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RESEARCH PAPER

A Resilience Analysis of a Motorway Tunnel Affected by a Traffic Accident Using the Average Vehicles' Speed as a Metric

Ciro Caliendo[1] · Isidoro Russo[1] · Gianluca Genovese[1]

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Abstract

Given the role of road tunnels in a road network, it is relevant to quantitatively assess their resilience due to disruptive events. In this respect, the travel speed of traffic flow, as a metric of resilience, in the event of traffic accidents in road tunnels has been scarcely used. This represents a gap of knowledge that this paper intends to fill. For the purpose, the research method applied involves the development of a traffic macro-simulation model, and the analysis of results using the average travel speed and its spatial profile as a resilience metric. Particularly, we have evaluated the resilience of a twin-tube motorway tunnel when a traffic accident occurs in a tube. The findings showed how the best functionality level of the system, expressed in terms of average vehicles' speed, with its related greatest resilience index, is associated with the partial closure of the disrupted tube rather than the complete one. Further benefits might be obtained by activating Variable Message Signs (VMSs) that alert only the Heavy Goods Vehicles (HGVs) to exit the motorway before entering the tunnel and to use an alternative itinerary identified in the nearby transportation network. In this respect, we found that by means of the activation of VMSs as a traffic control strategy, the resilience index increased by about 7–17% when the traffic accident caused the partial closure of the disrupted tube for 1–3 h. Improvements might also be achieved by rapidly opening the two traffic by-passes at the tunnel portals that allow for the use of the adjacent undisrupted tube for two-way traffic. The unavailability of an alternative itinerary in the nearby transportation network along which to re-route the HGVs is also examined, finding a reduction in the functionality conditions of the system. The results obtained might serve as a support tool in the choice of functional recovery strategies in the case of the temporary partial or complete block of a tunnel tube due to a traffic accident.

Keywords Road tunnels · Resilience index · Average travel speed · Traffic by-passes · Variable Message Signs · Alternative route

1 Introduction

Road tunnels, as part of a transportation network, often represent the most appropriate solution to overcoming certain spatial and/or environmental barriers, while also meeting the transit needs of goods and people. The functionality of a tunnel, however, might be temporarily compromised in the case of a traffic accident or maintenance works. In this respect, it is to be remembered that, according to a monitoring study regarding Italian motorway tunnels [1], the crash severity may be significantly higher in tunnels than on the corresponding open roads (e.g., an average rate of 12 severe accidents/10^8 vehicles/km in road tunnels in contrast to 9 severe accident/10^8 vehicles/km on the corresponding motorways was found). Similar results were also obtained by [2], who showed that in China the severity of injuries is higher in freeway tunnels than on open roads. Also [3] found that the severity of accidents occurring in Norwegian road tunnels is greater than those on the open roads. Therefore, there is reason to investigate in greater detail the effects on traffic flow due to

✉ Ciro Caliendo
ccaliendo@unisa.it

Isidoro Russo
isrusso@unisa.it

Gianluca Genovese
ggenovese@unisa.it

[1] Department of Civil Engineering, University of Salerno, Via Giovanni Paolo II, 132-84084 Fisciano, SA, Italy

traffic accidents occurring in road tunnels, as well as emergency management strategies.

The consequent partial or complete closure of the tunnel attributable to a traffic accident for a certain amount of time (e.g., for hours or days) might also extend the negative effects to the traffic flow of the nearby transportation network; as a result, a general decrease in the travel speed of vehicles (i.e., an increase in the travel time) is expected, which is also associated with adverse impacts on both the economic and social interests. Therefore, the recovery process of the functionality of a tunnel affected by a disruptive event, also in relation to the possibility of using alternative itineraries on open roads of the nearby transportation network, is becoming a more and more relevant issue.

A road tunnel, with the associated infrastructural network containing it, which has an adaptive response to a disruption (e.g., the occurrence of a collision within a tunnel tube) may be defined as resilient. There is no single shared definition of resilience in the current literature [4–7]. However, with respect to a transportation system, resilience might be described, for example, as the ability of the system to rapidly recover its functionality after a disturbing event.

Several metrics have been proposed to assess the resilience of transportation infrastructures. However, given that the resilience of a transportation system is primarily related to its functionality, traffic-based metrics could be used. Among the traffic parameters, since a disruption of the operating conditions of a tunnel might lead to a significant increase in the travel time of vehicles transiting along the infrastructure containing the tunnel, the travel speed, with its associated profile upstream and downstream of the entrance portal of the tunnel characterized by a disruptive event, appears to be a suitable measure to investigate resilience.

Resilience analyzes of complex systems such as a transportation network are usually performed using quantitative approaches based on traffic simulation models. The traffic simulation technique is widely used for comparing different scenarios and identifying any critical issues, thus representing a support tool in the choice of functional recovery strategies in the case of a temporary partial or complete unavailability of a road section of the network.

Traffic simulation modeling has been applied from different perspectives to investigate resilience. [8] for instance, assessed both the robustness of a road network in the event of the closure of a section and the efficiency of certain recovery strategies using the delay time as a metric. They showed: (1) that to assess the robustness of the network, the spillback phenomenon should also be modeled; (2) the positive effect of information that makes drivers adapt their itineraries; (3) the greater reduction of network performance when a link is closed. [9] proposed a framework based on the travel time to analyze the resilience of a road network interested by a disruptive event leading to the capacity loss of a link. They showed that a reduction of vulnerability is obtainable through the re-routing of vehicular flow to other undisrupted links. [10] developed a framework for assessing the effectiveness of Variable Message Signs (VMSs) in diverting traffic when an accident occurs along an infrastructure network. They found that predictive VMSs are effective in diverting significant numbers of vehicles along routes, resulting in reduced delays. [11] investigated the efficiency of various recovery strategies aimed at reducing traffic congestion after the occurrence of an incidental event in a tunnel. The results showed that ramp control provided the best benefits in terms of queue length reduction, while alternative itineraries were not advisable due to higher travel times. [12] proposed an approach for optimizing the position of guidance devices to divert the traffic of a road network following a disruptive event such as a natural disaster. They found that communicating road closures via guidance devices can decrease the travel time. [13] investigated the redundancy of transportation networks in the event of a serious traffic accident or an earthquake. To improve network redundancy, the authors demonstrated the importance of both introducing new routes as well as increasing the capacity of existing links. [14] proposed a network performance indicator, which is based on a relationship between the traffic flow and vehicular density, showing the effectiveness of re-routing when a link is closed due to an incident. [15], by using the travel time as a metric, presented an optimal framework of traffic signal settings in the case of disruption events in a road network. They found that the optimization of the traffic signals minimized the network travel time. [16] evaluated the effects of certain recovery strategies on the ability of a network to quickly recover its performance in the event of a disruption. They found that prioritizing the re-opening of the network inner links can reduce traffic congestion. [17], by employing the traffic capacity loss as a metric, evaluated the functionality loss of a tunnel interested by random events (e.g., traffic accidents) or planned events (e.g., maintenance works). [18], by using the time for road repair and the loss of performance as metrics, proposed a genetic algorithm for optimizing the functionality of a road network after a natural disaster or accident. The author showed that the functionality of the network could be restored by means of the intervention of repair teams. [19], by using the percentage of traffic demand satisfied as a metric, showed the effects of emergency teams equipped with a micronized water system on the resilience of a road tunnel in the event of a fire. [20], by using the delay time as a metric, assessed the functionality loss of a twin-tube road tunnel in the event

