal shocks and, for this reason, properties of the system such as vulnerability, reliability, resilience, robustness, redundancy, and recovery have been widely studied in recent years. These are technical and organizational properties of the network that highlight different characteristics of the system. Various vulnerability analyses have been proposed in the literature referring to different shocks: floods [1–3], landslides [4], earthquakes [5–7], hurricanes [8–10], sea-level rise [11–13], avalanches [14], tsunamis [15] and wildfire [16,17]. All these

* Corresponding author.
E-mail addresses: angelastefania.bergantino@uniba.it (A.S. Bergantino), gianmarco.troiani18@gmail.com (G. Troiani), t.bashir@studenti.unina.it (T. Bashir), fpagliara@unina.it (F. Pagliara).

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natural phenomena are becoming increasingly frequent and intense due to the rising levels of CO_2 in the atmosphere, and are therefore directly linked to climate change. In the transportation field, a growing number of authors consider it essential to include CO_2 and other greenhouse gas emissions in their vulnerability and resilience models to consider the impact of climate change [18–21]. Evaluating the vulnerability of a transportation network might be extremely difficult because of the uncertainty related to these disruptions.

These parameters may depend on the network topology [22–24] or transportation characteristics including travel time or flows [25–27] or accessibility [28–30]. A complementary aspect to vulnerability is the identification of the most important link in a network, referred to in the literature as “criticality analysis” ([31–33]; Jafino et al., 2020).

In this article, two methodologies, which can be considered complementary, have been developed and applied to real case studies, i.e. the cities of Avellino, Benevento, and Taranto, three middle size cities of south Italy.

The objective is to provide a simple but effective method for identifying vulnerable urban areas and the most important roads, Through the calculation of an accessibility indicator and a link importance index (LII) (Rupi et al., 2015), this study aims at answering the following research questions "which roads and urban areas show the highest transportation vulnerability, in terms of variation of accessibility and traffic flow, due to a disruption in the road network? How can these findings support infrastructure planning in medium-sized urban areas?

Despite their importance in the local economy, these medium-sized cities have not been studied. As far as we know, there are no vulnerability analyses based on accessibility and link importance indicators.

The paper is organized as follow: Section 2 provides a literature review on the topic of vulnerability; Section 3 reports the methodology. Section 4 illustrates the case studies and the main findings while Section 5 presents the discussion and Section 6 the conclusions.

2. Literature review

In the field of transportation engineering, there is no universally accepted definition of vulnerability. During the 1970s, vulnerability became a popular concept in disaster literature and since then, it has been applied in many disciplines such as ecology, psychology, and military context [34]. It was only in the 1990s, after the Kobe earthquake, that vulnerability was applied in the transportation context [12]. After this event, many definitions and methodologies have been proposed. One of the most frequently referenced definitions of vulnerability comes from Berdica [35], who stated that vulnerability is the susceptibility of the road network to incidents, resulting in a loss of system serviceability.

Husdal [36] asserted that the vulnerability of transportation systems is determined by the interaction of three factors. The first element relies on the topology of the network, the presence of critical elements such as tunnels and bridges, and the degree of curvature and slope. The second factor is environmental, depending on the topography and natural phenomena such as floods or landslides that may affect the road network. The third and final factor is related to mobility demand, traffic flows and the possibility of accidents. Vulnerability of road networks emerges from the interaction of these elements. Jenelius et al. [37] stated that: “*vulnerability is the society’s risk to incidents*” and it can be split into two components: probability of a disruption event and consequences [38]. According to many authors, a simple and effective way to calculate vulnerability is to consider accessibility [39,40]. If the accessibility of a node or link in the network decreases after a shock, these elements can be considered vulnerable.

Pan et al. [41] offered a definition of vulnerability that considers all these previously highlighted aspects, considering it as "*an abnormal sensitivity*" to various critical scenarios, resulting in a reduction in system capacity, an increase in travel times, and a decrease in accessibility. In this context, the transportation system needs to be studied from multiple perspectives, evaluating geometric-structural aspects, such as topological ones, transportation aspects like travel cost or capacity, and socio-economic aspects of the territory. Indeed, many properties have been studied that evaluate the system’s performance and its response to external events. Robustness, redundancy, resilience, and reliability are the most well-known technical and infrastructural properties, and their relationship to vulnerability is widely debated. According to MCEER (2007), robustness is the ability to ensure a certain level of performance when an external shock occurs. Redundancy is the system’s ability to connect the same pair of nodes through multiple paths [42,43]. In other words, it represents the network’s flexibility. Reliability is the probability of completing a trip between a pair of nodes [32]. It can be divided into three components: connectivity reliability, travel time reliability, and capacity reliability. The initial component refers to the likelihood of an origin-destination pair remaining connected during a particular disruption event [40,44]. Travel time reliability indicates the probability of travellers arriving at their destinations within a specified timeframe [45,46], while capacity reliability is associated with the likelihood that a network can meet a particular travel demand [47]. Resilience refers to the capacity of a system, community, or society encountering hazards to endure, absorb, adapt to, and recover from the effects of a hazard promptly and efficiently (UNSDR, 2009; [48,49]). This involves maintaining and sustaining its essential structures and functions. Although all these properties are connected, the link with vulnerability is not entirely clear in the literature. Robustness and redundancy are considered fundamental properties of resilience, alongside rapidity and resourcefulness [50]. Nevertheless, a different perspective is proposed by Snelder et al. [51], according to which vulnerability is the opposite of robustness. The latter property encompasses five other properties, among which there are resilience and redundancy.

Santos et al. [52] highlight a relation between robustness and reliability. The former is a physical property of the infrastructure, while the latter is centered on the system’s performance. Taylor et al. [40] suggest that reliability is a measure of connectivity associated with the probability of a certain event occurring, whereas vulnerability concentrates on the consequences.

According to some authors, vulnerability and resilience should be considered as two complementary aspects of the issue. Vulnerability focuses on the consequences of a disruption event while resilience concerns the ability to respond, recover, and implement strategies to mitigate the effects of future events [34,53]. Gonçalves and Ribeiro [54] suggest that a system is vulnerable when it is exposed to disruptions it is characterized by limited damage tolerance and low robustness. However, it can also show resilience by adapting and recovering some of its previous performances through redundancy. Thus, the system can concurrently exhibit both resilience and vulnerability. Within this framework, many indicators have been proposed with the aim of quantifying vulnerability.

