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Cross-border critical transportation infrastructure: a multi-level index for resilience assessment

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Abstract

Today, more than ever before, our society depends on interdependent infrastructure systems, such as transportation, energy, water, and telecommunications networks. These systems are often considered critical because they are necessary for the organization, functionality, and stability of a modern industrialized country. However, these infrastructures are vulnerable to accidents, malicious failures, and disruptions that could generate consequences impacting on the economy, health, safety, and welfare of the citizens of a country or of several neighboring countries. The disruption of critical cross-border transportation infrastructure, road or rail, as a result of a major event can affect the area where the event occurs and a wider area. Depending on the type and duration of an event, which can be natural or anthropogenic in origin, it is possible to estimate the impacts on the mobility of people and goods in terms of delays (alternative routes), increased traffic (congestion), and a potential increase in accidents. For instance, in 2019 there was an accident in Rastatt (Germany) that affected rail traffic on the Karlsruhe-Basel line of the Rhine-Alpine corridor in Europe. The rail line was disrupted for more than 50 days, causing disservices and about 2 billion Euro in economic losses in Germany, Switzerland, and Italy. The extended disruption of road and rail sections can have consequences (impacts) not only on the transport system but also on the socio-economic system in a macro-regional context. The research is part of the SICt project - Resilience of Critical Cross-Border Infrastructure developed in the Interreg VA Italy-Switzerland Programme 2014-2020. The work aims to define a *RI - Resilience Index* for the road and rail transport network falling within the study area. The *RI index* describes the capability of each network element (*i-th link*) to cope with a relevant event. The formulation of the index involves the calculation of three independent indicators: i) *RIRM* - Rescue Management related to the resources that can be activated and used to cope with an event; ii) *RIPP* - Plans & Management related to the speed with which the necessary resources can be activated and in fact, considers management aspects such as the presence of plans and procedures; iii) *RIRN* - Network & Traffic related to the robustness of the elements of the transport network. This work aims to present the proposed model and its application to the project area that includes the Lombardy Region (Italy) and the Canton Ticino (Switzerland) within the SICt Project.

Keywords: Transport resilience; critical infrastructures resilience, critical infrastructures safety; emergency management; transport vulnerability; road network; rail network; response and recovery; decision support system; cross-border infrastructures, GIS.

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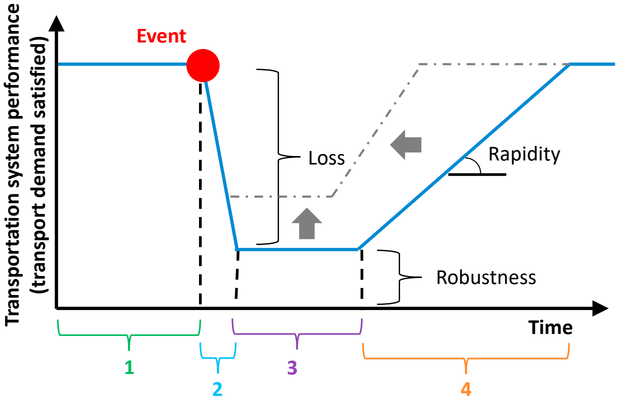
1. Introduction

