A Mesoscopic Approach for Calculating Resilience Indicators in Emergency Conditions

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Abstract. A transport system involved in a hazardous event may experience some changes in demand (the users want to move all together) and in supply (disruption). By considering these elements, this work aims to provide a measure of the resilience of a road network when a sudden event occurs, focusing on the use of some indicators for resilience evaluation to support an emergency plan. The approach considers both the outgoing flow from the study area and the incoming one (e.g., rescue vehicles). An aspect that will be evaluated concerns the variation in resilience over time. In fact, for events whose effects are not immediate or are distributed over a period of time, resilience may change because the magnitude of the effects on the network changes. A simulation of the transport system, based on a mesoscopic approach, allows one to calculate the indicators for each time interval.

Keywords: resilience · road network · dynamic assignment · assessment · indicators · planning

1 Introduction

Resilience of a system can be defined as its ability to return to its initial state after having undergone an event (natural or anthropic) that perturbed such a state. In a transport system, a sudden event, or an event whose effects spread over time, can cause disruptions in the road network, with impacts on how users move within the area (for example, because of reduction of the available routes). The impossibility of using some arcs in a road network due to damage or other obstacles that can arise in an emergency reduces the performance of the network in terms of travel times [1, 2]. The importance of resilience is even more evident in the situations where the event results in evacuation of the area considered ([3–7]). In this case, there are both people trying to leave the area to go to a safe place and rescue operators entering the area to provide help.

Thus, the problem arises of strengthening the transport network to minimize loss of performance. This can be achieved, for example, if there are alternative (redundancy) routes that allow one to bypass unusable arcs. This type of analysis provides information on the resilience of the transportation network and possible methods to quantify it.

Studies on road network provide information on the ability of the system to withstand extreme events and its ability to return to initial conditions. The resilience assessment

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passes through the evaluation of other network indicators, such as travel time reliability ([8, 9]), capacity ([10, 11]), vulnerability ([12, 13]).

Considering a sudden event, its effects will influence the system for a certain period of time during which resilience will first have a decrease and then a variation (growth or decrease) in relation to what happens within the system. However, if the event is not sudden [14], its effects spread throughout the system over a certain period of time, during which the performance continues to decrease. The recovery phase then follows with a gradual return to the initial value. The approach proposed in this paper allows us to evaluate the system performance indicators in both cases.

Figure 1 shows a general situation. An event occurs at instant *t1,* and the network performance decreases immediately. The duration of the event is up to instant t_2, where its effects end, causing a further decrease in performance due to congestion effects caused by the users moving in the network. Restoration operations could begin at instant t_3 with a consequent increase in performance (from t_2 and t_3 the performances could continue to decrease because network travel costs have increased). It is possible to note that, in the particular case of an evacuation, the start of the evacuation can be any instant after t_1. From the previous considerations, it emerges that two factors must be considered: the disruptions due to the event and the effects due to the peak demand using the road network.

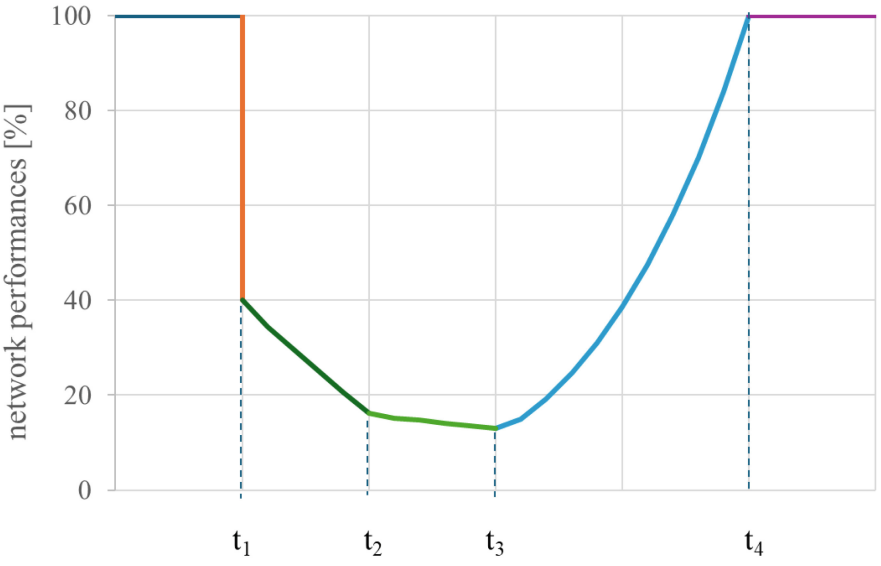


Fig. 1. Performance and resilience.

