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KEYWORDS

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JEL CODE

R41, R42, C63

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An analysis of road networks' vulnerability to disruptions through the specification of accessibility indicator

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January 7, 2025

Abstract

This study shows how the concept of accessibility can be used to measure the vulnerability of a mobility system, namely the amount of performance degradation experienced during the shock. Specifically, vulnerability is measured as the percentage variation of an indicator of accessibility before a certain event that hits the system occurs. As the authors show, this measure can be used to simulate the effects of various scenarios of disruptions, which may help administrators and urban planners to identify the most critical arteries and thereby target interventions.

Keywords: Transport vulnerability; Accessibility indicators; Road networks; Network disruption

JEL codes: R41; R42; C63

1. Introduction

Road networks are vulnerable to a range of risks, both natural and human-made, that can degrade the performance of the system, influencing the mobility of people and goods, with significant economic repercussions. Estimating the vulnerability of road infrastructure is essential for ensuring efficient and resilient urban management, as it allows for the identification of critical sections in the network and the planning of interventions aimed at reducing the impact of external shocks. The purpose of this study is to analyse the vulnerability of road networks in three different territorial contexts in Italy: the metropolitan area of city of Napoli, the medium-sized cities of Avellino, Benevento, and Taranto, and the inner areas of Irpinia and Piana del Sele. Using the Visum software, which allows for the simulation of different traffic disruption scenarios, the study aims to identify vulnerable areas. For each case study, an accessibility index has been calculated to assess the impact of disruptions on mobility and to determine the areas that could be most affected in the event of critical incidents. Although this framework is well-established in the literature (Papilloud and Keiler, 2021; Chen et al., 2007), our study tests this accessibility-based approach in various and new territorial contexts in Italy.

2. Outline of literature background

Vulnerability is determined by three factors: network topology, environmental characteristics, and mobility demand. The first factor concerns the physical structure of the network, including the geometric characteristics of the roads, the presence of critical elements such as bridges or tunnels, and the level of maintenance. The second factor relates to the topography of the territory and natural hazards, such as floods and earthquakes, which can affect network performance. The third and final factor involves the analysis of traffic flows and the areas within an urban zone that are most prone to congestion.

In recent decades, scientific literature has developed numerous approaches for analysing the vulnerability of road networks. These approaches include topological modelling, socio-economic analysis, and performance analysis of the transport system. Topological methods focus on network connectivity, aiming to identify critical sections, that is, specific roads whose disruption could cause significant damage to mobility. The study of properties such as redundancy, which measures the ability to reach the same destinations through alternative routes, helps to understand how flexible a network is in response to an external event. Topological methods often lead to determining rankings (hierarchies) of road importance within networks.

Socio-economic analysis assesses the impact of disruptions on mobility and access to essential services. Accessibility, defined as the ease with which people can reach destinations such as workplaces, hospitals, and schools, is often used as a key indicator to evaluate the impact of road interruptions. Variables such as the resident population and/or employees, the number of essential services like hospitals and schools present in a given area, can be used in defining various accessibility indices. As a result, the distribution of activities also plays a fundamental role in determining the mobility patterns of an area. Lastly, the approach based on performance analysis of the system measures the increase in perceived generalized cost by users, the increase in travel time, or the reduction in capacity following the disruption. Regardless of the methodology used, vulnerability analysis involves calculating an indicator, more or less complex, before and after a certain external shock (floods, traffic accidents, etc.).

3. Data and descriptive statistics

In this section, the case studies of the metropolitan area of the city of Naples, the medium-sized cities of Avellino, Benevento, and Taranto, and the inland areas of Piana del Sele and Irpinia are presented.