Table 1 Summary of the literature review

Year	Author(s)	Metrics	Scope
2008	[8]	Delay time	To assess the robustness of a road network in the event of the closure of a section
2011	[9]	Travel time	To analyze the resilience of a road infrastructure interested by a disruptive event
2011	[10]	Travel time	To develop a framework for assessing the effectiveness of VMSs in diverting traffic when an accident occurs
2012	[11]	Density and queue length	To investigate the efficiency of certain recovery strategies after an incidental event in a tunnel
2017	[12]	Travel time	To propose an approach for optimizing the position of guidance devices to divert the traffic following a natural disaster
2018	[13]	Spare capacity	To investigate the redundancy of transportation networks in the event of a serious traffic accident or an earthquake
2018	[14]	Traffic flow and vehicular density	To assess the effects of re-routing traffic in real-time on the network performance when a link is closed due to an incident
2021	[15]	Travel time	To present an optimal framework of traffic signal settings to minimize the network travel time in the event of disruptions
2021	[16]	Travel time	To evaluate the effects of the recovery process on the ability of a network to recover its performance
2021	[17]	Capacity loss	To propose a stochastic simulation model to evaluate the functionality loss of a tunnel interested by planned or random events
2021	[18]	Link repair time	To develop a genetic algorithm for optimizing the functionality of a road network after a natural disaster or accident
2021	[19]	Traffic demand satisfied	To investigate the effects of emergency teams on the resilience of a road tunnel in the event of a fire
2022	[20]	Delay time	To assess the resilience of a twin-tube road tunnel affected by a traffic accident in a tube
2022	[21]	Delay time and user safety	To develop a simultaneous analysis of the resilience and user safety of a road tunnel in the case of a fire
2022	[22]	Level of traffic congestion	To investigate the effectiveness of VMSs in improving the recovery process of a road network in the event of incidents
2022	[23]	Dynamic propagation of congestion	To develop a vulnerability analysis of a road network

of a traffic accident in a tube, and proposed certain strategies to recover its functionality. Subsequently, [21] developed a simultaneous analysis of the functionality and user safety of a road tunnel in the case of a fire. They individualized some traffic control strategies that are able both to reduce the delay time and to guarantee an appropriate safety level in the event of a fire. [22], using the level of traffic congestion as a functionality metric, showed the effectiveness of VMSs in improving the recovery process of a road network in the event of incidents and under congestion conditions. [23], by monitoring the dynamic propagation of congestion in the links close to that of the incident (i.e., impact area), developed a vulnerability analysis of a road network. They identified the critical links of the network, which helped in prioritizing the resources. The following section presents a summary of the metrics and scope of the mentioned studies (see Table 1).

The above chronological literature review shows how the travel speed of traffic flow, as a metric of resilience, in the event of traffic accidents in a road tunnel has been scarcely used. This represents a gap of knowledge that this paper intends to fill. In addition, the spatial profiles of travel speed in the case of a disruptive event in a tunnel, as far as the authors are aware, do not appear to have been built yet. Since these spatial profiles might provide additional insights into the choice of a recovery strategy, their lack represents a lacuna for Tunnel Management Agencies (TMAs). The aims of the paper, therefore, are partly to increase our knowledge by using the travel speed as a metric of tunnel resilience, and partly to use the spatial profile of travel speed to individualize more appropriate strategies to recover the functionality of tunnels.

In light of the above considerations, the goals of this paper are: (1) to present a traffic macro-simulation model to deal with this issue in more detail; (2) to enhance tunnel resilience by means of a recovery strategy that can limit the reduction in the travel speed; (3) to assess the effects of the intervention time, after the occurrence of a traffic accident in a tube, of the emergency team to reorganize the traffic flow, for example, by making the undisturbed parallel tube of a twin-tube road tunnel available for bi-directional traffic; (4) to evaluate the impacts of certain digital technologies such as VMSs to re-route traffic along an alternative itinerary identified in the nearby road network.

In this respect, an existing twin-tube motorway tunnel, characterized by unidirectional traffic (i.e., one-way traffic for each direction of travel), is investigated by assuming the occurrence of a traffic accident in a tube. The functionality of the road link containing the disturbed tube was assumed to be recovered by using the remaining undisturbed lane of the tube interested by the traffic accident (i.e., each tube presents two lanes and only a lane is closed to traffic flow) or by using the parallel tube for bi-directional traffic (i.e., both lanes of the disturbed tube are closed in this case). The effects of an alternative itinerary are also examined.

The paper is structured as follows: the next section reports a summary of the literature review. Afterward, the twin-tube motorway tunnel and the scenarios investigated are illustrated. Then, the traffic macro-simulation model is presented and implemented to assess the travel speed of the vehicles. Subsequently, the findings are analyzed and commented on, as well as certain comparisons made to individualize the most appropriate strategy to enhance tunnel resilience. Finally, some conclusions, recommendations, and future studies are discussed.

2 Summary of the Literature Review

This section presents a brief overview of the metrics and scope of the previously mentioned studies.

Table 1 shows that the average speed of traffic flow has not been sufficiently used as a metric of resilience of infrastructures. In the present paper, we use this parameter to investigate the resilience of a road network in the event of a traffic accident in a tunnel.

3 Materials and Methods

3.1 Description of the Twin-Tube Motorway Tunnel

An existing Italian twin-tube motorway tunnel, with each tube normally used for traffic in one driving direction, is investigated in the event of a traffic accident occurring within the northbound tube (i.e., the tube reported in red in Fig. 1 and defined by the entrance Portal *a* and the exit one *b*).

The tubes have a length of 850 m, are flat and straight, with an emergency exit located in the middle of the tunnel length that connects them transversely. The cross-section of each tube has a maximum height of 6.8 m and contains two lanes of 3.5 m, two shoulders of 0.25 m, and two sidewalks of 1 m (i.e., the total width is 9.5 m); moreover, it presents a horseshoe shape with an area of 55.2 m^2.

3.2 Impact Area

The northbound tube was assumed to remain partially (i.e., only one lane is closed) or completely blocked (i.e., both lanes are closed) to vehicular flow after the occurrence of a traffic accident in it. Since the partial or complete closure of the northbound tube might have negative effects, for example in terms of the reduction of traveling vehicles' speed, not only along the motorway section containing the disrupted tube but also on the nearby road network (especially if used as an alternative itinerary), an impact area (i.e., that part of the system most affected by the perturbation caused by the traffic accident in the tube) was preliminarily identified by means of a traffic macro-simulation modeling [20]. In this respect, the impact area was found to have a length of 25 km and a width of 8 km.

Figure 1 schematically reports a portion of the abovementioned impact area including: (1) the motorway section from the Nodes A to D containing the northbound tube; (2) the motorway section from the Nodes D to A including the southbound tube that, through the opening of the traffic bypasses located at the tunnel portals, might be interested by bi-directional traffic when the northbound tube is completely blocked due to a traffic accident; (3) the schematic representation of the alternative itinerary in the nearby road network that might be used to redirect the traffic flow traveling towards the northbound tube when it is partially or completely closed due to a traffic accident; in particular, the alternative route includes the two motorway junctions C and D, the two ramps C-E and L-D, a bi-directional major rural road from the Nodes E to I, and a bi-directional minor rural road from the Nodes I to L.

3.3 Maximum Speeds Allowed

With reference to the normal conditions of functionality of the road network investigated, the maximum speed allowed on the motorways is 130 km/h for passenger cars and 100 km/h for Heavy Goods Vehicles (HGVs), while it is 40 km/h on the ramps for all vehicles. Maximum speeds of 70 and 50 km/h are imposed on both major and minor rural roads for passenger cars and HGVs, respectively.