Today, more than ever, our society depends on the proper functioning of interdependent infrastructure systems, such as transportation (road, rail, air, and maritime), energy, water, and computer networks. These systems are often considered critical because they are necessary for the organization, functionality, and stability of a modern industrialized country (Cohen, 2010; European Commission, 2008). Each system may be vulnerable to incidental or malicious failure and/or unavailability that could generate consequences affecting the economy, health, safety, and welfare of the citizens of an entire country or of several neighboring countries (Eusgeld et al., 2011; Nan and Sansavini 2017). In this perspective, the disruption of a critical transport infrastructure, road or rail, may have effects not only where the event occurs, but also in a wider area. Depending on the type of event, which can be of natural origin (e.g., landslide) or anthropogenic (e.g., road accidents), and its respective duration, it is possible to estimate the impacts on the mobility of people and goods in terms of delays (alternative routes), increased traffic (congestion) and possible increase in accidents. More generally, economic, and non-economic impacts can be estimated for the community. In Europe, the Trans-European Transport Network (TEN-T) has been defined as the set of linear (rail, road and river) and punctual infrastructures (urban nodes, ports, interports and airports) considered relevant at Community level. Nine corridors of strategic importance have been identified with the aim of promoting the implementation and coordinated development of the Trans-European Transport Network. From a regulatory point of view, in 2008 the European Directive 2008/114/EC on the identification and designation of European Critical Infrastructures and the assessment of the need to improve their protection was released; the energy and transport sectors are covered by the Directive. With this in mind, the aim of this work is to propose and apply a quantitative method to characterize the links of a road or rail transportation network according to a resilience index that considers three independent indicators: i) *RIRM* - Rescue Management related to the resources that can be activated and used to cope with an event; ii) *RIPP* - Plans & Management related to the speed with which the necessary resources can be activated and in fact, considers management aspects such as the presence of plans and procedures; iii) *RIRN* - Network & Traffic related to the robustness of the elements of the transport network. The paper is organized as follows: section II provides background with reference to the technical-scientific literature, section III illustrates the method from an analytical point of view while section IV reports the main results within the Interreg SICt project; finally, section V presents the conclusions.

2. Background

In technical-scientific literature several authors have addressed the issue of resilience and vulnerability of transport networks. To define whether an infrastructure is critical or not, it is necessary to assess its vulnerability to certain events and its importance within the network. Hence, the need to define vulnerability regarding risks arises; risks can be estimated by considering the probability of a given hazard, identifying the affected elements, and assessing their vulnerability with respect to that specific hazard (Coburn et al. 1994; Linkov et al. 2018). To date, there are many definitions of vulnerability referring to the transportation field; making a focus on road transportation systems, vulnerability can be defined as the susceptibility to accidents that can result in significant reductions in road network operations (Berdica 2002; Mattsson and Jenelius 2015). Moreover, there are several vulnerability components concerning the transportation network, including for example physical, functional, organizational, systemic, and topological (Borghetti et al. 2021). Also, regarding the concept of resilience several authors in technical scientific literature have carried out studies on network systems such as energy, transport, water and communications (Mattsson and Jenelius 2015; Reggiani 2013). Among different definitions, resilience is the ability of a system to withstand a major disruption within acceptable degradation parameters and recover within acceptable timeframes and compounded costs and risks (Francis and Bekera 2014; Haimes 2009). More generally, a resilient system is characterized by reduced: i) probability of failure/malfunction; ii) consequences of failure considering e.g., loss of life, damage, and economic and social consequences; iii) recovery time (Bruneau et al. 2003; Carlson et al. 2012). In this perspective, resilience can be defined as the ability of an entity to anticipate, resist, absorb, respond, adapt, and recover from a disturbance. Fig. 1 shows the operational state of a transportation system as a function of time considering a relevant event (red point); in addition, the different components of resilience are illustrated. The trend of the blue curve represents the evolution of the system performance over time and can be a useful support tool for traffic and emergency management. With reference to traffic management, it is important to consider the availability, practicability, and redundancy of routes; these can offer alternatives in the event of a network element disruption. The system can be characterized by a high resilience not only if it can withstand an event, but also if there are shared procedures and plans for traffic and emergency management. On the other hand, considering the management of emergencies, it is important to consider the availability of resources that can be used to cope with a relevant event by analyzing, for example, the accessibility of rescues (Borghetti et al. 2021).



1	2	3	4
Preparedness	Mitigation	Response	Recovery
Activities taken by an entity to define the hazard environment to which it is subject	Activities taken prior to an event to reduce the severity or consequences of an hazard	Immediate and ongoing activities, tasks programs and systems that have been undertaken or developed to manage the adverse effects of an event	Activities and programs designed to effectively and efficiently return conditions to a level that is acceptable to the entity

Fig. 1. Resilience components for a transport system. Adapted from Carlson et al. (2012) and Deublein et al. (2019).