Table 4.0.1. Main characteristics of the 6 case studies considered

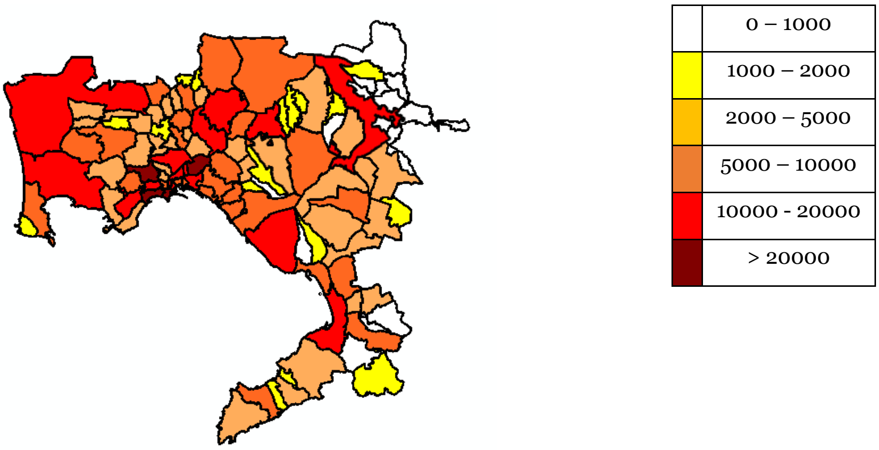
Region	Area [Km^2]	Traffic zones	Population	Jobs
Metropolitan area of Naples	1.171	112	3.055.000	783.490
Middle sized city of Avellino	30	24	52.063	24.966
Middle sized city of Benevento	130	30	55.815	22.381
Middle sized city of Taranto	250	52	186.258	67.208
Inner area of Irpinia	2.800	138	418.306	97.701
Inner area of Piana del Sele	250	52	160.095	39.193

3.1 Metropolitan area of Naples

The metropolitan area of the city of Naples covers approximately 1.171 km^2. It is bordered to the east by the Sorrentine Peninsula, to the west by the Phlegraean Fields, and to the northwest by the southern side of the Campanian plain. It is the third most populous metropolitan area in Italy, following Rome and Milan, with over 3 million inhabitants. It includes 82 municipalities, while the municipality of Naples, with a population of nearly one million people, is divided into 30 districts. For traffic analysis, the entire area has been divided into 112 zones, with Figure 4.1 showing the jobs distribution (source: ISTAT).

Figure 4.1. Naples: jobs distribution

Legend



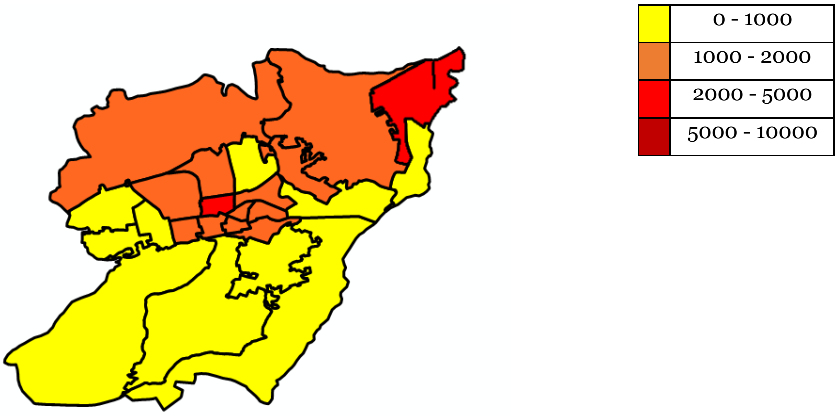
Approximately 41% of the workforce is located exclusively within the municipality of Naples. The road network has been imported from OpenStreetMap. The city plays a crucial role as a major hub for national road and highway networks. From the urban center, the A1 highway extends north, the A3 highway heads south, and the A16 highway leads towards the Adriatic coast. Within the city, the main road for traffic is the ring road (tangenziale), supported by other significant arteries such as the Asse Mediano, the Circumvallazione Esterna, the Melito-Scampia Perimeter Road, and State Road 162.
The demand matrix has been developed using data from the Urban Plan for Sustainable Mobility – Metropolitan City of Naples 2022 (Piano Urbano della Mobilità Sostenibile – Città Metropolitana di Napoli) and has been assigned to the road network using a stochastic user equilibrium assignment method, allowing for the estimation of car traffic during peak hours on a typical weekday morning.

3.2 Middle sized city of Avellino

The city of Avellino has approximately 52.000 inhabitants. This city is located in the flat part of a basin, a valley formed by volcanic activity in the southern Apennines. The city is bordered to the east by Mount Tuoro, to the southeast by the Picentini mountain range, and to the northwest by the Montevergine massif. Avellino has been divided into 24 homogeneous traffic zones. Figure 4.2 shows the distribution of workers in the city (source: ISTAT).