2.1. Measure of vulnerability

A consolidated framework in the vulnerability analysis has been developed using the concept of accessibility [3,12,29,55–57]. A method based on accessibility can accurately reflect traffic and socio-economic characteristics by taking into account factors such as distances, flows, generalized costs, population or jobs. Taylor et al. [40] proposed the ARIA accessibility index, which evaluates the social consequences on rural areas as an indicator of vulnerability. Coles et al. [1] created a method to evaluate network performance during flooding by examining accessibility to emergency services. Employing a hydrodynamic flood model, they simulated two flood events that affected York (UK) in 2014 and 2015. Gori et al. [10] examined how accessibility to emergency services was impacted by flooding by analysing increases in travel times and losses in connectivity. The increase of generalized travel cost is another widely used variable for assessing the vulnerability of a road network. Based on this variable Jenelius et al. [37] defined two indicators, link importance and area exposure, which were calculated for the road network of Sweden. Vulnerability has been also studied from a topological perspective. Betweenness centrality, connectivity, network efficiency, and closeness centrality are topological properties which aim to evaluate the most important segments or nodes and the ability of a system to remain connected. Betweenness centrality assesses how often a node v is positioned along the shortest path connecting two other nodes i and j in the network. This measure was introduced by Freeman et al. [58], but over the years it has been revisited and supplemented with other variables to adapt it to different needs. Nagurney and Qiang [59] integrated betweenness centrality with demand and travel costs. Erath et al. (2009) recommended a vulnerability assessment on the road and railway networks considering topological characteristics such as closeness centrality, betweenness centrality, global and local efficiency. Kermanshah and Derrible [60] merged betweenness centrality with accessibility metrics to establish a novel index termed "vulnerability surface" and applied it in an earthquake scenario. By incorporating additional variables such as flow, traffic demand and travel time, Li et al. [61] proposed the traffic flow betweenness index (TFBI). Recently, a new integrated parameter identified as betweenness-accessibility was introduced by Sarlas et al. [56] to incorporate topological and socio-economic aspect of a network. Other composite metrics such as traffic volume centrality were introduced by Mylonas et al. [62]. Using percolation theory Zhou et al. [63] estimated connectivity, global and local, on road network impacted by earthquakes. The shortest path between two nodes is frequently used in the formulation of various topological properties. Route efficiency $\eta(i,j)$ is measured by comparing the shortest path d between two nodes i and j before and after an interruption [2]. All these measures are useful for identifying nodes or links that play a critical connectivity role within the network. Within the criticality analysis, considerable attention has been given to network robustness indices. The most recognized metric is the Network Robustness Index (NRI) [64], which computes the cost variation resulting from the re-assignment of demand when a specific link becomes unusable. Generally, network robustness indices are a function of travel time, flow, or capacity. Santos et al. [52] investigated three measures of robustness. The first measure is based on the link's maximum service flow and the population of a region (city evacuation capacity). The second measure considers the variation of traffic flow and the generalized travel cost when a link is disrupted (network vulnerability). The third measure is influenced by the link's length, traffic flow, and the maximum service flow (network spare capacity). Dowds et al. (2017) examined the Network Robustness by investigating various levels of demand aggregation and network resolution. Their findings indicated that increasing demand aggregation or lowering network resolution could lead to skewed effects on the criticality ranking. Travel time, robustness and travel time reliability are studied by Snelder et al. [51]. They classified robustness indicators into three categories: static indicators, which remain constant regardless of traffic flow, dynamic indicators, which vary with traffic flow, and indirect indicators, which are associated with travel time. They suggested using an indirect indicator, particularly the travel time losses resulting from incidents. Reynaud et al. (2018) combined the Network Robustness Index (NRI) with road emissions to develop an emission-based parameter (ENRI). Their paper shows that in cases of capacity reduction on bridges, both parameters yield similar results, while in other scenarios, the outcomes differ. Rupi et al. (2015) devised a procedure that classifies links based on traffic flow and their effects on the overall network connectivity. This approach has been implemented in the current study and will be explained in detail in Section 3. The comparison among many different indices is a good practice found in literature emerged in recent years. Gu et al. [45] demonstrated the relationship among reliability, vulnerability, and through various topological and system-based indicators. Through numerical examples, the authors observed that a highly reliable network doesn't necessarily indicate a low vulnerability level, and resilience isn't solely correlated with vulnerability. De Oliveira et al. (2016) contrasted vulnerability and reliability metrics, emphasizing that vulnerability measures are heavily influenced by the characteristics of alternate paths, whereas reliability metrics are affected by the level of congestion, decreasing as road saturation increases. Almotahari and Yazici [31] performed a comparison of five indices, demonstrating a procedure which considers both topological attributes and network transportation characteristics to choose a parameter from various options. Jafino et al. (2020) conducted a review of seventeen criticality metrics, finding that the network's topology has a significant impact on the development of an experimental equivalence between the metrics. However, they highlight that parameters that are conceptually similar might not always demonstrate similar empirical findings.

From the analysis of the literature review, a very large number of indices and methodologies emerge. There seems to be a lack of a synthesis of the different methodological approaches and a standardization of these indices. In this context, the need to integrate socio-economic aspects, where accessibility is the most significant factor, with transportation characteristics, such as traffic flows or travel times, becomes evident. These two approaches have been extensively studied separately; however, as far as we know, there are few studies that attempt to combine these two aspects within the same analysis. This makes it difficult to compare the results of the papers and draw conclusions on a larger scale. Most studies analyze the system by considering a single mode of transportation, generally the private road transport. The actual behaviour of transport networks resulting from the integration of public and private transportation is not explored. Another relevant aspect that has not been sufficiently studied is the long-term impact of a disruption. From a transportation perspective, this involves examining how users' travel behaviour has changed, while from an economic point of view, it means considering the effects on commercial activities in an urban area.

Furthermore, most studies focus on densely populated urban areas, such as European, American, and Asian metropolises. To the best of our knowledge, there is a lack of studies on medium-sized urban areas. These cities have a less developed transportation system compared to larger urban centers, and for this reason, they may show a higher vulnerability to disruptive events.

Our methodology, which will be explained in the following section, aligns with two well-established research streams: the accessibility-based and link importance indicators. It also aims to fill the gap between these two complementary approaches. We believe that both the socio-economic aspects and the more strictly transport-related element connected to traffic flows are necessary components in a vulnerability analysis.

3. Methodology

A well-established approach in the literature involves calculating the vulnerability of road transport networks as a reduction of accessibility in urban area [40]. Accessibility refers to the ease for transportation system users to reach different destinations within the territory. According to Cascetta et al. (2016), it is distinguished into active and passive accessibility. The former expresses the users' ability to reach the desired destination like services or activities. On the contrary, passive accessibility describes how easily activities can be achieved by travellers. This paper refers to active accessibility and has the following formula:

$$AA_i = \sum_{j=1}^{n} K_j^{\beta_1} * \exp\left(-\beta_2 T_{ij}\right) \tag{1}$$

AA_i represents the active accessibility of node i while K_j represents the number of jobs located in j supplied by Census. T_{ij} represents the travel time between node i and j. Finally, β_1 and β_2 are parameters with value of 1.17 and 1.14, respectively. These parameters have been previously estimated by Henke et al. [65].

Travel times were estimated using the Visum software, which allows simulating the interaction between road transport infrastructure and mobility demand. One of the main effects following a shock, natural or anthropogenic, is the reduction in accessibility to a given node of the network. According to Chen et al. [39], vulnerability of the generic node i can be related to the change in accessibility:

$$Vulnerability_i = \frac{Acc_i^0 - Acc_i^1}{Acc_i^0} \tag{2}$$

Acc_i^0 represents the accessibility of node i before the shock while Acc_i^1 represents the accessibility of node i after the shock.

A complementary approach to estimating vulnerability involves ranking the roads in a network. In this paper, the methodology proposed by Rupi et al. (2015) is applied, and it has the following expression:

$$LII_j = \beta\, F(ADT_j) + (1-\beta)\, G(\Delta C_j) \tag{3}$$

ADT_j denotes the average daily traffic on road j, as calculated through Visum simulations. ΔC_j is the extra cost faced by network users due to the interruption of link j, calculated relative to the network's normal, undamaged state. G and F represents a function of $\Delta C_j$and ADT_j respectively. Lastly, β represents a sensitivity parameter.