3. The proposed model

The road and rail transport network are characterized by a *Resilience Index - RI*; the index describes the capacity of each element of the network (*i-th link*) to face a relevant event, be it anthropic or natural. The definition of the index requires the calculation of three independent indices as reported below:

$$RI_i = f(RIRM_i; RIPP_i; RIRN_i) \tag{1}$$

Where:

- *RIRM* aggregates resilience indices related to the Resources that can be Managed to cope with a relevant event
- *RIPP* considers how quickly resources can be activated by assessing the presence, the sharing, and the application of Plans and Procedures
- *RIRN* considers the Robustness and the importance of Network elements based on their relationship to the whole network.

The used approach for the calculation of *RI* is of comparative type: comparing the different links that compose the transport network it is possible to identify possible critical situations and to define (priority) interventions that can improve the resilience. Such interventions can be both infrastructural and organizational - procedural. Beyond representing *RI* it is also possible to represent the single indices that compose it according to specific needs of the user - analyst. The proposed model can be considered a decision support system (*DSS - Decision Support System*) for those who are responsible for the protection and management of critical infrastructure with reference to resilience. This paper shows the procedure for calculating the *RIRM* index, which depends on:

- type of resources that can be activated and used in case of a relevant event; for instance, we can consider: i) Medical Rescue - *RI_MR*; ii) urgent Technical Rescue - *RI_TR*; iii) Civil Protection - *RI_CP*
- vehicles and equipment used by each resource; for example, the following may be used for Medical Rescue (*RI_MR*): i) ambulance - *RIRM_MR01*; ii) medical car - *RIRM_MR02*; iii) helicopter - *RIRM_MR03*
- attributes associated with the vehicles used by each resource; for instance, for each vehicle the following can be defined: i) accessibility - *RI ACC MR01*; ii) redundancy - *RI RED MR01*.

Fig. 2 shows the structure for calculating the *RI* index with reference to three possible resources: medical rescue, urgent technical rescue, and civil protection. Three vehicles are identified for medical rescue, two vehicles for urgent technical rescue and two vehicles for civil protection. Two attributes are adopted for all vehicles of each resource: accessibility (ACC) and redundancy (RED).

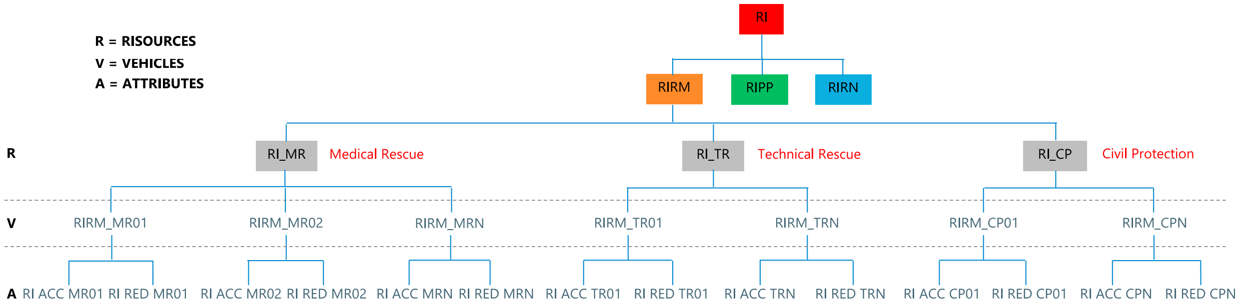


Fig. 2. *RI - Resilience Index* analytical structure for each element of the transportation network.

The following is an analytical description of the *RIRM* indicator related to resources that can be activated and used to cope with a relevant event. This indicator is made up of the weighted sum of three indicators:

$$RIRM = \omega_1 * RI\_MR + \omega_2 * RI\_TR + \omega_3 * RI\_CP \quad (2)$$

Where:

- *RI_MR* is the indicator related to Medical Rescue
- *RI_TR* is the indicator related to urgent Technical Rescue
- *RI_CP* is the indicator related to Civil Protection
- $\omega 1$, $\omega 2$, and $\omega 3$ are the relative importance weights of each indicator.