Figure 4.2. Avellino: jobs distribution

Legend



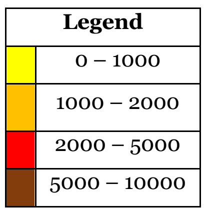
The road network has been obtained from the OpenStreetMap site and covers an area of approximately 30 km^2. The city is traversed by the A16 highway to the northwest and by State Road 7, known as Via Appia, in the southern part.

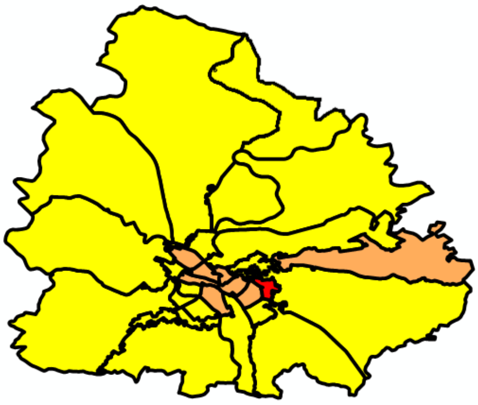
The origin-destination (O-D) matrix has been derived from data collected during the 15th general census of population and housing in 2015 (ISTAT), which analysed commuter movements. The O-D matrix was then integrated into the road network using a stochastic user equilibrium approach, allowing for the estimation of car traffic flow between the 24 zones during morning peak hours on a typical weekday.

3.3 Middle sized city of Benevento

The city of Benevento has a population of approximately 56.000 inhabitants. It is located in the Apennine inland region and is crossed by the Calore and Sabato rivers. The whole urban center is situated in a large basin surrounded by hills; to the west rises the Taburno Camposauro massif, while to the southwest stands Mount Avella. Benevento has been divided into 30 homogeneous traffic zones, and Figure 4.3 shows the distribution of workers (source: ISTAT).

Figure 4.3. Benevento: jobs distribution





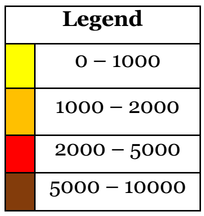
The road network of the city of Benevento has been obtained from the OpenStreetMap site and covers an area of approximately 130 km^2. The city is encircled by the “SS 752 Benevento Ring Road” and is crossed by several state roads, including “SS 372 Telesina,” “SS 90,” “SS 7,” “SS 88,” and “SS 87.”

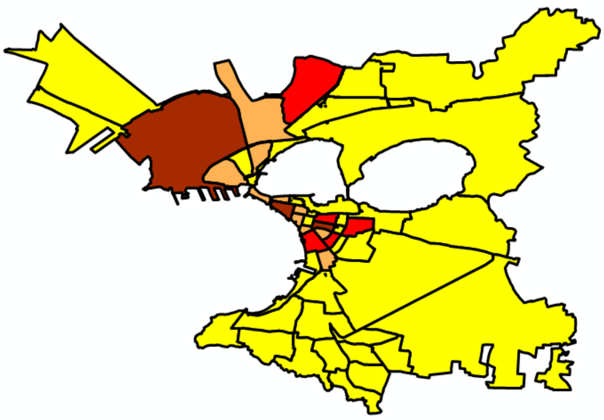
The origin-destination (O-D) demand matrix for car traffic has been built using data collected during the 15th general census of population and housing in 2015 (ISTAT). The O-D matrix was integrated into the road network through a stochastic user equilibrium method, providing an estimate of car traffic demand between 30 traffic zones during morning peak hours on a typical weekday.

3.4 Middle sized city of Taranto

The city of Taranto has approximately 186.000 inhabitants. It is the second most populous city in the Puglia region and overlooks the Ionian Sea. The city's territory is primarily flat and extends over three natural peninsulas and an island, the latter being home to the historic center. Taranto has been divided into 52 homogeneous traffic zones, and Figure 4.4 shows the distribution of workers (source: ISTAT).