$F(ADT_j)$ is referred to as local importance, while $G(\Delta C_j)$ is termed global importance. According to Rupi et al. (2015), β can range from 0 to 1, with its specific value to be decided at the policy level [37]. In this paper, we assume that $F(ADT_j)$ and $G(\Delta C_j)$ have equal weight, thus setting β to 0.5. The local importance indicator is directly related to the traffic volume on the road. Indeed, a link is vulnerable if the traffic flow increases. The $F(ADT_j)$ is calculated as follows:

$$F_j = F(ADT_j) = \frac{ADT_j - ADT_{min}}{ADT_{max} - ADT_{min}} \tag{4}$$

where ADT_{min} and ADT_{max} represent the minimum and maximum ADT values estimated across the set of links with known ADT. $G(\Delta C_j)$ function requires evaluating ΔC_j, which indicates the total change in trip costs throughout the network due to the closure of a certain road j:

$$\Delta C_j = C_j - C_0 \ \forall j \in B \tag{5}$$

C_j denotes the total cost of the network in the event of road j being closed, while C_0 signifies the total cost of the network in its unharmed state, and B is the set of links being studied. The total trip cost C encompasses the cumulative total of all generalized costs incurred by users during the journey, and is computed as:

$$C = \frac{\sum_{\forall OD} T_{od} \cdot V_{od}}{\sum V_{od}} \tag{6}$$

T_{od} represents the travel time of the generic O-D calculated during the simulation while V_{od} represents the simulated volume between origin o and destination d derived from the O-D matrix.

The G_j can be calculated as:

$$G_j = \frac{\Delta C_j - g_{min}}{g_{max} - g_{min}} \tag{7}$$

where g_{min} and g_{max} are the total minimum and maximum travel times evaluated through the software Visum. ΔC_j is the total trip cost variation when road j is disrupted.

4. Case study

The methodology outlined above has been applied to three medium-sized areas the city of Avellino, the city of Benevento, and the city of Taranto. The selection of these cities is based on several motivations, linked both to their regional impact and to the need to address certain gaps in the literature. Medium-sized cities are often undervalued in vulnerability analyses, with a general focus on large urban centers such as metropolises. Compared to other countries, there are relatively few studies in general and in Italy in particular that calculate the impacts on accessibility following a disruption event (Rupi et al., 2015; [66–69]). Most of these contributions analyse the road networks of cities in northern Italy. Although fewer in number, there are also studies for some municipalities in southern Italy [70–72] or for the road network in Sardinia [29,73].

The cities selected for our research are important centers for the regional economy, but as far as we know, they have not been yet the object of a vulnerability analysis based on accessibility or road importance indicators. These cities in southern Italy are interesting to study for several reasons. Avellino and Benevento are inland cities located in a mountainous area, while Taranto is a coastal city. In terms of transportation, Taranto has a greater strategic importance due to its port, whereas Avellino and Benevento have smaller road networks and fewer connections with the rest of the country.

Regarding the motorization rate, Benevento is above the national average (66 cars per 100 inhabitants, source: ACI, 2022) with 69 cars/100 inhabitants. Avellino follows the national trend with 65 cars/100 inhabitants, while Taranto is below the national average with 59 cars/100 inhabitants. As for the public transportation performance, Benevento is well below the national average (28 trips per inhabitant per year) with 12 trips per inhabitant per year. Avellino is in line with the average, with 29 trips per inhabitant per year, while Taranto has 49 trips per inhabitant per year. Compared to medium-sized cities in northern Italy, these indicators show lower development of public transportation [74].

Furthermore, the cities of Avellino, Benevento, and Taranto are affected by extreme events related to climate change. The Irpinia region is prone to landslides and mudslides due to its geological formation and heavy rainfall. In recent years, various extreme phenomena have occurred. The most significant event took place on the 15th October in 2015 in Benevento, when heavy rains hit the basins of all the waterways in the province, particularly the Calore, Sabato, and Tammaro rivers. These events caused severe disruptions to traffic and significant damage to the agricultural and industrial sectors. The city of Taranto, located on the Ionian coast, has been struck by several tornadoes and marine storms, causing damage to coastal structures. Taranto has also experienced flooding due to torrential rains, resulting in damage to urban infrastructure and the lower-lying districts of the city. Despite their increasing fragility, these cities are still not equipped with hydraulic containment works and slope stability measures, which are predominantly concentrated in the central-northern part of the country [74]. The topographical, infrastructural, and natural risk diversity provide an opportunity to evaluate the methodology in complementary scenarios. This approach could be replicated in different urban contexts, contributing to the generalization of the results. These cities offer an ideal testing ground for the link importance index. In mountainous areas, the focus is on the challenges related to the lack of redundancy, while in a coastal context, the analysis emphasizes the dependence on strategic infrastructures such as bridges and access to ports.

The following paragraphs describe these three case studies.

4.1. Case study of city of Avellino

The city of Avellino is in Campania, a region of southern Italy, and is populated by approximately 52,000 inhabitants. It is located in the southern Apennines, in a valley of volcanic origin. The city is surrounded by Mount Tuoro to the east, the mountain range of the Picentini to the southeast, and the massif of Montevergine to the northwest. The city's territory is at medium seismic risk. The city has been divided into 24 homogeneous traffic zones, and the following Figs. 1 and 2 show the distribution of the active population and jobs in the area provided by the Census. The active population comprises individuals within the working age range (16–65 years old), whereas jobs refer to individuals who must travel from their residence to work.

On average, each zone contains 4 % of the active population and employees, with only four zones having a concentration of active

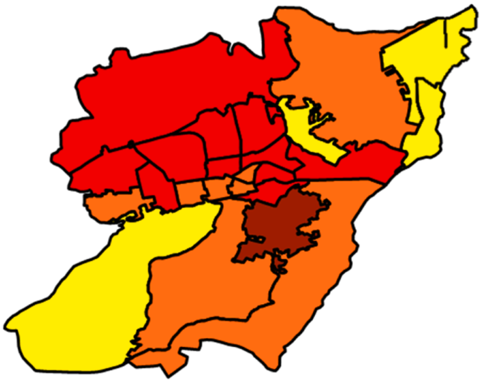

Fig. 1. Active population distribution.

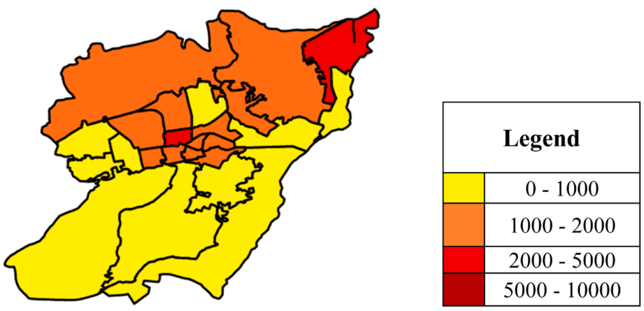

Fig. 2. Jobs distribution.

population below 1000 and one zone exceeding 5000. The road network of the city of Avellino has been imported from the OpenStreetMap website and it covers an area of about 30 km^2. It is crossed to the northwest by the A16 motorway and in the southern area by the SS7 Via Appia. The following Fig. 3 illustrates the main arteries crossing the city.

The O-D matrix has been estimated based on a data gathered by Census, which analyzed commuting movements during the 15th general population and housing census in 2015. Within the population and housing census, a commuting matrix at the municipal level has been calculated, containing data on the number of resident individuals who commute between municipalities—or within the same municipality—classified by purpose of travel, gender, departure time slot, and duration of the trip. The O-D matrix has been integrated to the road network using a stochastic user equilibrium approach and provided the car traffic flow between 24 zones (Cascetta, 2009). Using the Visum® software, five different scenarios have been simulated. Fig. 4 shows the five roads investigated during the simulation.