This work, taking into account that road network performance (and consequently resilience) depends on time, proposes an approach based on dynamic assignment (a mesoscopic approach) able to assess the network over time (the approach is based on

discrete time intervals). The indicator used in this (preliminary) approach is based on the variation in the available routes and in their cost.

The paper is structured as follows. Section 2 contains a review of the literature, Sect. 3 summarizes the proposed methodology, and Sect. 4 reports on a test application. Finally, the conclusions and future developments.

2 Literature Review

The impacts of hazardous events cause disruptions to the road network, which affect resilience. Several works in the literature tackled this topic from different points of view. Without the presumption of exhaustiveness, we will follow a brief review on this topic.

Ilbeigi [15] introduced a statistical approach to evaluate resilience in relation to the duration of the disturbance caused by the event and the variation in the performance of the network before and after the event. Ganin et al. [16] estimated the resilience of a road network by considering the effects resulting from road disruption. In this approach, the resilience has been evaluated for different degrees of arc disruption, using as an indicator the total user delay. Hsieh and Feng [17] examined the resilience of an highway network, highlighting the factors that can be used in modeling resilience. Edrissi et al. [18] linked resilience to the concept of network reliability. Classifying arcs in relation to their contribution to network resilience, the importance of an arc is derived from the probability of failure. In this way, the operations needed to improve the network start with the most important arcs. Similarly, Martin et al. [19] developed a framework capable of assessing resilience in relation to accessibility, also considering the cumulative effects on the arcs of different events. Qiang and Xu [20] proposed measuring the resilience of a road network in relation to the variation of accessibility during a disruption event. Gauthier et al. [21] quantified the resilience of the network by considering as a measure the variation in travel costs. Identified the arcs most critical for the operation of the road network, a procedure is proposed to assess the impact of disruptions on the network and the ability of the network to return to its initial state. Li et al. [1] proposed a framework for assessing resilience when a chain of disruptive events occurs, taking into account that repair actions may not be concluded between one event and the next. This approach can be used for long-term planning in order to define measures for resilience improvement. Similarly, Aydin et al. [22] proposed a multistep approach to plan recovery procedures after network disruption and compared the time to return to normality in relation to the recovery strategies adopted. Zhang et al. ([23]) presented an approach to assess the resilience of the road network based on the fundamental diagram ([24]) inserted within a dynamic model, the purpose being to simulate the trend of traffic congestion in relation to speed. Faturechi and Miller-Hooks [25] developed a bilevel approach to evaluate and optimize the reliability of a road network (in terms of travel time) when a disruptive event occurs. In the resilience evaluation, the behavior of users is considered.

Kaviani et al. ([26]) proposed a model to optimize the locations of roadside information systems with the aim of reducing total travel time in a disrupted network. Ma et al. [27] developed a framework to assess the resilience of a road network when rainwater accumulates on roads and affects speed. Similarly, Chalkiadakis et al. [28] proposed a framework for evaluating the resilience of a road network under the assumption of

failure of some elements, while Akbarzadeh et al. [29] evaluated the effect that the failure of a node or arc has on the entire network, linking this aspect with the definition of resilience. Aghababaei et al. [30] proposed a resilience measure that evaluates the impact of not available trips and the increased travel time in a post-disaster situation. This indicator, evaluated over time, also takes road network recovery actions. Wu and Chen [31] developed a methodology for the assessment of road resilience taking into account the counter-flow operations needed in the affected area to provide assistance to people. The aim of the approach is to increase the availability of routes (redundancy) to facilitate access to emergency vehicles.

3 Methodology

It is useful to remember that when an event causes an emergence condition, the decline in network performance (and therefore its return to initial conditions) depends not only on disruptions caused by the event but also on the fact that the users move on the network despite the impediments.