Figure 4.4. Taranto: jobs distribution



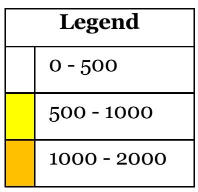


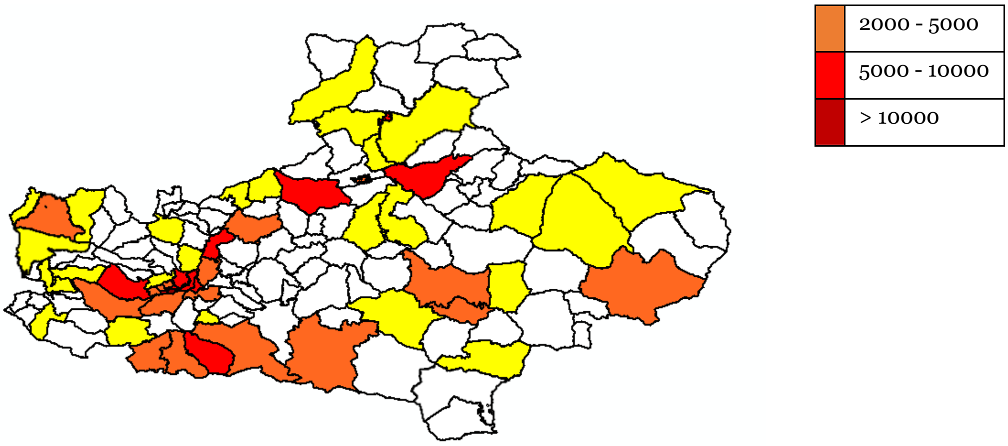
The road network of Taranto has been obtained from OpenStreetMap and covers an area of approximately 250 km². The city is crossed by several major national roads, including the "A14" highway, "SS 106," "SS 100," and "SS 7."
The origin-destination (O-D) demand matrix for car traffic has been created using data collected during the 15th general census of population and housing in 2015 (ISTAT). The O-D matrix was integrated into the road network through a stochastic user equilibrium method, determining car traffic demand between 52 traffic zones during morning peak hours on a typical weekday.

3.5 Inner area of Irpinia

Irpinia is an inner region situated within the heart of Campania, spanning a large area of about 2.800 km², predominantly made up of hills and mountains in the Avellino province. To the north, it is bordered by the Picentini Mountains, to the east by the Dauni Mountains, and to the south, it stretches to the Sele River valley and the Terminio massif. Irpinia is predominantly a rural area, with an economy largely based on agriculture and livestock farming. Administratively, Irpinia comprises 118 municipalities. The total population is about 420.000, with a relatively low population density of around 100 inhabitants per square kilometer. The area has been divided into 138 homogeneous traffic zones, and Figure 4.5 shows the distribution of workers (source: ISTAT).

Figure 4.5. Irpinia: jobs distribution



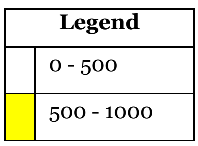


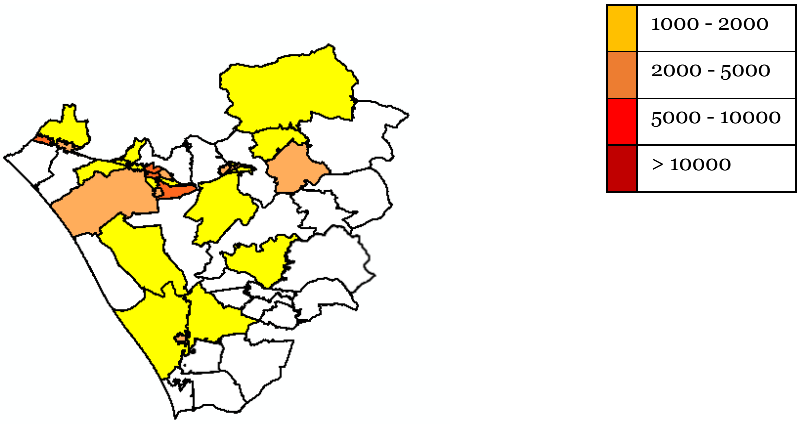
The road network of Irpinia, obtained from OpenStreetMap data, is quite complex and presents several challenges due to the geographical terrain. Among the main arteries crossing this region are State Road 7 (Via Appia), which connects Avellino with Benevento and the rest of Campania; State Road 303, which traverses the mountainous areas connecting the small towns of inland Irpinia; and the A16 Napoli-Canosa highway, which ensures Irpinia's connection to the national highway network.
The travel demand matrix has been developed using data collected by ISTAT in the 2015 survey. Subsequently, the mobility demand has been distributed across the road network using a stochastic user equilibrium model, allowing for the calculation of car traffic demand during peak morning hours on a typical weekday.