3.4 Scenarios Examined

The occurrence of the traffic accident within the northbound tube was assumed to cause its partial or complete closure for different durations: 1, 2, or 3 h (i.e., 7:00–8:00 a.m., 7:00–9:00 a.m., or 7:00–10:00 a.m., respectively). Specifically, the disruptive event was supposed to occur at 7:00 a.m., namely at the beginning of the first peak hour in the morning, to consider the worst effects on the travel

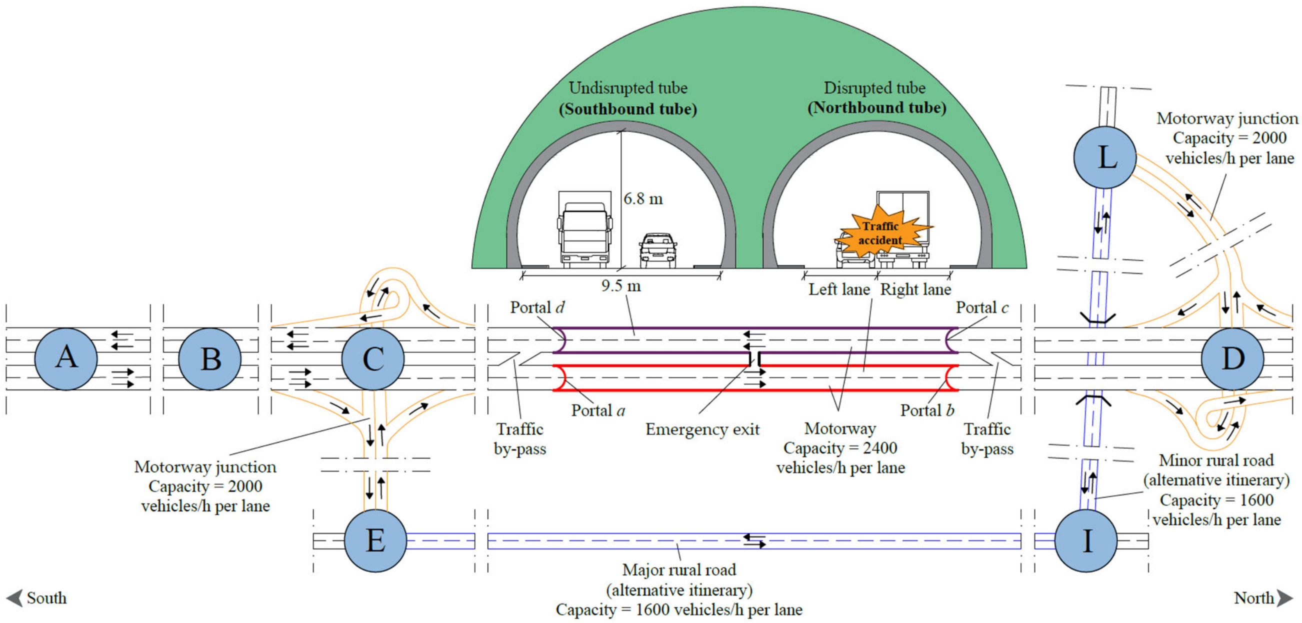


Fig. 1 Schematic representation of the cross-section of the twin-tube motorway tunnel investigated, and of the impact area on traffic flow due to the occurrence of a traffic accident in the northbound tube, which is reported in red and defined by Portals *a* and *b* (the image is not to scale)

speed of traffic flow. The scenarios analyzed are graphically described in Fig. 2.

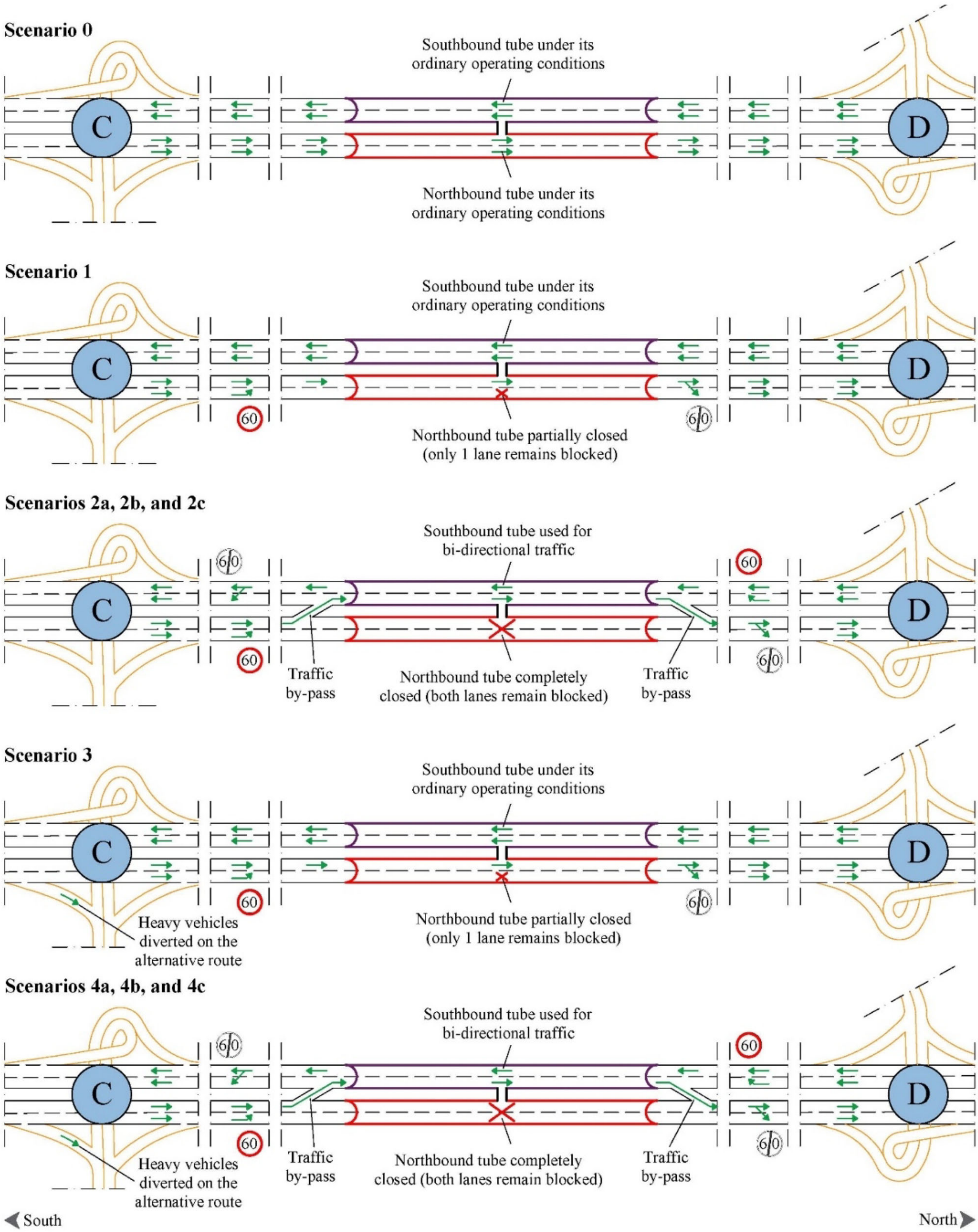
Figure 2 shows: (1) Scenario 0 in which the tunnel system is not affected by any disruptive events and operates at its ordinary level of functionality (i.e., both lanes of each tube are used for unidirectional traffic); (2) Scenario 1 where the occurrence of a traffic accident within the northbound tube leads to its partial closure (i.e., only one lane is blocked and the entire vehicular flow entering the northbound tube uses the other lane to keep traveling towards the north); (3) Scenario 2 in which the northbound tube is completely closed to traffic flow (i.e., both lanes are blocked) and the southbound tube is used for bi-directional traffic after the activation of the two traffic by-passes located at the tunnel portals; in this respect, it is to be said that the intervention time of the emergency team, which is computed from the occurrence of the traffic accident in the northbound tube, is given by the sum of the time necessary to arrive at the tunnel portals, to temporarily install the appropriate road signs such as, for example, the speed limit of 60 km/h in the proximity of the tubes, and to open the two mentioned traffic by-passes; this intervention time was assumed to be 10, 20, or 30 min, which refers to Scenarios 2a, 2b, or 2c, respectively; (4) Scenario 3 is similar to Scenario 1, but with only heavy goods vehicles traveling northbound being diverted along the alternative route in the nearby road network; in other terms, drivers of HGVs are alerted to leave the motorway by VMSs placed at a certain distance upstream of the motorway junction C and to use this junction, which is located before the northbound tube, for the scope; (5) Scenarios 4a, 4b, and 4c that are similar to Scenarios 2a, 2b, and 2c, respectively, but with the activation of the mentioned alternative itinerary for only HGVs traveling along the motorway in the north direction.