The approach described in this section (Fig. 2) aims to calculate some network and resilience indicators based on dynamic simulation of road transport dynamic simulation. The dynamic approach allows these indicators to be evaluated for each time interval, allowing us to evaluate how resilience varies over time. The simulation of the system is carried out using a mesoscopic approach [32], considering a set of discrete time intervals.

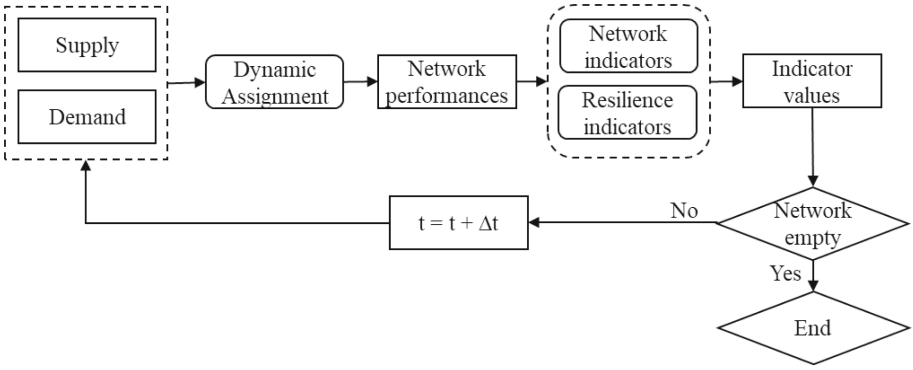


Fig. 2. The proposed procedure.

The procedure takes as input the *supply* and *demand*; both depend on the discrete time interval t considered. The supply is represented by a graph $G\ (N, L)$, where N is the set of nodes and L is the set of arcs. Each arc is supposed to consist of two parts: a running segment and a queueing segment; the separation point S between them is influenced by the flow conditions and its position is calculated at the beginning of each simulation interval. Other elements considered in the width of the simulation are the arc (C_a), the capacity (Q_a, assumed as the capacity of the final section of the arc), and a threshold value for the density of the arc ($k_a{}^{max}$). In this approach, vehicles moving on the network

are grouped into homogeneous packets, each of which is characterized by a departure instant η, an origin-destination pair *rs,* and a vehicle class u (each vehicle class has some characteristics, such as speed and occupancy, associated with it). Thus, considering a packet $p\{\eta, rs, u\}$ such a packet contains vehicles of the same class u that travel from r to s starting in the same instant η. The outflow conditions are supposed to be homogeneous for each arc and do not vary within a time interval. The output of the assignment is the *network performances* (for each interval) in terms of link flows and travel costs. From this output, some *indicators* (both for the *network* and for *resilience*) are considered. In normal situations, it may happen that the user adapts the route choice while moving from the origin to the destination (re-routing). Even in emergency situations, such an eventuality can be hypothesized. In both cases, the available routes depend on the user's location on the network. Without harming the generality of the approach, it is assumed that the user evaluates the available routes at the beginning of each simulation interval. Let be: x the position of the generic user (such a position coincides with the origin at the beginning of the first interval), I_{xs} the set of routes from current position to destination s, the first *resilience indicator* is defined as follows:

$$R_k = \frac{\sum_x \sum_s \sum_{k \in I_{xs}} \gamma^B_{xsk} \cdot g^B_k}{\sum_x \sum_s \sum_{h \in I_{xs}} \gamma^A_{xsh} \cdot g^A_h} \tag{1}$$

A transformation of the indicator reported in Eq. (1), to which a behavioral interpretation can be given [33], can be the following:

$$R_a = \frac{\ln \sum_k \exp(-g^B_k)}{\ln \sum_h \exp(-g^A_h)} \tag{2}$$

Equation 1 considers as the resilience metric the variation of the available routes before (superscript B) and after (superscript A) the event. γ^B_{xsk} is a binary variable equal to 1 if the route k connects the current position x of the user with the destination s, 0 otherwise; ${g^B}_k$ is the cost of the route from the current position of the user to the destination. Equation 2 deals with the variation in satisfaction of the users (can also be seen as a variation in accessibility), expressed the ratio between the logsum [33] of systematic utility V of the available routes before and after the event. Obviously, the value of both indicators is equal to 1 if, in a specific time interval, the system does not change.