The next step in the method is to determine the indicator for each resource according to the equipment/vehicles considered. For instance, in the case of the indicator *RI_MR* (Medical Rescue) there may be three vehicles that can be used in case of need:

$$RI\_MR = \lambda_1 * RIGS\_MR01 + \lambda_2 * RIGS\_MR02 + \lambda_3 * RIGS\_MR03 \quad (3)$$

Where:

- *RIGS_MR01* is the indicator related to the vehicle 01 (e.g., ambulance) of the Medical Rescue
- *RIGS_MR02* is the indicator related to vehicle 02 (e.g., medical car) of the Medical Rescue
- *RIGS_MR03* is the indicator related to vehicle 03 (e.g., helicopter) of the Medical Rescue
- $\lambda 1$, $\lambda 2$, and $\lambda 3$ are the relative importance weights of each indicator associated with the vehicle.

The last step of the calculation model concerns the evaluation of the attributes associated with each vehicle. Considering the example related to medical rescue and specifically to vehicle 01 (ambulance) we have:

$$RIGS\_MR01 = \theta_1 * RI\ ACC\ MR01 + \theta_2 * RI\ RED\ MR01 \quad (4)$$

Where:

- *RI ACC MR01* identifies the Accessibility attribute of vehicle 01 (ambulance) of Medical Rescue
- *RI RED MR01* identifies the Redundancy attribute of vehicle 01 associated with the Medical Rescue
- $\theta 1$ and $\theta 1$ are the relative importance weights of each attribute associated with the vehicle.

The Accessibility of a vehicle of a resource can be defined by studying the time of intervention to reach the *i-th* link; considering as an example the vehicle 01 (ambulance) associated with the Medical Rescue we have:

$$RI\ ACC\ MR01 = f(TINT\_MR01) \quad (5)$$

The intervention time of each vehicle may depend on at least two components: the activation time of the resource and the travel time from the starting facility to *link i*:

$$TINT\_MR01 = TACT\_MR01 + TTRAV\_MR01 \quad (6)$$

Where:

- *TACT_MR01* is the Activation time of vehicle 01 (ambulance) of Medical Rescue
- *TTRAV_MR01* is the Travel Time of vehicle 01 from the point of departure (facility - depot) to the generic *link i* of the transport network in which the relevant event is considered.

The Redundancy of a resource can be defined by analyzing how many vehicles of the same type (belonging to the same resource) can reach the *i-th link* in which the relevant event is assumed to occur in a given time of intervention; always considering the example of medical rescue and in particular vehicle 01 (ambulance), we have:

$$IR\ RED\ MR01 = f(NMR01T) \quad (7)$$

NMR01T represents the number of vehicles 01 (ambulances) that can reach the link of the network in each time interval. For instance, it is possible to estimate how many ambulances can reach a *link i* of the transportation network in a time interval of 15 minutes as shown in Fig. 3; the higher this value, the more reasonable it is to expect that the link will be characterized by a high redundancy value since even the most distant resources can be considered for the event management. In the example of Fig. 3, the red point represents the location of the event, and the blue area represents the 15-minute isochrone calculated from the red point: only two facilities, *F1* and *F2*, fall within the isochrone while facility *F3* has a travel time greater than 15 minutes. With reference to Fig. 3, it follows that the *NMR01T* value is equal to three, since in 15 minutes the *F1* facility can intervene with two vehicles and the *F2* facility with only one vehicle.

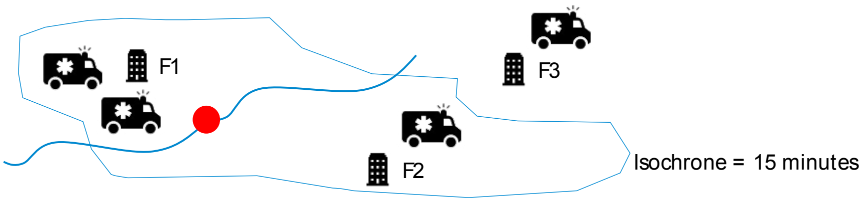


Fig. 3. Example of calculating the redundancy of the Medical Rescue (ambulance) considering a 15-minutes isochrone.