3.6 Inner area of Piana del Sele

The Piana del Sele is a plain located in the province of Salerno. This territory is bounded to the east by the Alburni Mountains, to the north by the Picentini Mountains, to the south by the Cilento hills, and to the west by the Tyrrhenian Sea. The plain covers an area of approximately 250 km^2 and is known for its strong agricultural and livestock production. Several rivers cross the plain, including the Sele River, which stretches for about 64 km, and the Calore Lucano River, an important tributary of the Sele, extending for about 70 km. Administratively, the Piana del Sele spans 9 municipalities and has been divided into 52 traffic zones. Figure 4.6 shows the jobs distribution (source: ISTAT).

Figure 4.6. Piana del Sele: jobs distribution





The road network has been obtained from OpenStreetMap and includes essential arteries such as State Road 18 Tirrena Inferiore, which runs along the coast, and the A3 highway (Salerno-Reggio Calabria), which connects the area to the rest of the region and the country.
The travel demand matrix has been developed using data collected in the latest ISTAT survey conducted in 2015. This matrix has been assigned to the road network using the stochastic user equilibrium method, allowing for the estimation of car traffic during peak morning hours on a typical weekday.

4. Methodology

The methodology used in this study employs the concept of accessibility to identify vulnerable areas. Accessibility measures how easily a user, located in a specific place, can engage in activities in other locations. Active accessibility refers to users' ability to reach a specific destination, such as a shop or a service, and is calculated as follows:

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

The active accessibility of traffic zone i (AA_i) is a function of the travel time T_{ij} between zones i and j, the number of workers K present in zone j weighted by two parameters β_1 and β_2. The change in accessibility of a traffic zone in the network observed after a traffic disruption represents its degree of vulnerability:

$$Vulnerability_i = \frac{Acc_i^1 - Acc_i^0}{Acc_i^0} \quad (2)$$

Vulnerability of traffic zone i is measured as the percentage change in accessibility before (Acc_i^0) and after (Acc_i^1) a certain event. This event refers to an occurrence that disrupts the normal flow of traffic on a road. A traffic zone is defined as an area from which movements can be assumed to start and end at the same point, referred to as the zone centroid. This area is homogeneous from a transport perspective. This methodology was conducted using Visum software, which calculates travel times between the various traffic zones in the area. It has been tested at different and new territorial scales in Italy. The base scenario represents normal traffic conditions within the study area, while in the "disruption scenario," a traffic disruption on a specific road is assumed. By comparing the base scenario and the disruption scenario, a vulnerability map can be produced. The vulnerability maps generated from the simulations provide an immediate overview of high-risk areas, allowing local authorities to plan targeted interventions to improve the resilience of the network.

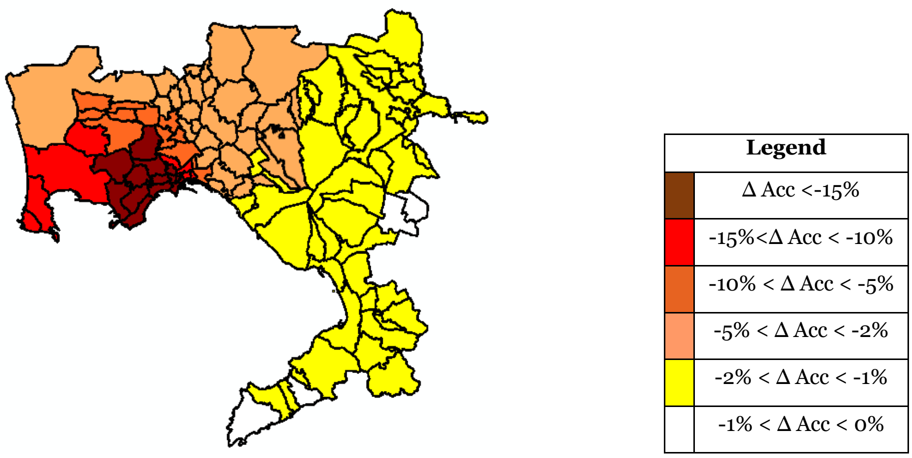
5. Findings and discussion

For each case study, various disruption scenarios were hypothesized. Among all the simulated scenarios, the one with the most significant impact on urban mobility will be referenced. In accordance with equations 1 and 2, only the corresponding vulnerability maps are presented.