The basic scenario represents the usual traffic patterns in the region, with no interruptions occurring. In the first scenario, the road "Via Circumvallazione" has been interrupted. This road is 2.95 km long, passes through 2 districts located into the historic centre and has one lane in each direction. This scenario tries to estimate the local effect in the urban area. In the second hypothesis the road "Strada Comunale dei Cappuccini" has been eliminated. This road is 3.76 km long, passes through 3 districts located in the northeast part of the centre and includes two lanes in each direction. This road features a tunnel along its route and is the main access route to the area with the highest number of jobs per zone. In the third scenario the road "Via Due Principati" has been interrupted. The road is 2 km long, crosses 2 districts located in the southeast part of the city and has one lane in each direction. It is the main access route to the historic centre from the south and along his route there is a bridge called "Ponte della Ferriera." In the fourth scenario the road "Via Tagliamento" has been eliminated from the network. This road is 1.8 km long, passes through 2 districts located in the northwest part of the city and includes one lane in each direction. It is the main access route to the historic centre from the north and it is the last section of trunk road "SP88". In the last scenario "Autostrada dei Due Mari" has been deleteted. Stretching for 172 km, this motorway connects Campania to Puglia. It consists of two lanes in each direction and only the sections that cross the city of Avellino has been removed.

4.2. Case study of city of Benevento

The city of Benevento is located in Campania and populated by approximatively 56,000 inhabitants. The city is located in the Apennine hinterland of Campania, at the confluence of two rivers: the Calore and the Sabato. The entire urban centre is situated in a large basin surrounded by hills; to the west lies the Taburno Camposauro massif, while to the southwest lies Mount Avella. The city's territory is at high seismic risk. Furthermore, the low-lying area is subject to periodic floods. The city has been divided in 30 homogeneous traffic zones, and the following Figs. 5 and 6 display the distribution of the active population and jobs in the area provided by the Census.

On average each zone contains 3.3 % of active population and jobs. 16 zones have a concentration exceeding 2000 of active population and only 1 zone exceeding 2000 of jobs. The road network of the city of Benevento has been imported from the OpenStreetMap website and it covers an area of about 130 km^2. The city is surrounded by "SS 752 Tangenziale di Benevento" and it is crossed by many national roads such as: "SS 372 Telesina", "SS 90″, "SS 7″, "SS 88″ and "SS 87″. The following Fig. 7 shows the main arteries crossing the city.

The O-D car demand matrix was derived from data collected during the 15th general population and housing census in 2015, which

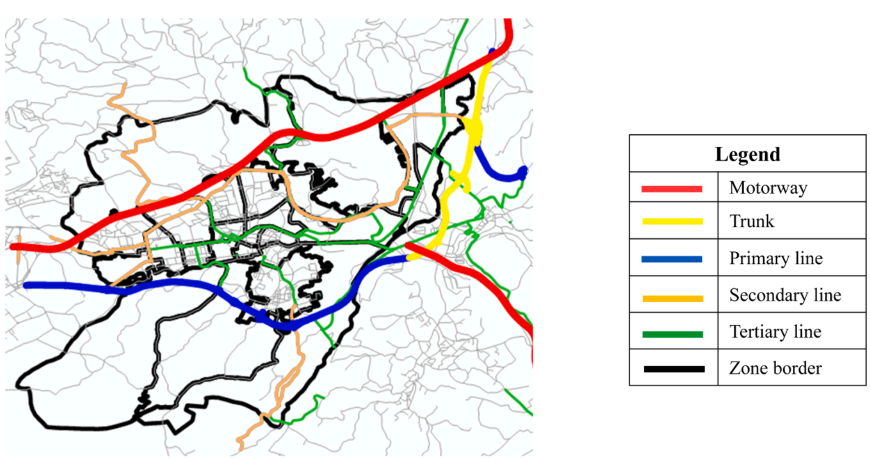

Fig. 3. Main links in the study area.

Legend	
Scenario 1	Via Circumvallazione
Scenario 2	Strada Comunale dei Cappuccini
Scenario 3	Via Due Principati
Scenario 4	Via Tagliamento
Scenario 5	Autostrada dei Due Mari (A16)

Fig. 4. Links investigated.

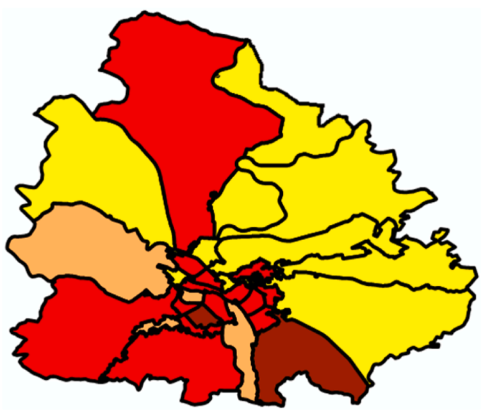

Fig. 5. Active population distribution.

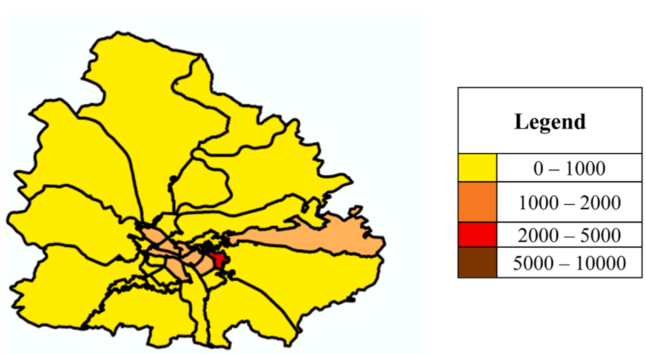

Fig. 6. Jobs distribution of city of Benevento.

examined commuting patterns. This census included a detailed analysis of commuting movements at the municipal level, categorizing resident individuals by their reasons for travel, gender, departure time, and trip duration. The O-D matrix has been integrated into the road network using a stochastic user equilibrium method and provided the car demand between 30 traffic zones (Cascetta, 2009). Utilizing the VISUM® software, simulations were carried out based on five distinct scenarios. Fig. 8 illustrates the five links examined in the simulation.

The basic scenario represents the usual traffic patterns in the region, with no interruptions occurring. In the first hypothesis the tunnel “Galleria Avellola” has been deleted. This tunnel is 906 m and is part of national trunk road “SS 7″. It has one lane in each direction and passes through two districts. In the second scenario the bridge “Vanvitelli” has been eliminated from the network. This bridge is 110 m long and it includes two lanes in each direction. This critical link crosses over the Calore River and is one of the access routes to the city centre from the north. In the third scenario the bridge “Tibaldi” has been erased from the network. This bridge is 300 m long and consists of one lane in each direction. This critical link crosses over the Sabato River and is one of the access routes to the city centre from the north. In the fourth scenario the bridge “Viadotto delle Streghe” has been interrupted. This road is 1.02 km long and has one lane in each direction. This road passes through three districts and it is an access route to the city centre from the west. In the last scenario the road “Via dei Longobardi” has been eliminated. This road is 1.5 km long, it includes one lane in each direction and crosses three districts. Along this road there is a bridge crossing the Calore River.

4.3. *Case study of city of Taranto*

The city of Taranto is in Puglia region, in the south of Italy, and is populated by approximatively 190,000 inhabitants. It is the second most populous city in Puglia and is situated on the Ionian Sea. The territory is predominantly flat and stretches along three natural peninsulas and an island, with the latter being the historical centre. The city has been divided into 52 homogeneous traffic zones and the following Figs. 9 and 10 display the distribution of active population and jobs.