Another indicator considered ([12]) is related to each packet moving on the network, and can be considered as the weakness of the network. Let:

$$n^K_{xs} = \sum_{k \in I_{xs}} \sum_{l \in L} \delta_{lk} \tag{3}$$

$$\xi^l_{xs} = \sum_{k \in I_{xs}} \delta_{lk} \quad \forall l \in L \tag{4}$$

$$\zeta_l^{xs} = \begin{cases} \xi_{xs}^l & if\ \xi_{xs}^l = 1 \\ 1 & if\ \xi_{xs}^l > 1 \\ 0 & otherwise \end{cases} \tag{5}$$

$$n_{xs}^G = \sum_{l \in L} \zeta_l^{xs} \tag{6}$$

where x is the current position of the generic packet, δ_{lk} is the generic element of the arcs-routes incidence matrix (equal to 1 if the arc l belongs to the route k, 0 otherwise) and I_{xs} is the set of routes for the origin-destination pair xs (*choice set*).

Following the previous definitions, the index is formalized as follows:

$$R_w^{xs} = \begin{cases} \dfrac{\frac{n_{xs}^K}{n_{xs}^G} - 1}{|I_{xs}| - 1} & if\ |I_{xs}| > 1 \\ 1 & if\ |I_{xs}| = 1 \end{cases} \tag{7}$$

In Eq. (7) the resilience indicator relies with routes and their topology for each origin-destination pair. In fact, the element n_{xs}^K is the count of the arcs belonging to the routes in the choice set (without considering overlaps), while the element n_{xs}^G is also a count of arcs, but counting the arcs common to different routes only once. The value of this indicator is in the interval [0, 1]: a value of 0 indicates that for the xs pair there is more than one route and that there is no overlap between the routes, while a value of 1 indicates the availability of just one route for the xs pair. Note that, since the number of routes depends on the position of the user, the size of the choice set may vary during simulation.

Regarding network indicators, a first indicator is the network clearance time, defined as the difference between the time the last packet p reaches the destination and the beginning of the simulation τ.

$$T_C = \max_{i,r,s} \left[\eta_s^i - \tau \right] \quad i \in P \tag{8}$$

where P is the set of packets.

Let T_s be a threshold value for the clearance time and P_s ($P_s \subseteq P$) the set of packets arriving at the destination in a time less than T_s, defined as:

$$P_s = \left\{ i \in P | (\eta_s^i - \tau) \leq T_s \right\} \tag{9}$$

The second indicator considered is the rate at which packets arrive at their destination before T_s:

$$S = |P_s|/|P| \tag{10}$$

4 Application

An application is provided to test the effectiveness of the proposed approach. The site test chosen for the application is the city of Avellino, located in the Campania region, South Italy (Fig. 3). The city ([34]) covers an area of approximately 2.8 square kilometers and has approximately 420.000 inhabitants. For the objectives of this work, the central part of the city (Fig. 4, approximately 55.000 inhabitants) was considered. The road network is represented by a graph (Fig. 4) consisting of 112 nodes and 283 arcs. Each arc is characterized by length, width, number of lanes, free flow speed, and capacity.

For the purposes of this test, an emergency scenario is generated by assuming that the river crossing the city overflows its banks and partially floods some streets, affecting the capacity and speed with related reduction in the network performance (this scenario is one of those hypothesized by the Italian civil protection in relation to the emergency plans made for the city). The arcs involved in the event are eleven, and for these arcs the speed is reduced by 75%, the capacity is reduced by 90%.

The simulation is done for discrete intervals, each of which has a width of 10 min, and the demand is generated for the first 6 intervals. The event occurs in the interval $h = 2$: it is assumed that the effect is immediate on the arcs.

Figure 5 shows a comparison between the total travel time in the current scenario and the travel time in the emergency scenario. To make the figure clearer, couples for which the travel time increased by more than 20% were considered. In this application, there are about 27% of simulation intervals where the travel time remains the same, about the 12% where the increase in travel time is less than 5%, and the 10% for whom the time more than doubled (Fig. 6).