5.1 Metropolitan area of Naples

The worst scenario for the metropolitan area of the city of Naples is with the closure of the section of the ring road (Tangenziale di Napoli from exit 4 to exit 6). Figure 4.7 shows the corresponding vulnerability map.

Figure 4.7. Naples: accessibility variation (%) following the disruption of the Tangenziale di Napoli

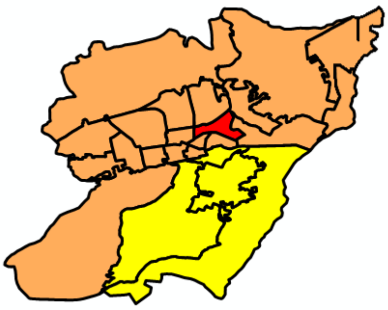


The section of the ring road from exit 4 to exit 6 is approximately 3 km long and has three lanes in each direction. It passes through three neighborhoods in central Naples. According to the PUMS (Urban Plan for Sustainable Mobility – Metropolitan City of Naples, 2022), the Naples ring road is used by about 17.000 vehicles daily and serves as the main artery connecting the western and eastern parts of the city, as well as being the primary access route to the airport. Following the closure, the average accessibility decreased by 5.43%. Only four zones were unaffected by the ring road closure. In 22 zones, accessibility reductions exceeded 10%, while in 11 zones, the decrease ranged between 5% and 10%. Notably, 14 zones recorded a reduction in accessibility of more than 15%.

5.2 Middle sized city of Avellino

The greatest impact on mobility within the city of Avellino occurs with the closure of "Via Circumvallazione." Figure 4.8 shows the corresponding vulnerability map.

Figure 4.8. Avellino: accessibility variation (%) following the disruption of via Circumvallazione



Legend	
	Δ Acc <-15%
	-15%<Δ Acc < -10%
	-10% < Δ Acc < -5%
	-5% < Δ Acc < -2%
	-2% < Δ Acc < -1%
	-1% < Δ Acc < 0%

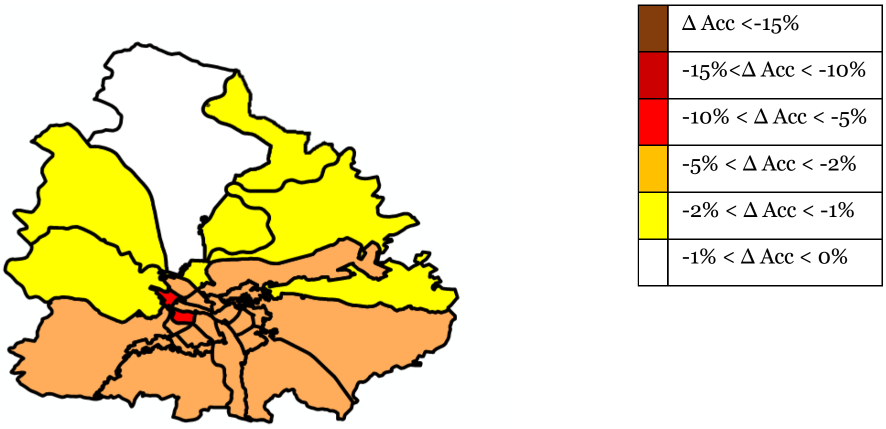
This road crosses two zones in the historic center of Avellino, is approximately 3 km long, and has one lane in each direction. Following the closure of this road, accessibility within the study area decreases by 3.42%. All zones are affected by the disruption, with 19 zones experiencing a decrease in accessibility ranging between 2% and 5%, while only one zone sees a reduction greater than 5%.