The two considered attributes in the calculation model, Accessibility and Redundancy of the resources, have respectively two different units measure: time and n° of resources/time. To calculate the indicator, it is therefore necessary to normalize the two attributes using utility functions. For both attributes 5 intervals have been defined which give rise to 5 values of the indicator. The next step consists in defining the points on the transport network where the two attributes are calculated; the calculation procedure is different for the road network and for the railway network. The road network is divided into macro-links, i.e., links between two points - nodes where it is possible to make a change of direction (e.g., junction, round-about, etc.) as shown in Fig. 4. For each road macro-link, the midpoint is determined as a function of the real length.

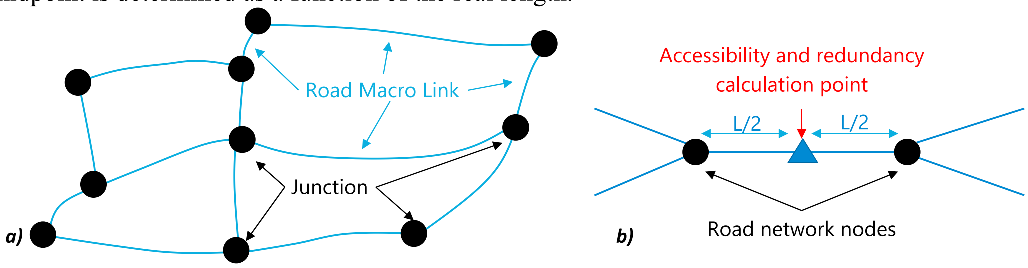


Fig. 4. a) Division of the road network into macro-links included between junctions or intersections (nodes); b) Point for calculating accessibility and redundancy.

The calculation of the two attributes is carried out for the midpoint of each macro-link; consequently, the various indices, including *RI*, are also referred to the midpoint. The next step is to associate the value of the midpoint to the road macro-link so that all the calculated indices can be represented on the map.

In the rail network case, the division into macro-links follows another logic; a macro-link is included between two points that determine the accessibility to the railroad: for instance, a level crossing or a station as shown in Fig. 5. The Time of Intervention of each vehicle (resource) can depend on at least three components: the time for activating the resource, the road travel time and the walking time needed to reach the point of the event (see Fig. 5):

$$TINT\_MR01 = TACT\_MR01 + TTRAV\_MR01 + TWALK\_MR01 \quad (8)$$

Where:

- *TACT_MR01* is the Activation time of vehicle 01 (ambulance) of Medical Rescue
- *TTRAV_MR01* is the road Travel Time of vehicle 01 from the point of departure (facility - depot) to the access point to the rail network (A1 and A2)
- *TWALK_MR01* is the Walking Time of the crew of vehicle 01 from the access point (A1 and A2) to the railway network to the point where the relevant event takes place.

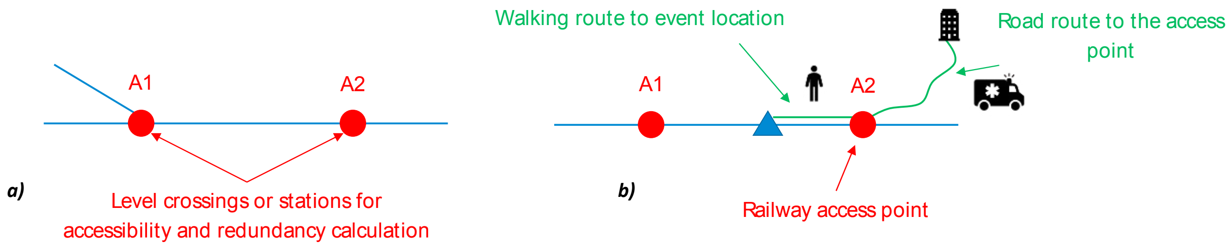


Fig. 5. a) Determination of access points to the rail network for accessibility and redundancy calculations; b) Representation (green line) of the road and walking route to an event on the rail network.