On average each zone contains 1.92 % of active population and jobs. 18 zones have a concentration of active population exceeding 2000 while 8 zones have a concentration of jobs exceeding 2000. There is only one area that alone gathers over 18 % of jobs (over 12,000), located in the northwestern part of the city. Here, there is an important industrial complex called "Ilva di Taranto." The road network of the city of Benevento has been imported from the OpenStreetMap website and it covers an area of about 250 km^2. The city is crossed by many national roads such as: motorway “A14”, “SS 106″, “SS 100″ and “SS 7″. The following Fig. 11 displays the main arteries crossing the city.

The O-D car demand matrix was created using data gathered during the 15th general population and housing census in 2015, which investigated commuting patterns. This census included a thorough analysis of commuting movements at the municipal level, categorizing resident individuals by their reasons for travel, gender, departure time, and trip duration. The O-D matrix has been incorporated into the road network using a stochastic user equilibrium method and provided the car demand between 52 traffic zones (Cascetta, 2009). Simulations were carried out based on five distinct scenarios using Visum® software. Fig. 12 illustrates the five links examined in the simulation.

The basic scenario represents the usual traffic patterns in the region, with no interruptions occurring. In the first scenario the bridge “Punta Penna” has been deleted from the network. The bridge is 1.9 km long and reaches a height of 45 m above sea level. It features 2 lanes in each direction. It serves as a crucial roadway for the city, providing a quick connection between the northern and southern part of the city. In the second scenario the national road “SS 7 Appia” has been eliminated. This trunk road section is 4.36 km long and passes through three districts. In

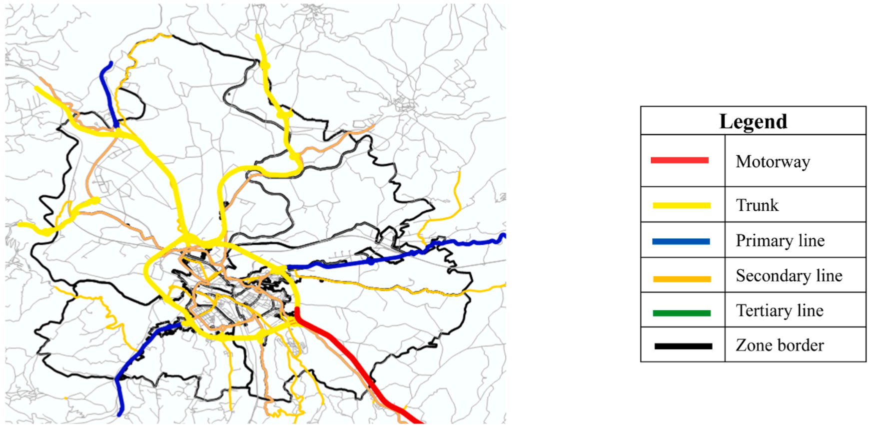

Fig. 7. Main links crossing the city of Benevento.

Fig. 8. Links investigated.

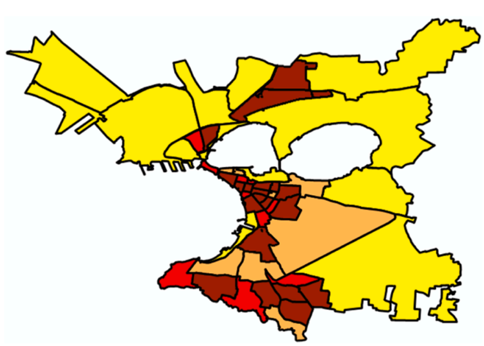

Fig. 9. Active population distribution of city of Taranto.

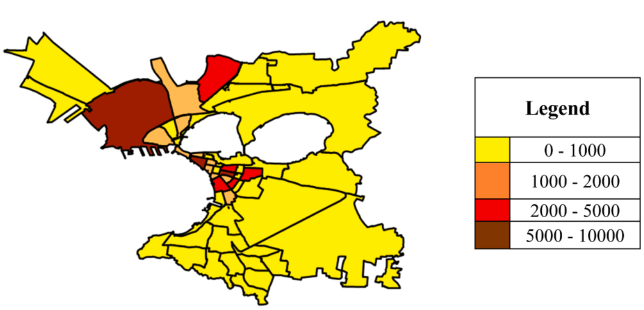

Fig. 10. Jobs distribution of city of Taranto.

the third scenario the bridge “Ponte di Porta Napoli” has been deleted. This bridge is 115 m long and it includes 1 lane in each direction. In the fourth scenario the bridge “Ponte San Francesco di Paola” has been erased. This bridge is 90 m long and it has 1 lane in each direction. These two bridges connect the old town island and the rest of the city. The "San Francesco di Paola" bridge has the capability to open for the passage of ships, spanning a navigable canal that is 375 m long. In the last scenario the road “Viale Magna Grecia” has been eliminated. This road is 2.5 km long and includes two lanes in each direction.

The following Table 1 summarizes the main characteristics of the three study areas.

The following three paragraph show the main results.

4.4. Results for city of Avellino

The closure of "Via Circumvallazione" (1st scenario) results in a decrease in accessibility to the mid-sized city of Avellino, with an average reduction of 3.42 %. The reduction in accessibility ranges between 2 and 5 % for 19 zones, while only four zones exhibit a decrease of <2 %, and one zone alone experiences a reduction in accessibility exceeding 5 %. The removal of the road “Strada Comunale dei Cappuccini” (2nd scenario) leads to an average accessibility reduction of 3.37 %. The reduction in accessibility ranges between 2 and 5 % for 18 zones, while 5 zones exhibit a decrease of <2 % and one zone experiences a reduction in accessibility greater than 5 %. The closure of “Via Due Principati” (3rd scenario) shows an average accessibility reduction of 3.22 %. The reduction in accessibility ranges between 2 and 5 % for 20 zones while 4 zone experience a reduction in accessibility lower than 2 %. By removing “Via Tagliamento” (4th scenario) the accessibility is reduced by an average of 3.16 %. The reduction in accessibility ranges between 2 and 5 % for 18 zones, while 5 zone have a reduction lower

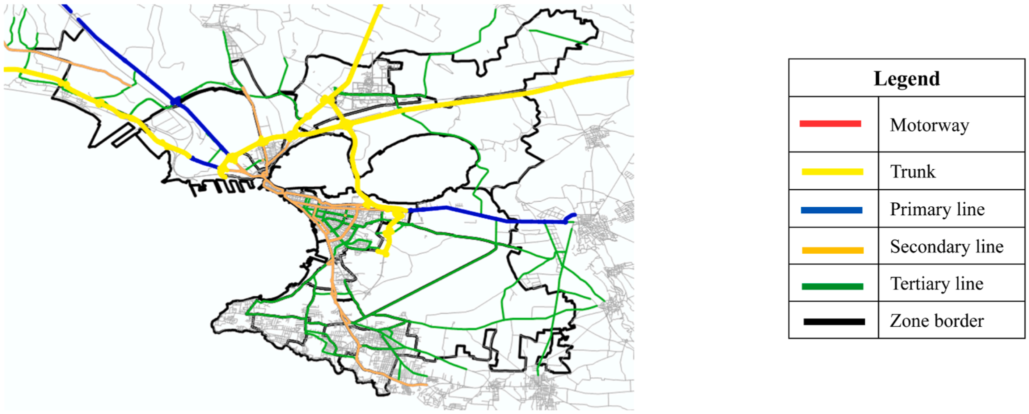

Fig. 11. Main links in the study area.