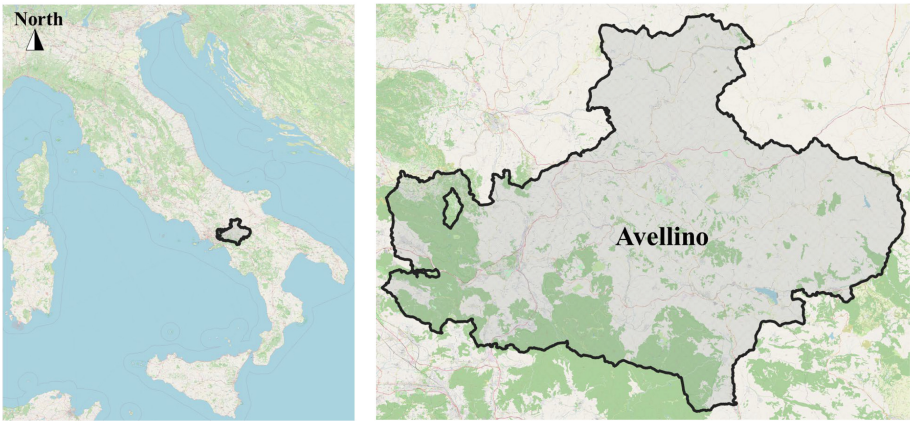


Fig. 3. Avellino test area (background map from OpenStreetMap, [35]).