3.5 Traffic

The hourly traffic volumes during the simulation analysis period (i.e., 7:00–10:00 a.m.) along the various road segments of the impact area investigated were obtained from the traffic database of the road management agencies and are reported in Table 2. According to traffic data, the hours from 7:00 a.m. to 9:00 a.m. are peak hours, while the hour from 9:00 a.m. to 10:00 a.m. is an off-peak hour. With reference to each road section considered in the analysis, the percentage of heavy vehicles (i.e., buses and HGVs), extracted from the above-mentioned database, was found to be about the same between 7:00 a.m. and 10:00 a.m.

The capacities per lane of the above-mentioned road segments under the ordinary operating conditions of the tunnel system (i.e., Scenario 0) are reported in Fig. 1. By comparison, it can be noted that the hourly traffic volume on each road section is less than the corresponding capacity.

With reference to the other scenarios analyzed, the capacity per lane of the northbound tube when it remains partially closed due to the occurrence of a traffic accident in it (i.e., Scenarios 1 and 3) was assumed to be 1700 vehicles/h, while that of the southbound tube used for bi-directional traffic when the northbound tube is completely


Scenario 0
Southbound tube under its ordinary operating conditions
Northbound tube under its ordinary operating conditions
Scenario 1
Southbound tube under its ordinary operating conditions
Northbound tube partially closed (only 1 lane remains blocked)
Scenarios 2a, 2b, and 2c
Southbound tube used for bi-directional traffic
Traffic by-pass
Northbound tube completely closed (both lanes remain blocked)
Traffic by-pass
Scenario 3
Southbound tube under its ordinary operating conditions
Heavy vehicles diverted on the alternative route
Northbound tube partially closed (only 1 lane remains blocked)
Scenarios 4a, 4b, and 4c
Southbound tube used for bi-directional traffic
Heavy vehicles diverted on the alternative route
Traffic by-pass
Northbound tube completely closed (both lanes remain blocked)
Traffic by-pass
South
North

◀**Fig. 2** Graphical description of the scenarios analyzed. Scenario 0 where the twin-tube motorway tunnel operates at its ordinary level of functionality; Scenario 1 in which the northbound tube is partially closed; Scenario 2 where the northbound tube is completely closed and the southbound tube is used for traffic in two driving directions through the opening of the traffic by-passes after 10 (Scenario 2a), 20 (Scenario 2b), or 30 min (Scenario 2c) from the occurrence of the disruptive event in the northbound tube; Scenario 3 that is similar to Scenario 1, but with only HGVs traveling northbound diverted along the alternative route; Scenarios 4a, 4b, and 4c that are similar to Scenarios 2a, 2b, and 2c, respectively, but with the activation of the alternative itinerary for only HGVs traveling along the motorway in the north direction

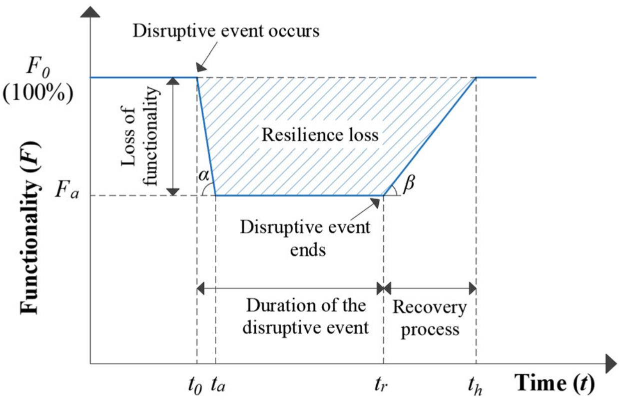


Fig. 3 Schematic representation of a typical functionality curve over time of a road section affected by a disruptive event

closed (i.e., Scenarios 2a, 2b, 2c, 4a, 4b, and 4c) was taken to be 1600 vehicles/h. The assumed values of the capacity per lane under the different scenarios investigated are those provided by [24] for similar roads.

3.6 Resilience Metrics

The metric used in this work to assess the resilience of the twin-tube motorway tunnel investigated is the travel speed of vehicles averaged over the time of partial or complete closure of the northbound tube (i.e., 1, 2, or 3 h). In the paper, it is simply indicated as average travel speed.

The functionality level of the tunnel system, when the northbound tube is partially or completely closed, was calculated as the ratio between the average vehicles' speed traveling northbound after and before the occurrence of the traffic accident. In this respect, Fig. 3 shows a typical functionality curve over time of a road segment affected by a disruptive event. From the above-mentioned figure, it is possible to note that: (1) the functionality level (F) of the system is equal to F_0 = 100% until the time instant t_0 at which the traffic accident occurs; (2) subsequently, it decreases and achieves the minimum level of functionality F_a at the time instant t_a (in other terms, the functionality loss might not occur instantly, which depends on the ability of the system to adapt to the disruptive event [25]); (3) then, the functionality level remains constant at F_a until the time instant t_r when the disruptive event ends; (4) finally, the system starts to recover its ordinary operating conditions, reaching its maximum functionality level (i.e., F_0 = 100%) at the time instant t_h.

Moreover, from Fig. 3 it can be noted that the resilience loss is given by the area of the trapezoid ($R_{LOSS} = \int_{t_0}^{t_h}[100 - F(t)dt]$), the functionality loss speed is equal to $tan\,\alpha = \frac{F_0 - F_a}{t_a - t_0}$, while the recovery speed is given by $tan\,\beta = \frac{F_0 - F_a}{t_h - t_r}$. However, in order to represent the resilience of the system investigated with a synthetic parameter, the resilience index $\left(R(t_h) = \frac{\int_{t_0}^{t_h} F(t)dt}{(t_h - t_0)}\right)$, which can assume values between 0 and 1, was used as a metric in this paper. A low resilience index denotes a high resilience loss.