The calculation of the two attributes is carried out for the two extreme points (A1 and A2) which in general do not have the same value: also, in this case the value of the highest point is associated to the macro-link.

4. The Interreg SICt project

The SICt - Resilience of Cross-border Critical Infrastructures project is part of the Interreg V-A Italy-Switzerland 2014 - 2020 cooperation program that contributes to the achievement of the Europe 2020 strategy targets (https://www.progetti.interreg-italiasvizzera.eu/it/b/78/sictproject). The project is organized in 6 - Work Packages (WP) and its area includes the Lombardy Region in Italy and the Canton Ticino in Switzerland as shown in Fig. 6.

Fig. 6. Main information and area of the Interreg SICt project. Adapted from Borghetti et al. (2020).

The main goal of the SICt project is to increase the sharing of knowledge and information on critical cross-border infrastructures that represent important and strategic corridors for the people and goods mobility also at European level. The three specific goals are: i) increase and enhance cross-border governance cooperation for anthropogenic and natural events that may affect critical infrastructure (road and rail); ii) strengthen joint capacities for the management of the impacts caused by the disruption of critical cross-border infrastructures that may cause effects on both countries (emergency and traffic management); iii) verify and improve the effectiveness of the cooperation system for the monitoring and management of relevant events in the cross-border area (macro-regional area). Fig. 7 and Fig. 8 show some representative results related to the study and impact area of the project and *RIRM* index for the road network.

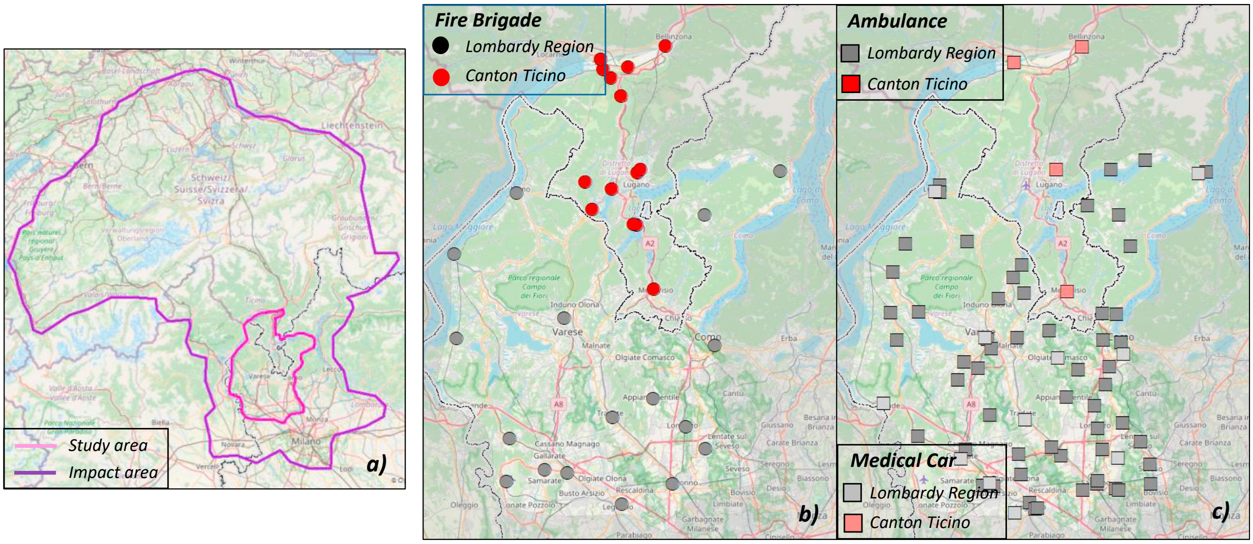


Fig. 7. a) Study and impact area of the SICt project; b) mapping of technical rescue; c) mapping of medical rescue.