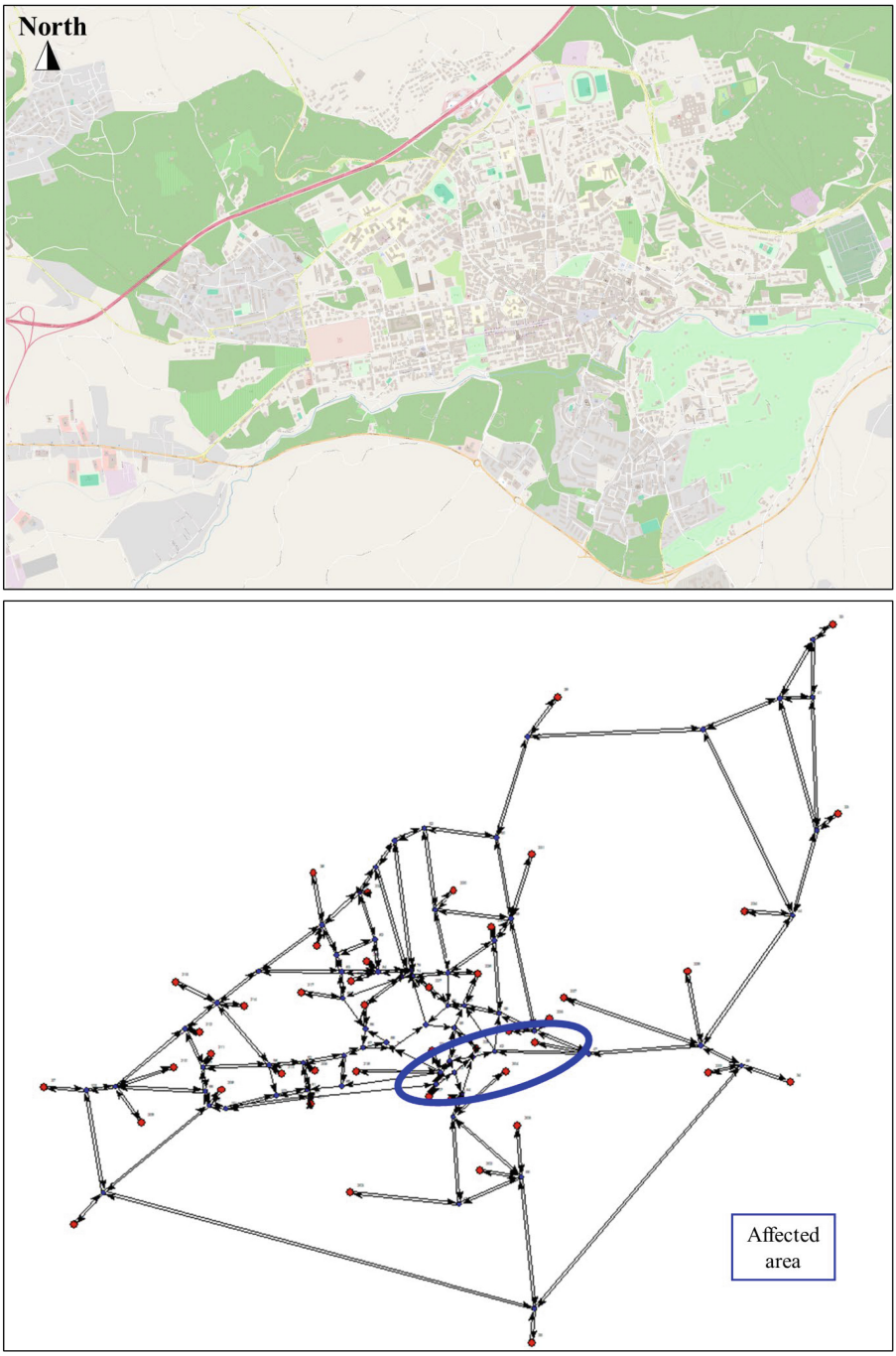


Fig. 4. The central area of the city and the related graph (background map from OpenStreetMap, [35]).

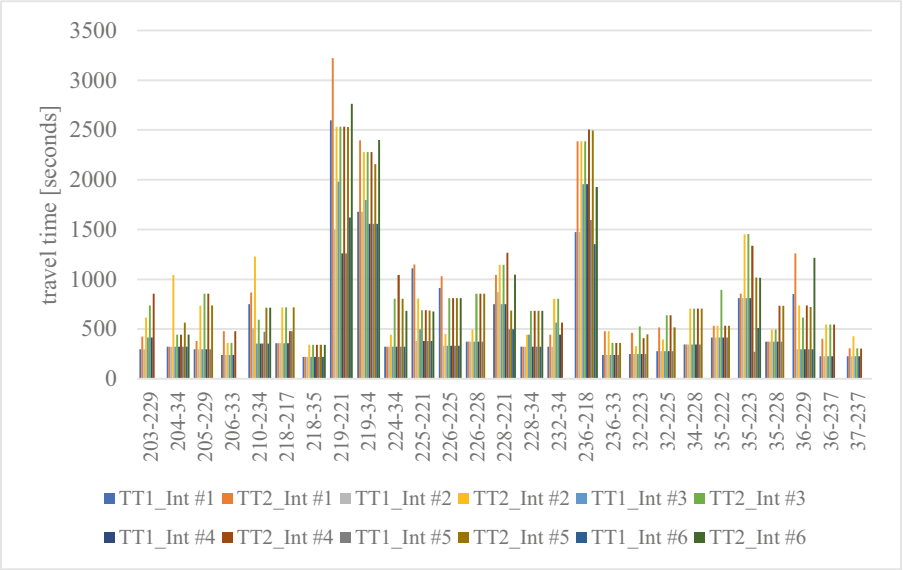


Fig. 5. Comparing the travel time: current scenario *vs* emergency scenario.