3.7 Research Framework

The study is set in the field of tunnel resilience when a traffic accident occurs in the structure. However, it extends the state of knowledge by using the average travel speed of vehicles and its longitudinal spatial profile, computed by

Table 2 Hourly traffic volumes during both peak hours (i.e., 7:00–9:00 a.m.) and the off-peak hour (i.e., 9:00–10:00 a.m.) in the morning along the various road segments of the impact area

Travel direction	Hourly traffic volumes [vehicles/h per lane]								
	Motorway junctions				Major rural road		Motorway		
	C → E	L → D	C ← E	L ← D	E⇔I	B → C	C → D	B ← C	C ← D
Peak hours: 7:00–9:00 a.m	499	571	504	550	776	1099	1100	1039	1038
(% of heavy vehicles)	(20)	(20)	(20)	(20)	(2.5)	(25)	(25)	(25)	(25)
Off-peak hour: 9:00–10:00 a.m	125	143	126	259	194	275	275	260	260
(% of heavy vehicles)	(20)	(20)	(20)	(20)	(2.5)	(25)	(25)	(25)	(25)

The percentage of heavy vehicles (i.e., buses and HGVs) is reported in brackets. The arrows denote the travel directions means of a traffic macro-simulation modeling, as a resilience metric. Moreover, this paper provides additional insights into both the intervention time of the emergency team to reorganize the vehicular flow and the effectiveness of VMSs to re-route traffic along an alternative route identified in the nearby road network. Therefore, the study aims to serve both as a potential reference for tunnel operators in choosing the best functional recovery strategy in the event of a traffic accident in a tunnel as well as to increase our experience in the traffic analysis of a road network in the case of a partial or complete closure of a link.

Figure 4 shows the flowchart of the methodology.

The methodology applied involves the following main steps: definition of the road network geometry (including the tunnel), assignment of traffic demand, development of a traffic macro-simulation model and its validation, definition of the scenarios to be investigated, analysis of the results and their comparisons using the average travel speed as a resilience metric, and choice of the recovery strategy.

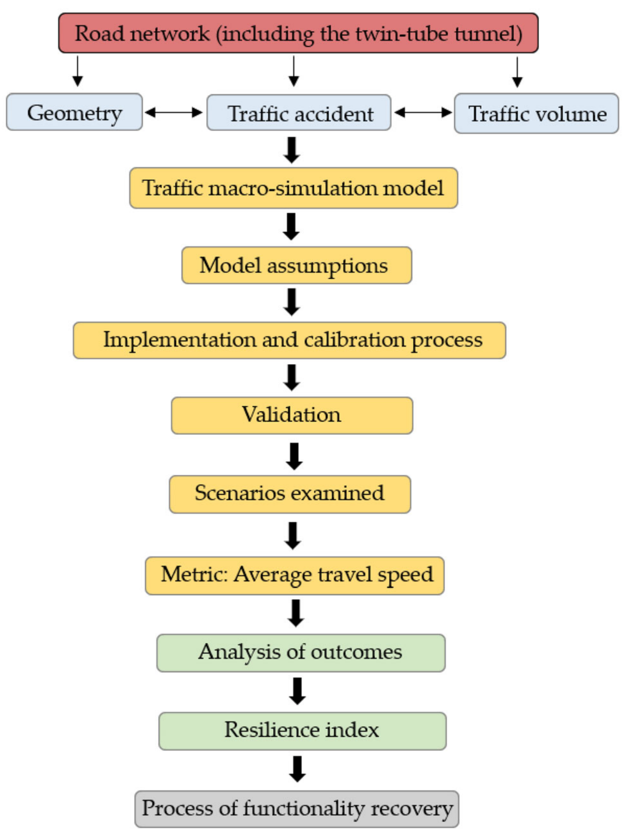


Fig. 4 Flowchart of the methodology

4 Traffic Macro-Simulation Model

4.1 Implementation Process

The PTV Visum 17 version [26] was used as a traffic macro-simulation tool. The analysis period for the simulations was assumed to be 7 h (i.e., from 6:00 a.m. to 1:00 p.m.). It is to be stressed that the traffic accident is considered to occur at 7:00 a.m. in the northbound tube. Therefore, the mentioned analysis period includes: (1) 1 h (i.e., 6:00–7:00 a.m.) before the occurrence of the traffic accident in the northbound tube to achieve stationary traffic conditions along the road network of interest; (2) 3 h (i.e., from 10:00 a.m. to 1:00 p.m.) after the end of the partial or complete closure of the northbound tube in the worst condition (i.e., when the traffic accident causes the partial or complete blockage of the northbound tube for 3 h, namely from 7:00 a.m. to 10:00 a.m.) in order to investigate the recovery process of the ordinary operating conditions of the road network.

The PVT Visum code involves: (1) the geometric definition of the road network of interest (i.e., the impact area); (2) the assignment of the traffic capacity to each link and/or node, as well as the speed limits; (3) the implementation of the traffic demand; (4) the choice of the traffic assignment procedure, in this case a Dynamic User Equilibrium (DUE) procedure was selected in order to account for the variability over time of both the transport supply and traffic demand; (5) the setting of the rate of flow period; it was assumed for every 5 min of the analysis period; (6) the definition of the simulation time interval; it was set equal to 5 min so that the code provides the travel speed of the vehicles on the different road segments investigated with a time interval of 5 min for the entire analysis period.

The criterion applied to verify the convergence of the analysis predictions was to stop the runs when the simulation results of two consecutive runs differed from each other by less than 5% (10 runs were required in our case).

The calibration of the proposed traffic-macro simulation model consisted of comparing the simulated and observed hourly traffic volumes and verifying that the GEH statistic was less than 5 for each road segment investigated.

4.2 Validation

The outcome of the traffic-macro simulation model was preliminarily validated by means of a comparison with the queue length measured in the field by the Tunnel Management Agency (TMA) as a consequence of a real frontal crash between a car and a HGV in the northbound tube.

In particular, the mentioned frontal collision occurred at 7:30 a.m., causing the complete blockage of the northbound tube. At 8:00 a.m., the emergency teams forced all the vehicles to leave the motorway using the motorway junction C (Fig. 1) located upstream of the entrance portal of the blocked northbound tube. The queue length upstream of the cited junction C was measured to be equal to 2 km at 8:30 a.m., and 4 km at 9:15 a.m. Lastly, one lane of the blocked northbound tube was re-opened at 9:30 a.m., so the traffic queue ended at 11:00 a.m. The mentioned real accident was simulated using our traffic model, and the result showed that the queue length upstream of the mentioned junction C was 2.1 km at 8:30 a.m., and 4.2 km at 9:15 a.m.; then the simulated traffic queue ended at 11:10 a.m. In other terms, the outcomes of the simulation model showed a good level of conformity with the measured values of the queue. More details about the above-mentioned calibration and validation processes can be found in [20].

Therefore, the authors of this study are confident that, by means of a rigorous analysis based on the calibration and validation of the proposed macro-simulation model, they have sufficiently assessed the resilience of a road network in the event of a traffic accident in a tunnel.

5 Analysis and Discussion of the Results

5.1 Longitudinal Spatial Profiles of the Average Travel Speed

The main output provided by the PTV Visum code is the travel speed of vehicles every 5 min. By averaging these travel speeds over the time of partial or complete closure of the northbound tube due to a traffic accident (i.e., 1, 2, or 3 h), the corresponding average travel speed of the vehicles was computed.

Figures 5, 6, and 7 show the longitudinal spatial profiles of the average travel speed of the vehicular flow transiting north along the motorway section containing the disrupted tube (i.e., from the Nodes A to D) when it remains partially or completely closed for 1, 2, and 3 h, respectively. In these figures, the entrance and exit sections of the northbound tube for Scenarios 0, 1, and 3 or those of the southbound tube for Scenarios 2a, 2b, 2c, 4a, 4b, and 4c are reported in red lines in order to identify its longitudinal spatial location.