5.3 Middle sized city of Benevento

The traffic disruption on the "Vanvitelli" bridge in the historic center of Benevento represents the worst-case scenario. Figure 4.9 shows the corresponding vulnerability map.

Figure 4.9. Benevento: accessibility variation (%) following the disruption of Vanvitelli bridge

Legend

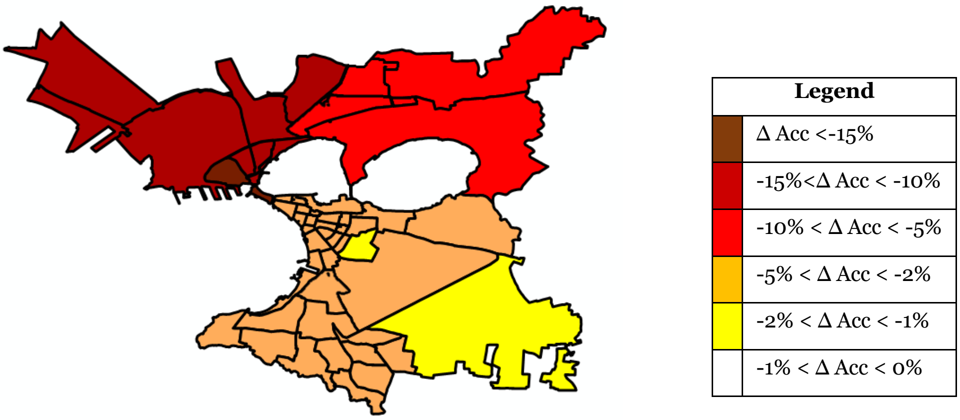


The Vanvitelli bridge is approximately 110 meters long and has two lanes in each direction. It is located in the northwest area of the city center and serves as the main access route to the historic center, passing over the Calore River. Following its closure, two zones experience a decrease in accessibility of over 5%, while in 20 zones, the reduction in accessibility ranges between 2% and 5%. Overall, accessibility across the city decreases by an average of 3%.

5.4 Middle sized city of Taranto

For the city of Taranto, the closure of the San Francesco di Paola bridge represents the worst-case scenario. Figure 4.10 shows the corresponding vulnerability map.

Figure 4.10. Taranto: accessibility variation (%) following the disruption of San Francesco di Paola bridge

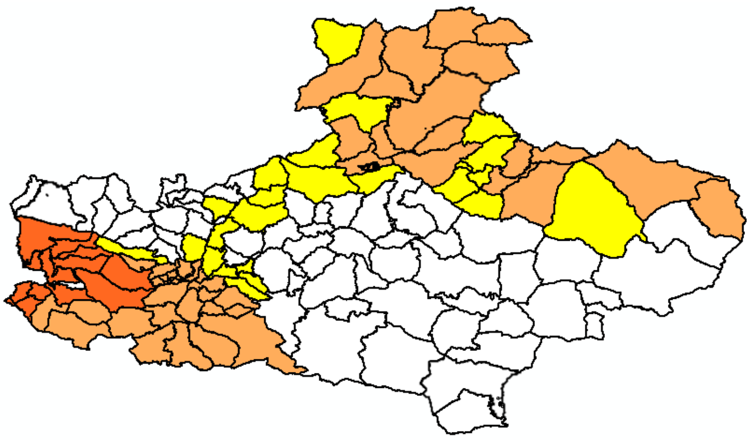


The San Francesco di Paola bridge is 90 meters long and has one lane in each direction. Along with the Porta Napoli bridge, it connects the historic center with the rest of the city. The traffic disruption on the San Francesco di Paola bridge results in an average accessibility reduction within the city of 5.65%. Two zones experience a decrease of over 15%, while nine zones see a reduction of more than 10%.

5.5 Inner area of Irpinia

The closure of the tunnel along the A16 highway, which falls within the territory of the municipality of Montemiletto, represents the worst-case scenario for the inland area of Irpinia. Figure 4.11 shows the corresponding vulnerability map.