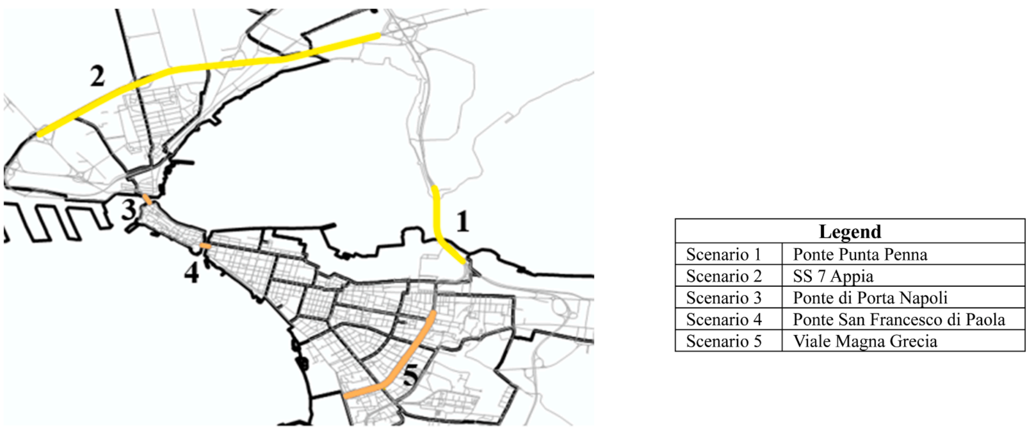

Fig. 12. Links investigated in the study area.

Table 1
Main characteristic of the three study areas.

Case study	Population	Active population	Jobs	Area [km^2]	Traffic zones	Motorization rate (cars/100 inhabitants)
Middle sized city of Avellino	52,056	24,966	22,493	30	24	65
Middle sized city of Benevento	55,814	24,648	22,381	130	30	69
Middle sized city of Taranto	190,089	73,117	67,208	250	52	59

than 2 % and only one zone has a reduction greater than 5 %. The closure of “Autostrada dei due Mari (A16)” (5th scenario) induces an average accessibility reduction of 3.17 %. The reduction in accessibility ranges between 2 and 5 % for 20 zones while 4 zones have a reduction lower than 2 %.

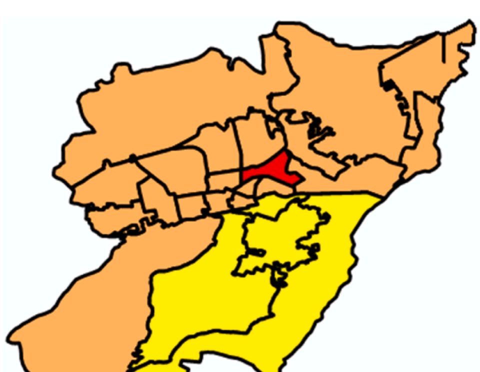

Fig. 13. Accessibility variation (%) for 1° scenario.

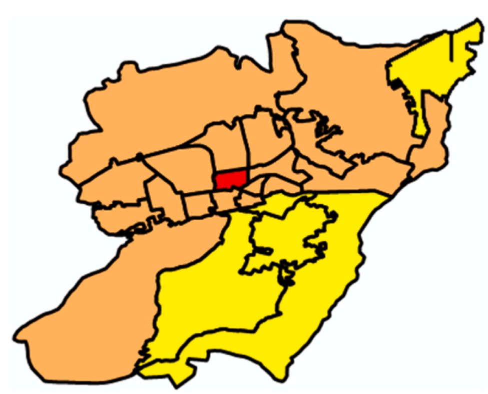

Fig. 14. Accessibility variation (%) for 2° scenario.

Figures 13-17 illustrate the change in accessibility (%) across all districts within the city of Avellino for scenarios 1 to 5. Based on Eq. (3), a ranking among the roads is determined. ADT_j and the travel time are

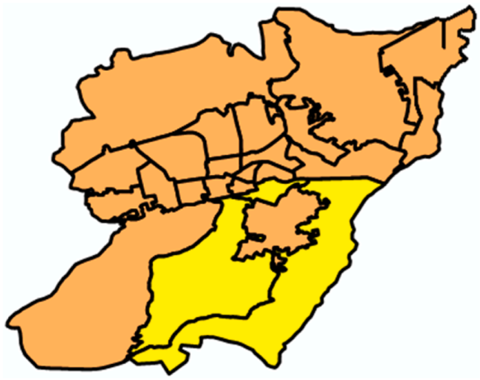

Fig. 15. Accessibility variation (%) for 3° scenario.

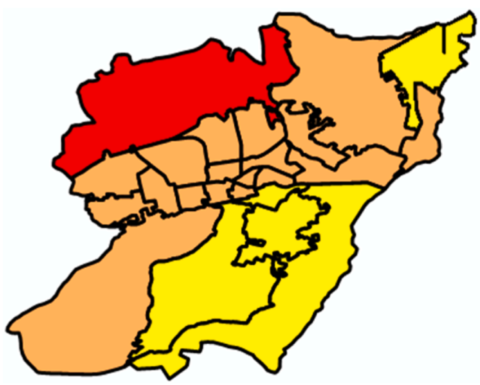

Fig. 16. Accessibility variation (%) for 4° scenario.

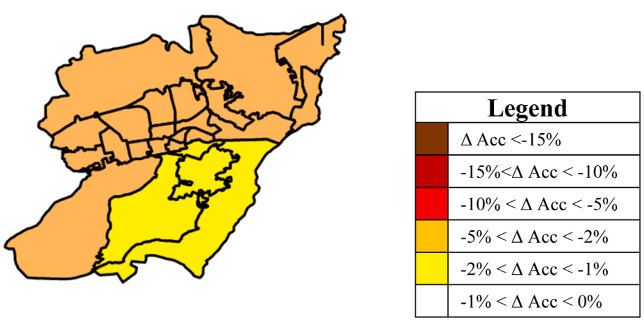

Fig. 17. Accessibility variation (%) for 5 scenario.

computed using Visum® software. The parameter β was set to 0.5, balancing the global and local indices equally. Table 2 presents the findings for the five links examined.

4.5. Results for city of Benevento

The service disruption of “Avellola” Tunnel (1st scenario) leads to a reduction in average accessibility of 0.78 %. This scenario has significant effects only on 12 zones located to the west and east of the tunnel. The traffic disruption on the “Vanvitelli” bridge (2nd scenario) has a much more significant impact on mobility. The average area accessibility decreases by 3 %, with 20 zones experiencing a reduction in accessibility between 2 % and 5 %, while for 2 zones located into the historic centre accessibility decreases by >5 %. Only one zone is not affected by the service disruption on the “Vanvitelli” bridge. The traffic flow disruption on the “Tibaldi” bridge (3rd scenario) has a significant effect limited to 5 areas near the bridge, where a reduction in accessibility slightly above 1 % is recorded. The average accessibility decreases by 0.58 %. The fourth scenario does not cause an important reduction within the urban area of Benevento because the service disruption on the “Viadotto delle Streghe” leads to a reduction in accessibility greater than 3 % in only one zone. The traffic closure of “Via dei Longobardi” causes an average accessibility reduction of 2.21 % within the area. 18 zones experience a reduction in accessibility greater than 2 %, while in 7 zones the decrease is <1 %. Figs. 18-22 illustrate the change in accessibility (%) across all districts within the city of Benevento for scenarios 1 to 5. Based on Eq. (3), a ranking among the roads is determined. ADT_j and the travel time are computed using Visum® software. The parameter β was set to 0.5, balancing the global and local indices equally. Table 3 presents the findings for the five links examined.