From the above-mentioned figures, it can be noted that in Scenario 0, in which the northbound tube is not affected by any disruptive events and operates at its ordinary level of functionality, the average travel speed of the traffic flow towards the North, which includes all the vehicles (i.e., both passenger cars and HGVs), is about 120 km/h and remains more or less the same along the entire motorway section investigated. In this respect, it is to be said that the mentioned average travel speed of 120 km/h was calculated as the average weighted over the traffic volume of passenger cars and HGVs, which had been computed to be about 130 and 100 km/h, respectively.

With reference to Scenario 1 (i.e., the partial closure of the northbound tube with only one lane open to traffic) from Fig. 5(a), which is related to the case where the northbound tube is partially closed for 1 h and the alternative route is not used yet, it can be noted that: (1) the average travel speed of 120 km/h of the vehicular flow towards the North starts to decrease, as a consequence of the traffic accident that occurred in the northbound tube, at a distance of 4.2 km from the entrance portal (i.e., Portal *a*) of the disrupted tube; (2) it reaches approximately 80 km/h in the proximity of the motorway junction C located at about 1.3 km upstream of Portal *a*; (3) at the entrance portal of the northbound tube, the average vehicles' speed is approximately equal to the imposed speed limit of 60 km/h; (4) the average travel speed of 60 km/h remains constant along the entire length of the northbound tube; (5) downstream of the exit portal (i.e., Portal *b*) of the disrupted tube, the average vehicles' speed starts to increase, reaching the value of 120 km/h at a distance of 3.3 km from Portal *b*. Figure 5a also shows that the longitudinal spatial profile of the average travel speed resulting from a traffic accident in the northbound tube is not symmetric. This might be attributed to the behavior of drivers that downstream of Portal *b*, having overcome the disruptive event in the northbound tube, accelerate more than when they are forced to decelerate upstream of Portal *a*; consequently, vehicles reach, downstream of Portal *b*, the average travel speed of 120 km/h in a shorter space.

With reference to the case in which there is the activation of VMSs that alert only HGVs to use an alternative itinerary in the nearby road network (i.e., Scenario 3), Fig. 5b shows that: (1) the average travel speed (computed by considering both the passenger cars and HGVs) of 120 km/h starts to decrease, due to the traffic accident in the northbound tube, at a shorter distance from the entrance portal (i.e., Portal *a*) of the disrupted tube than in Scenario 1 (i.e., 3.3 km against 4.2 km); this might be attributed to the positive influence on the longitudinal spatial profile of the average travel speed of the re-routing of the HGVs that, alerted by VMSs, leave the motorway section using the motorway junction C (located at 1.3 km upstream of Portal *a*) to enter the alternative route identified in the nearby road network (and subsequently return again on the northbound motorway using the motorway junction D located at a distance of about 7 km downstream of the exit portal (i.e., Portal *b*) of the disrupted tube); (2) at Portal *a*, the average travel speed (computed by considering only passengers cars) is still equal to the imposed limit of 60 km/h and remains constant along the entire length of the northbound

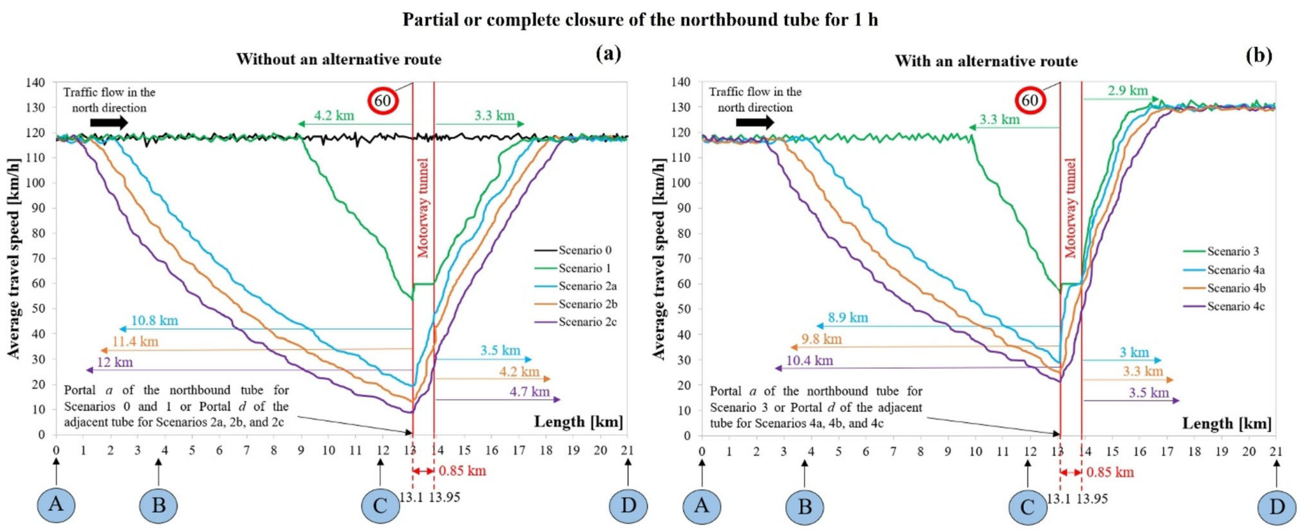


Fig. 5 Longitudinal spatial profiles of the average travel speed of the vehicular flow transiting along the motorway segment in the north direction (i.e., from the Nodes A to D) when the northbound tube is partially or completely closed for 1 h: **a** without an alternative route, **b** with an alternative route. Scenario 0 where the twin-tube motorway tunnel operates at its ordinary level of functionality; Scenario 1 in which the northbound tube is partially closed; Scenario 2 where the northbound tube is completely closed and the southbound tube is used for traffic in two driving directions through the opening of the traffic by-passes after 10 (Scenario 2a), 20 (Scenario 2b), or 30 min (Scenario 2c) from the occurrence of the disruptive event in the northbound tube; Scenario 3 that is similar to Scenario 1, but with only HGVs traveling northbound diverted along the alternative route; Scenarios 4a, 4b, and 4c that are similar to Scenarios 2a, 2b, and 2c, respectively, but with the activation of the alternative itinerary for only HGVs traveling along the motorway in the north direction