Figure 4.11. Irpinia: accessibility variation (%) following the disruption of the tunnel



	Legend
	Δ Acc <-15%
	-15%<Δ Acc < -10%
	-10% < Δ Acc < -5%
	-5% < Δ Acc < -2%
	-2% < Δ Acc < -1%
	-1% < Δ Acc < 0%

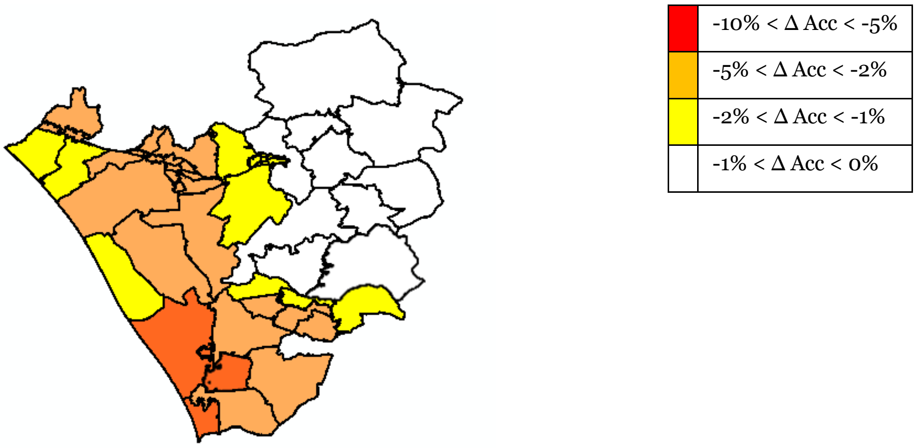
The tunnel along the A16 in the municipality of Montemiletto is approximately 950 meters long and has two lanes in each direction. Following its closure, there is an average decrease of 2.42% across the entire Irpinia region. In over 30 zones, the decrease ranges between 2% and 5%, while in 13 zones the reduction is between 5% and 10%.

5.6 Inner area of Piana del Sele

For the case study of the Piana del Sele, the worst-case scenario occurs with the traffic disruption on the "Barrizzo" bridge along State Road 18. Figure 4.12 shows the corresponding vulnerability map.

Figure 4.12. Piana del Sele: accessibility variation (%) following the disruption of Barrizzo bridge

	Legend
	Δ Acc <-15%
	-15%<Δ Acc < -10%



The Barrizzo bridge is approximately 52 meters long, has one lane in each direction, and is located in the municipality of Capaccio. Following its closure, the accessibility of the Piana del Sele decreases by about 2.22%. Three zones experience an accessibility decrease of more than 5%, while 23 zones see a reduction of over 2%.

6. Policy implications and recommendations

Considering the results obtained, road infrastructure management policies must be adapted to the specificities of different territorial contexts. The metropolitan area of Naples is crucial hubs for regional and national mobility. The vulnerability of road networks in this area, especially for key arteries such as ring roads and highways, has significant implications for the entire transportation system. For instance, the blockage or interruption of the Naples ring road could paralyze a large portion of the city's traffic and vital connections to other regions. It is essential to address infrastructure vulnerability through a multi-level approach. This entails managing the network with targeted maintenance interventions focused on the most critical arteries, as well as infrastructure investments aimed at improving network resilience. At the same time, it is advisable to promote the use of efficient public transportation and the development of bike lanes to reduce road congestion. Local authorities should also invest in continuous infrastructure monitoring systems and preventive maintenance to identify and promptly address issues.

Medium-sized cities, such as Avellino, Benevento, and Taranto, face specific challenges related to their geographical location and urban structure. The vulnerability of their road networks can significantly impact local mobility and the quality of life of residents. An example is Taranto, where the geographic location and the importance of the port necessitate improving the accessibility and safety of key arteries, both to facilitate freight transport and ensure better local mobility. Given the lower complexity of road networks, policies should focus on improving the accessibility and safety of local roads.

The mid-sized areas, such as Irpinia and Piana del Sele, are characterized by low population density and often underdeveloped road networks. However, vulnerability in these areas, often exacerbated by hydrogeological risks, can isolate rural communities and hinder access to essential services. Policies should focus on preventive measures, such as regular maintenance of local roads, and on environmental monitoring systems to prevent risks associated with natural events. In these contexts, it is crucial to invest in resilient and safe infrastructure, implementing alternative routes and enhancing the existing road network to ensure that communities do not become isolated.

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