4.6. Results for city of Taranto

Interrupting the traffic flow on the "Punta Penna SS7ter" bridge (1st scenario) leads to a reduction in accessibility of 5.65 % for the urban area of the city of Taranto. For 11 zones the reduction in accessibility is greater than 15 %, while in 2 zones the decrease is between 10 % and 15 %. For 2 zones, the reduction in accessibility is between 5 % and 10 %. Accessibility decreases between 2 % and 5 % in 19 zones, while for 18 zones the variation is <2 %. The traffic disruption hypothesized in the

Fig. 18. Accessibility variation (%) for 1° scenario.

Table 2
Key findings.

Interrupted link	Average Accessibility reduction for the middle-sized city of Avellino	Number of districts with accessibility variation greater than 5 %	Link Importance Index	Ranking
Via Cirmuvallazione	−3.43	1	0.20	2
Strada Comunale dei Cappuccini	−3.37	1	0.18	3
Via Due Principati	−3.22	0	0.22	1
Via Tagliamento	−3.16	1	0.17	4
Autostrada dei due mari (A16)	−3.17	0	0.14	5

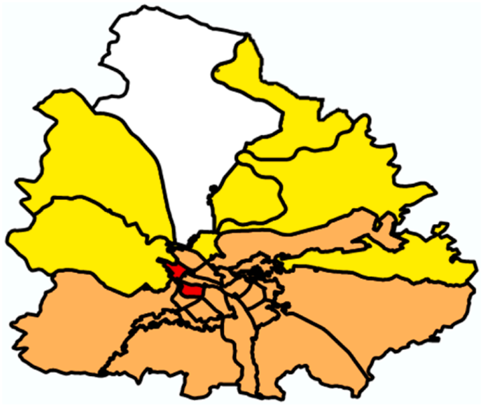

Fig. 19. Accessibility variation (%) for 2° scenario.

Fig. 20. Accessibility variation (%) for 3° scenario.

Fig. 21. Accessibility variation (%) for 4° scenario.

second scenario leads to an average accessibility reduction of 0.98 %. 7 zones experience a decrease in accessibility between 2 % and 5 %, while 5 zones have a reduction in accessibility between 1 % and 2 %. The closure of the Porta Napoli bridge (3rd scenario) causes a reduction in accessibility of 4.65 % for the entire urban area. In 9 zones, a change in accessibility greater than 10 % is observed, while in 5 zones, a reduction between 5 % and 10 % is noted. In 25 zones, a reduction between 2 % and 5 % was observed. The traffic disruption on the "San Francesco di Paola" bridge (4th scenario) represents the worst situation. Accessibility is reduced on average by 5.65 % across the entire urban area. For 2 zones, a decrease in accessibility greater than 15 % is observed, while in 9 zones, the reduction is between 10 % and 15 %. 4 zones experience a

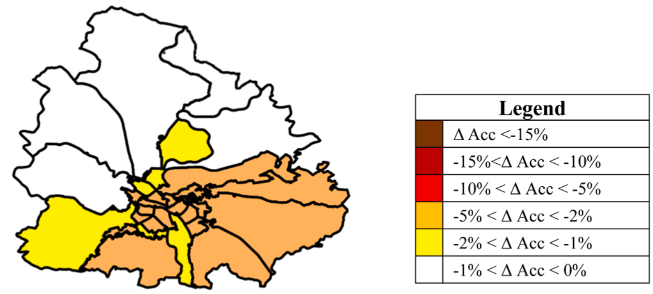

Fig. 22. Accessibility variation (%) for 5° scenario.

reduction in accessibility between 5 % and 10 %, while 35 zones show a decrease between 2 % and 5 %. The traffic disruption on "Via Magna Grecia" affects only 2 zones, where the reduction in accessibility is <2 %. Figs. 23-27 illustrate the change in accessibility (%) across all districts within the city of Taranto for scenarios 1 to 5. Based on Eq. (3), a ranking among the roads is determined. ADT_j and the travel time are computed using Visum® software. The parameter β was set to 0.5, balancing the global and local indices equally. Table 4 presents the findings for the five links examined.

5. Discussion

Starting from the case study of the urban area of the city of Avellino, the traffic disruption that causes the most significant impacts is the 1st scenario. In this case, there is an average accessibility reduction of 3.42 %, with one zone experiencing an accessibility reduction exceeding 5 %. The least impactful scenario from a transportation perspective is the closure of the "Autostrada dei Due Mari" highway (5th scenario). Regarding the case study of the urban area of the city of Benevento, the worst-case scenario involves the closure of the bridge “Vanvitelli” (2nd scenario). These closures have a significant impact on 20 zones, with an accessibility reduction exceeding 5 % for 2 zones. The 3rd and 4th scenarios involved the closure of the "Tibaldi" bridge and the viaduct "Viadotto delle Streghe." These scenarios did not cause significant damage to urban traffic, impacting only 5 zones and 1 zone respectively. Regarding the case study of urban area of city of Taranto, the worst-case scenarios involve the closure of the bridge “San Francesc di Paola.” Every zone of the city is negatively affected by the bridge closure, with 2 zones being highly vulnerable as they show an accessibility reduction exceeding 15 %, while 9 zones are moderately vulnerable as the accessibility reduction ranges between 10 and 15 %. The best-case scenario is the closure of "Vale Magna Grecia" road. In this scenario (5th), only 2 zones experienced a significant reduction in accessibility. Regarding the complementary approach based on the Eq. (3) (Rupi et al., 2015), it is possible establish a hierarchy between the roads. For the case study of the city of Avellino, the most important roads are "Via Circumvallazione" and "Via Due Principati". For the Benevento case study, the most crucial roads are the "Vanvitelli" bridge and " Via dei Longobardi," and for the Taranto case study, the most links are "San Francesco di Paola" bridge and the "Porta Napoli" bridge. The calculation of the LII confirms the results obtained with the accessibility approach, as both methods identify the same critical scenarios.

Thanks to this indicator, policy makers can identify the critical points of the network and propose infrastructure prioritization programs. From this study, it is possible to highlight some interesting transport planning policies at both the national and local levels. At the national level, policymakers could use the study’s results to identify critical infrastructures and organize a funding allocation plan to enhance resilience. The proposed methodology could be used for vulnerability analyses at the national level. However, this procedure should necessarily be coordinated and integrated with European policies. Reducing the vulnerability of transport systems means making the system more

Table 3
Key findings.

Interrupted link	Average Accessibility reduction for the middle-sized city of Benevento	Number of districts with accessibility variation greater than 5 %	Link Importance Index	Ranking
Galleria Avellola	−0.78	0	0.22	3
Ponte Vanvitelli	−3.06	2	0.34	1
Ponte Tibaldi	−0.58	0	0.21	4
Viadotto delle Streghe	−0.41	0	0.09	5
Via dei Longobardi	−2.20	0	0.23	2

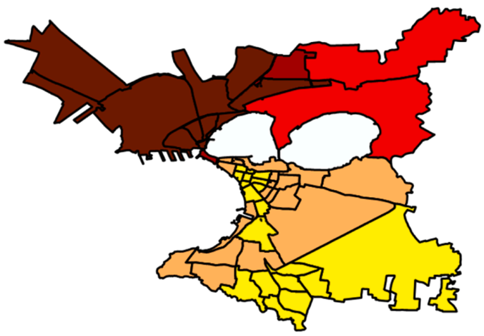

Fig. 23. Accessibility variation (%) for 1° scenario.

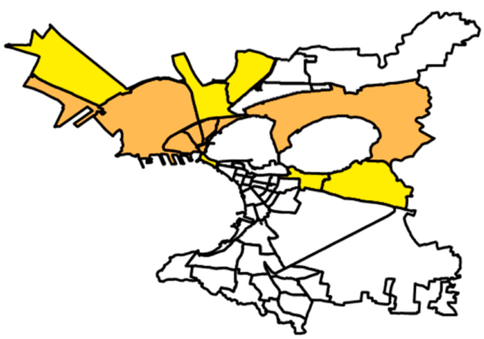

Fig. 24. Accessibility variation (%) for 2° scenario.