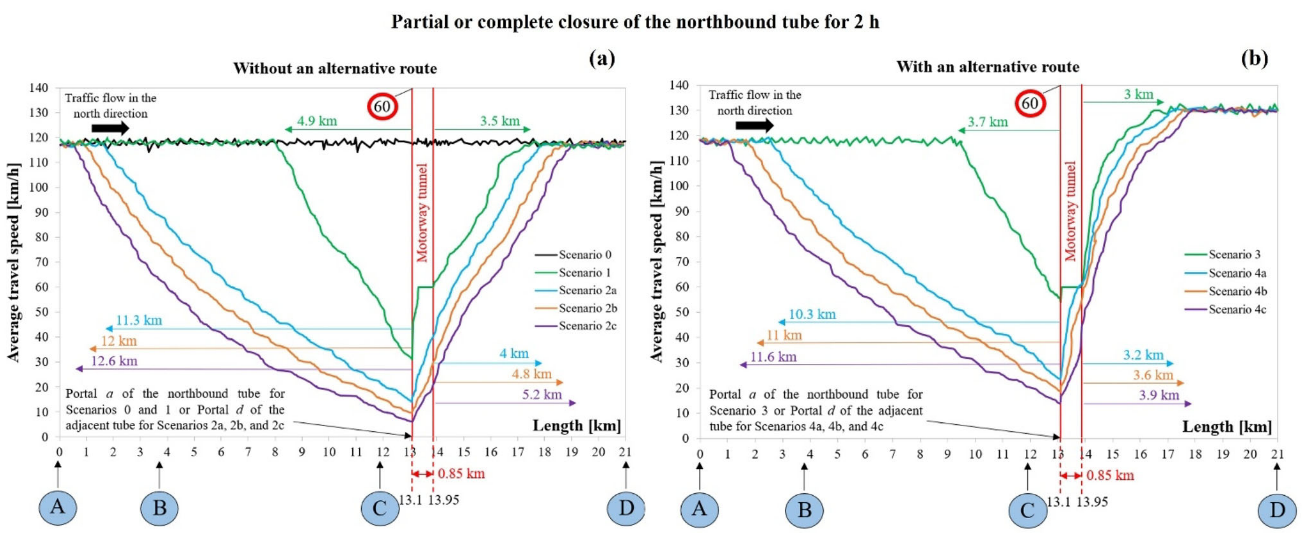


Fig. 6 Longitudinal spatial profiles of the average travel speed of the vehicular flow transiting along the motorway segment in the north direction (i.e., from the Nodes A to D) when the northbound tube is partially or completely closed for 2 h: **a** without an alternative route, **b** with an alternative route. Scenario 0 where the twin-tube motorway tunnel operates at its ordinary level of functionality; Scenario 1 in which the northbound tube is partially closed; Scenario 2 where the northbound tube is completely closed and the southbound tube is used for traffic in two driving directions through the opening of the traffic by-passes after 10 (Scenario 2a), 20 (Scenario 2b), or 30 min (Scenario 2c) from the occurrence of the disruptive event in the northbound tube; Scenario 3 that is similar to Scenario 1, but with only HGVs traveling northbound diverted along the alternative route; Scenarios 4a, 4b, and 4c that are similar to Scenarios 2a, 2b, and 2c, respectively, but with the activation of the alternative itinerary for only HGVs traveling along the motorway in the north direction

tube; (3) downstream of Portal *b*, the average vehicles' speed increases up to achieve, at a distance of 2.9 km from the exit portal of the disrupted tube, the value of 130 km/h; it is to be recorded that the maximum average travel speed downstream of Portal *b* is 10 km/h higher than that of Scenario 1 since it only concerns passenger cars. Therefore, the results show the positive effects of VMSs with the associated alternative itinerary.

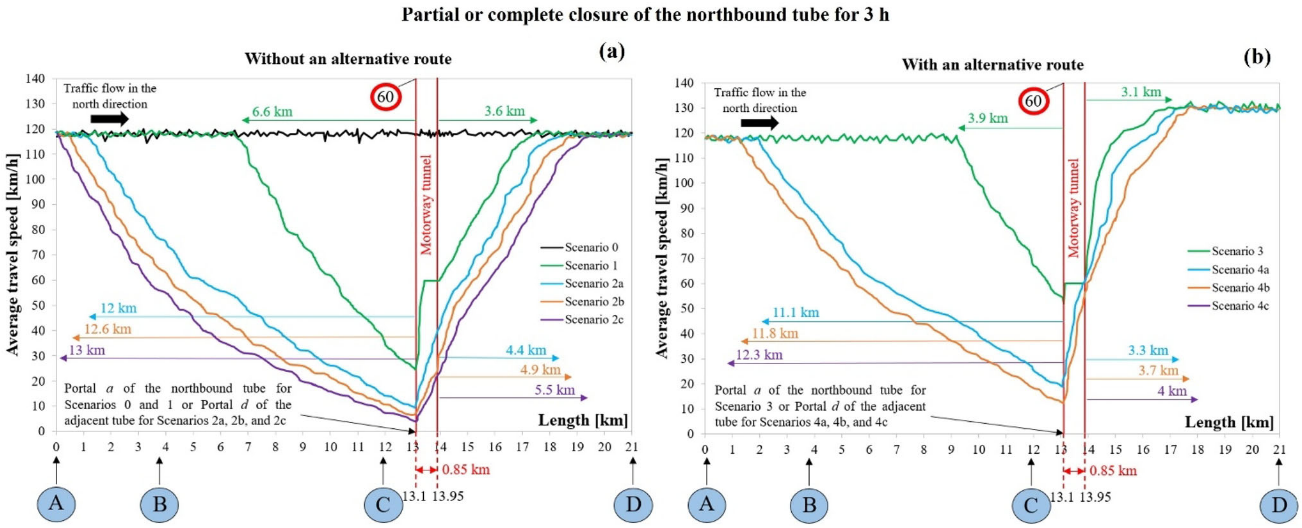


Fig. 7 Longitudinal spatial profiles of the average travel speed of the vehicular flow transiting along the motorway segment in the north direction (i.e., from the Nodes A to D) when the northbound tube is partially or completely closed for 3 h: **a** without an alternative route, **b** with an alternative route. Scenario 0 where the twin-tube motorway tunnel operates at its ordinary level of functionality; Scenario 1 in which the northbound tube is partially closed; Scenario 2 where the northbound tube is completely closed and the southbound tube is used for traffic in two driving directions through the opening of the traffic by-passes after 10 (Scenario 2a), 20 (Scenario 2b), or 30 min (Scenario 2c) from the occurrence of the disruptive event in the northbound tube; Scenario 3 that is similar to Scenario 1, but with only HGVs traveling northbound diverted along the alternative route; Scenarios 4a, 4b, and 4c that are similar to Scenarios 2a, 2b, and 2c, respectively, but with the activation of the alternative itinerary for only HGVs traveling along the motorway in the north direction

Figure 5a related to Scenarios 2a, 2b, and 2c (i.e., the complete closure of the northbound tube for 1 h, the alternative itinerary not activated yet, and the use of the southbound tube for bi-directional traffic through the opening of the two traffic by-passes after 10, 20, or 30 min from the occurrence of the traffic accident in the northbound tube, respectively) shows that: (1) the average travel speed of 120 km/h of vehicles traveling towards the North starts to decrease at a distance of 10.8, 11.4, or 12 km from Portal *a* when the intervention time of the emergency team to rearrange traffic in the parallel tube from one-way to two-way increases from 10 to 20 or 30 min, respectively; thus indicating that the reduction in the average travel speed extends upstream of the disrupted tube over a greater length when this time increases; (2) at the entrance portal (i.e., Portal *d* of the southbound tube), the average vehicles' speed is much lower than the imposed speed limit of 60 km/h, which is representative of congested traffic conditions, with values of 20, 13, or 9 km/h if the mentioned intervention time increases from 10 to 20 or 30 min, respectively; in other terms, a significant reduction in the average travel speed in the proximity of Portal *d* is found by increasing the intervention time of the emergency team; (3) downstream of Portal *d*, namely in the southbound tube, the average travel speed of vehicles transiting towards the North increases, but always remains below 60 km/h along the entire tube length; (4) downstream of the exit portal (i.e., Portal *c* of the southbound tube) and after the return of vehicles to the north carriageway, the average travel speed increases up to reach the value of 120 km/h at a distance of 3.5, 4.2, or 4.7 km from Portal *b* if the intervention time increases from 10 to 20 or 30 min, respectively; this indicates that a greater distance from Portal *b* is necessary to achieve the average travel speed of 120 km/h if the mentioned intervention time increases. Also in this case, it is confirmed that each longitudinal spatial profile of the average travel speed is not symmetric, which is due to the mentioned behavior of drivers that downstream of Portal *b* accelerate more than when they are forced to decelerate upstream of the northbound tube; consequently, vehicles reach, downstream of Portal *b*, the average travel speed of 120 km/h in a shorter space.