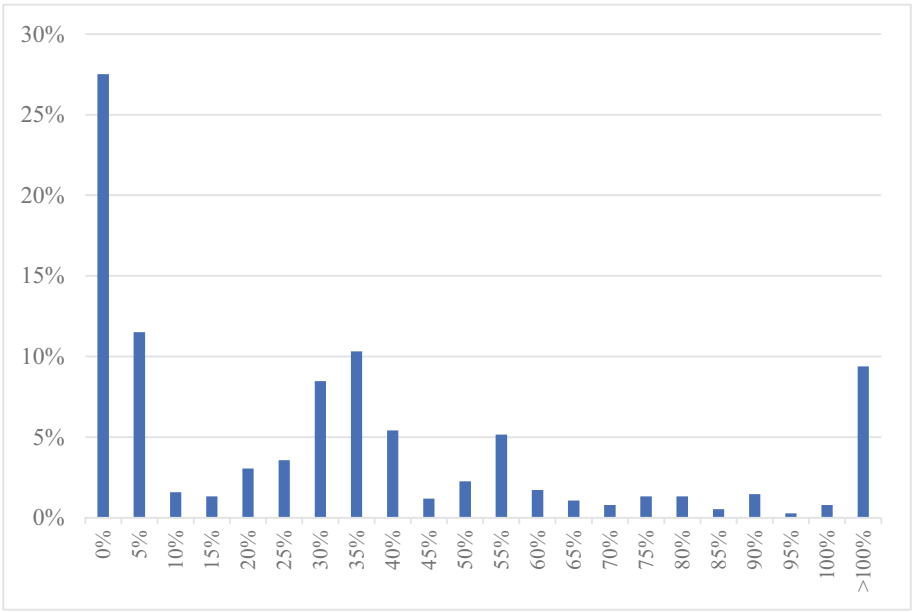


Fig. 6. Frequency analysis of travel time variation.

Figure 7 shows the trend of the resilience indicator for some o-d pairs per time interval. For definition, such and indicator decrease increasing the travel time. For some o-d pairs in Fig. 7 the indicator decreases as expected, but for other increases in the first interval. This can be explained considering that there are users who, due to the disruption, have to change their route and do not load the arcs belonging to the route of another o-d pair.

In relation to the other indicators, the weakness has no appreciable changes (less than 1%). The network clearance time is of 112 min in current scenario and of 222 min in the emergency scenario. Assuming the clearance time of the network in the current scenario as the reference time, the rate of packets that reach the destination in such a time during emergency is equal to the 74.9%.

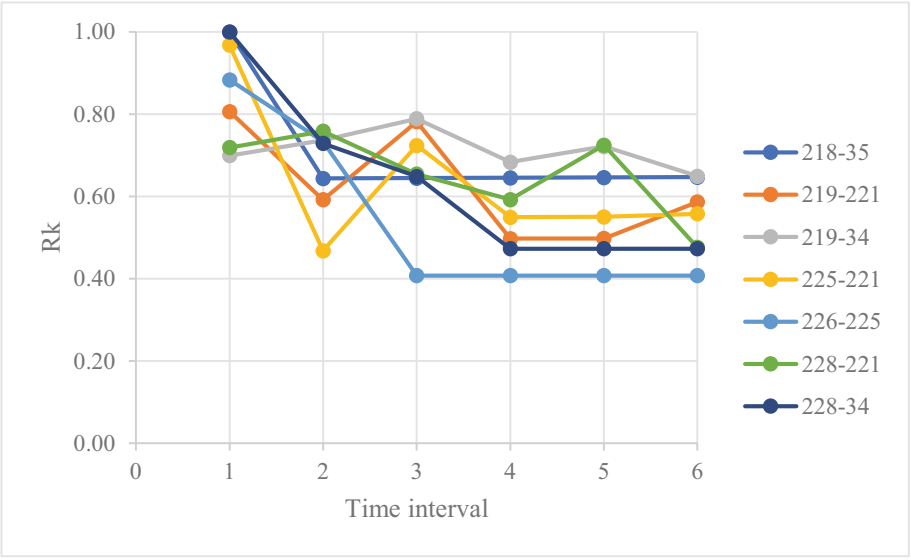


Fig. 7. Resilience indicator per o-d pair.

5 Conclusion

The response of a road network when a sudden event causes an emergency is essential to guarantee the reliability of the travel time of users. To do this, it is possible to evaluate the resilience of the network using appropriate indicators. In this paper, two resilience indicators have been proposed. A first indicator compares the variation of the available routes before and after the event (this value can also be interpreted as the variation of the satisfaction of the users). A second indicator is still on routes, but it is topological and compares the alternative routes in terms of arcs. Besides, two additional performance indicators are defined; they are related with the clearance time and the rate of users arriving at the destination before a reference time. These indicators have been used to evaluate the performance of a real network when an event occurs and produces disruptions.

As a case test, an emergency scenario has been defined in a real city (Avellino, south Italy) where the overflowing of a small river has been hypothesized. Two mesoscopic simulations have been performed, performed on the test network, to evaluate the performance in the current scenario and in the emergency scenario.

Future developments are based on the definition of more resilience indicators and with a large-scale application, also considering the overlapping effects of different events.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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