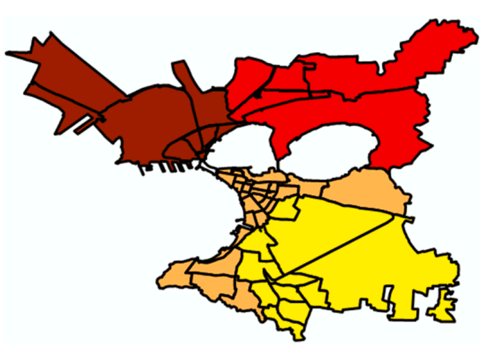

Fig. 25. Accessibility variation (%) for 3° scenario.

efficient and sustainable, in line with the guidelines of the European Green Deal [75], and thus more resilient to extreme events in line with the UE strategy on adaptation to climate change.

At the local level, this study could support the development of transport planning policies aimed at promoting targeted maintenance interventions, creating alternative routes, enhancing public transport, and managing hydrogeological risk. The analysis of the results shows that Taranto is the most vulnerable city to traffic disruptions. Its urban

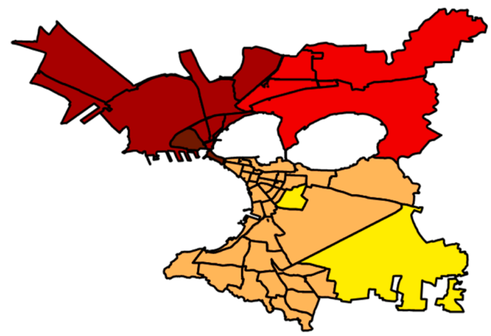

Fig. 26. Accessibility variation (%) for 4° scenario.

configuration, with a historic center located on an island, and the presence of only a few crucial connections make it more fragile compared to the other cities. Although the disruption scenarios also have an impact on the city of Avellino, the effects are much more significant for Taranto, with areas experiencing a reduction in accessibility of >15 % due to the lack of redundancy.

To reduce the vulnerability of the three cities, it is necessary to adopt targeted interventions based on the specific characteristics of each area. For Taranto, it would be essential to strengthen the maintenance of existing infrastructures and create alternative and redundant road routes that can be used in case of disruptions to the main connections. For Avellino and Benevento, given their mountainous geographical position, interventions such as slope stabilization and improved water management could reduce the risk of landslides or floods that could compromise the road network. Additionally, to reduce dependence on private transport, these cities could focus on improving public transport, which is less developed compared to Taranto. In the cities of Avellino and Benevento, the local public transport consists of bus and tram lines, while the city of Taranto also has a waterway service. Although the local public transport is not particularly well developed, it could be heavily impacted by road disruptions. These disruptions could increase travel times, cause overcrowding, and reduce accessibility for users who rely on public transport.

The internal urban accessibility of the two Irpinian cities could be improved by promoting cycling and pedestrian networks, especially considering their smaller surface area compared to Taranto.

6. Conclusion

This paper analyses the effects on urban mobility induced by the disruption of certain roads in three middle size cities of Avellino, Benevento, and Taranto, in south Italy. The proposed approach involves calculating two complementary indicators based on jobs distribution, changes in travel time and traffic flows to assess the impacts on urban areas from a transportation perspective. This research determines vulnerable regions by utilizing an accessibility index. Active accessibility serves as a valuable indicator for identifying disruptions in the road network and highlighting key critical links. Using Visum® software it was possible to identify the worst and best scenario for every analysed

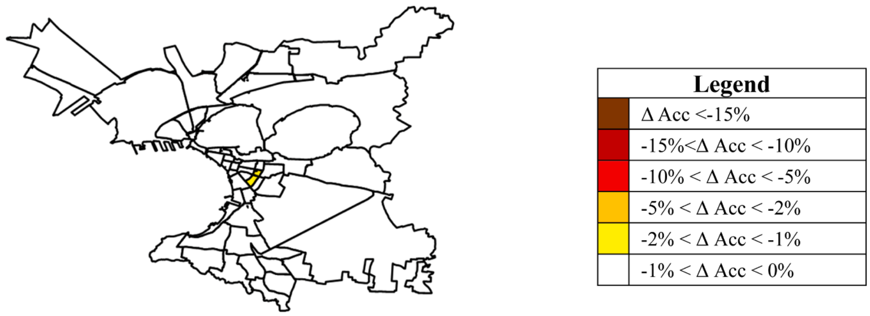

Fig. 27. Accessibility variation (%) for 5 scenario.

Table 4
Key findings.

Interrupted link	Average Accessibility reduction for the middle-sized city of Taranto	Number of districts with accessibility variation greater than 5 %	Link Importance Index	Ranking
Ponte Punta Penna SS7	−5.65	15	0.19	5
SS7 via Appia	−0.96	0	0.23	3
Ponte Porta Napoli	−4.65	14	0.39	2
Ponte San Francesco di Paola	−5.44	15	0.44	1
Via Magna Grecia	−0.37	0	0.20	4

case study.

There are many limitations in this research. It primarily examined a single mode of transportation, that is car demand. This means that the shift to other modes of transportation due to service interruptions is not considered. Another weakness concerns the use of bicycles, both electric and non-electric, which is growing. Benevento and Taranto demonstrate a stronger focus on promoting cycling mobility through the development of dedicated infrastructure and the provision of bike-sharing services. Another problem is the lack of identification of the external shock that leads to network closures. Simulating disruption scenarios for specific shocks would lead to a more accurate analysis. It would be possible to quantify not only the short-term effects on the system but also the long-term dynamic impacts, such as changes in commuter behaviour or network adjustments following prolonged events. This analysis is crucial when considering that these cities are fragile from a hydrogeological perspective. Moreover, the accessibility indicator introduced in this study considers only the distribution of jobs across the territory. Other socioeconomic variables, such as average income, population density, gender, age, or social vulnerability, already considered in some studies [76–78], could provide a more comprehensive picture of the impacts on the affected population.

Further research perspectives should include the following considerations. Firstly, the development of a multimodal supply model that allows the simulation of a more realistic behaviour. Indeed, the integration with other transportation modes is continuously improving, and this trend will need to be considered in a more accurate vulnerability analysis. It is essential to evaluate the impacts of integrating different transportation modes on the system's performance, and to specifically evaluate how disruptions influence the efficiency and reliability of public transport services. Secondly, this study could be integrated with the hydrogeological risk models, to identify the most vulnerable urban areas. The use of hydrogeological models for simulating landslides and floods would be essential. Compared to cities in northern Italy, which are also increasingly threatened by extreme weather events, the cities studied here have less developed road networks, less efficient public transportation, and a lower economic capacity to cope with and/or prevent from natural events. As a result, these cities could benefit more from preventive studies, as their resilience capacity is less developed.

Finally, to improve the methodology proposed in this paper, future research should develop a more inclusive vulnerability parameter. The latter should integrate both technical properties of the network, such as redundancy, reliability, robustness, rapidity, and socioeconomic characteristics of the population.

CRediT authorship contribution statement

Angela Stefania Bergantino: Supervision. **Gianmarco Troiani:** Writing – original draft, Methodology, Formal analysis, Data curation. **Tahseen Bashir:** Data curation. **Francesca Pagliara:** Writing – review & editing, Supervision.

Declaration of competing interest

I confirm that there are no conflicts of interest.

Data availability

Data will be made available on request.

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