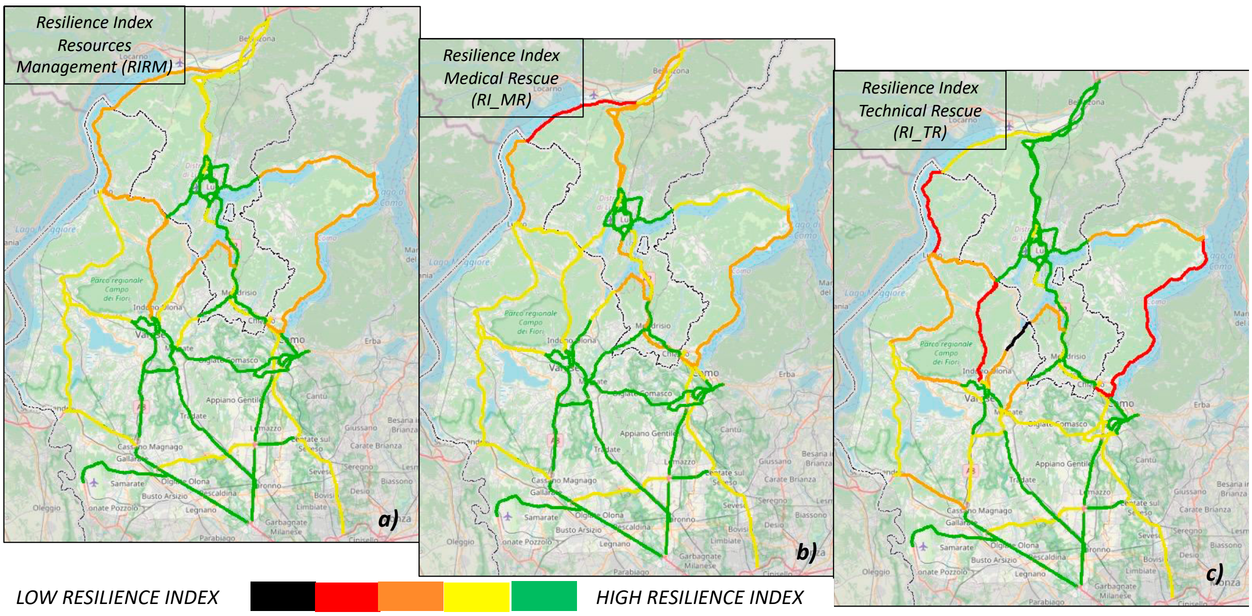


Fig. 8. Mapping of a) *RIRM*; b) *RI_MR*, and c) *RI_TR* indices in the study area of the SICt project.

Fig. 8 shows the mapping of the *RIRM* index composed of the *RI_MR* (Medical Rescue) and *RI_TR* (Technical Rescue) indexes. For each road macro-link 5 levels of variation have been defined (from 1 to 5) where 1 represents a low value (black) and 5 a high value (green).

5. Conclusions

The Resilience Index (RI), determined for each element of the road and rail network, can be used in two phases. These are the reported hereby: i) planning phase when the joint response of available resources needs to be simulated and each operator can share and know the critical points of the transportation network; ii) emergency phase to provide an assessment about the impact of the event on the network based on the resources available. A weakness of the model concerns the dependence on the quality of data such as (i) resource mapping, (ii) transport graph, (iii) traffic data, (vi) availability of plans and procedures, etc.

On the other hand, there are many strengths: first, the proposed method is replicable, modular, and expandable; in fact, it can also be replicated in other contexts at different levels of detail depending on the analyst's needs: e.g., local, main, regional, national, and macro-regional scales. In addition, it allows the representation of specific indicators and allows the consideration and inclusion of new parameters for resilience assessment. Also, from an analytical point of view, the calculation process does not require special resources thus making the method streamlined and operational. Finally, the proposed approach can be considered as a useful Decision Support System (DSS) that can be used by the subjects involved in the decision-making process of planning and managing the resilience of transportation infrastructure (infrastructure managers, first responders, administrations, etc.). So, the method allows to prioritize interventions, identifying situations where it is most urgent to allocate resources to improve resilience by acting on different indicators.

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