With respect to the case where there is the activation of VMSs that alert only HGVs to use an alternative itinerary in the nearby road network (i.e., Scenarios 4a, 4b, and 4c), Fig. 5b shows that: (1) the average travel speed (computed by considering both the passenger cars and HGVs) of 120 km/h starts to decrease at a shorter distance from Portal *a* than in Scenarios 2a, 2b and 2c, thus finding values of 8.9, 9.8, or 10.4 km when the intervention time of the emergency team increases from 10 to 20 or 30 min, respectively; this appears to confirm the positive influence on the longitudinal spatial profile of the average travel speed of the re-routing of the HGVs that, alerted by VMSs, leave the motorway section using the motorway junction C to enter the alternative itinerary; (2) at the entrance portal (i.e., Portal *d* of the southbound tube), the average travel speed (computed by considering only passengers cars) is still below the imposed speed limit of 60 km/h, but its values are much higher than those in Scenarios 2a, 2b, and 2c; (3) downstream of Portal *d*, the average travel speed of vehicles (i.e., only passengers cars) traveling towards the North increases, achieving, in the proximity of the exit portal (i.e., Portal *c* of the southbound tube), values slightly lower than the speed limit of 60 km/h; (4) downstream of Portal *c* and after the return of vehicles (i.e., only passengers cars) to the north carriageway, the average vehicles' speed increases up to reach the value of 130 km/h at distances of 3, 3.3, or 3.5 km from Portal *b* if the intervention time of the emergency team increases from 10 to 20 or 30 min, respectively; in other terms, the maximum average travel speed is 10 km/h higher than that upstream of the northbound tube and is achieved at smaller distances from Portal *b* than in Scenarios 2a, 2b, and 2c. Therefore, also in these Scenarios, the positive effects of VMSs with the associated alternative route are confirmed.

Figure 6a and b are related to the partial or complete closure of the northbound tube for 2 h, without and with the use of the alternative itinerary, respectively. Figure 7a and b are related to the partial or complete closure of the northbound tube for 3 h, without and with the use of the alternative route, respectively.

By comparing Figs. 5, 6 and 7, it is possible to note that by increasing the time of partial or complete closure of the northbound tube from 1 to 2 or 3 h, the longitudinal spatial profiles of the average travel speed get worse. In particular, the average travel speed of 120 km/h starts to decrease at much greater distances from the entrance portal, and the values of the average travel speed at the entrance portal are even smaller.

In light of the above considerations, the best functionality level of the system, expressed in terms of average travel speed, in the case of a traffic accident in the northbound tube is found with the partial closure of the disrupted tube rather than the complete one. Additional benefits may be obtained by means of the activation of VMSs that alert only HGVs to leave the motorway and to use an alternative route in the nearby road network. Moreover, with the aim of containing a very significant reduction in the functionality level of the system due to a potential complete closure of the northbound tube, the traffic by-passes should be opened in a very short time (i.e., $\leq$ 10 min) by the emergency team to allow for the quick use of the parallel tube for bi-directional traffic.

5.2 Unavailability of an Alternative Route in the Nearby Road Network

The aforementioned alternative route identified in the nearby road network, however, might not be available for use by HGVs for different reasons. In order to consider this circumstance, a further scenario (i.e., Scenario 5) was also investigated in which, after the complete blockage of the northbound tube due to a traffic accident, it is assumed that the emergency team is able to re-open at least one lane of the disrupted tube that is used only by HGVs traveling towards the North, while passenger cars are redirected towards the southbound tube that is used for bi-directional traffic. In this respect, it is also assumed that the emergency team was able to open the two traffic by-passes located at the tunnel portals, as well as the lane of the disrupted tube used only by HGVs, in a very short time (i.e., 10 min from the occurrence of the traffic accident in the northbound tube).

Figure 8 shows the results obtained in terms of the longitudinal spatial profiles of the average travel speed of the vehicles moving north along the motorway section containing the northbound tube (i.e., from the Nodes A to D) for the different durations of the traffic accident in this structure (i.e., 1, 2, or 3 h).

From Fig. 8, it is possible to note that in Scenario 5: (1) the average travel speed (computed by considering both the passenger cars and HGVs) of 120 km/h starts to decrease at a longer distance from the entrance portal (i.e., Portal *a*) of the northbound tube than in Scenario 4a (i.e., at 9.4, 10.6, or 11.5 km against 8.9, 10.3, or 11.1 km of Scenario 4a when the duration of the traffic accident is 1, 2, or 3 h, respectively), which is attributable to the fact that in Scenario 5 the HGVs do not leave the motorway section, thus causing a reduction in the average travel speed; (2) at the entrance portal (i.e., Portal *d*) of the southbound tube, the average vehicles' speed (computed by considering only the passengers cars) is lower than that corresponding in Scenario 4a; (3) downstream of Portal *d*, namely in the southbound tube, the average travel speed of the vehicles (i.e., only passenger cars) traveling towards the North increases, but still remains below the value of that corresponding to Scenario 4a; (4) at the exit portal (i.e., Portal *c*) of the southbound tube, the average travel speed of 60 km/h is reached in all the cases as in Scenario 4a; (5) downstream of Portal *c* and after the return of the passenger cars to the north carriageway, the average travel speed (computed by considering both the passenger cars and HGVs) increases up to reaching the value of 120 km/h at a distance of 3.3, 3.5, or 3.6 km from Portal *b* by increasing the duration of the traffic accident in the northbound tube from 1 to 2 or 3 h, respectively (against a maximum average

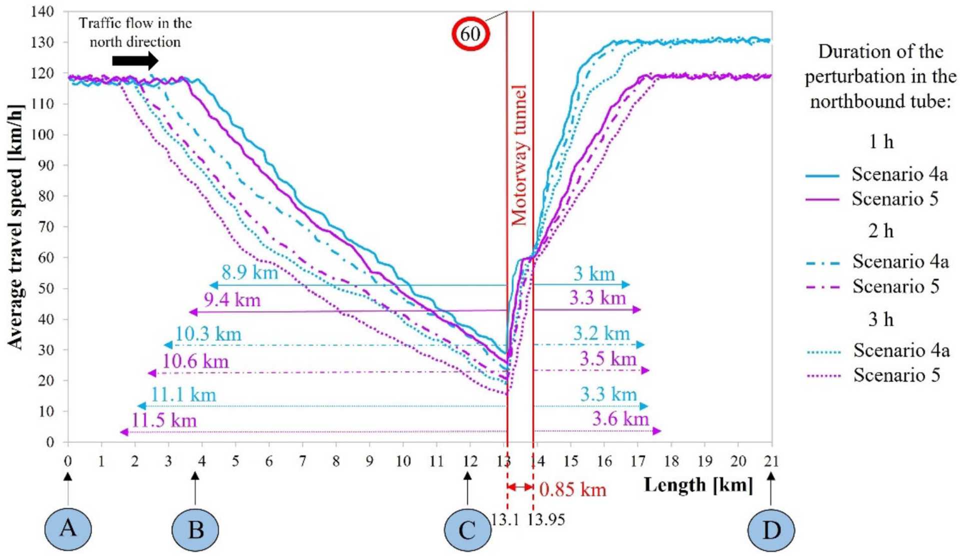


Fig. 8 Longitudinal spatial profiles of the average travel speed of the vehicular flow transiting along the motorway segment in the north direction (i.e., from the Nodes A to D) for the duration of the traffic accident in the northbound tube of 1, 2, or 3 h. Scenario 4a where the northbound tube is completely closed, the southbound tube is used for traffic in two driving directions through the opening of the traffic by-passes after 10 min from the occurrence of the disruptive event in the northbound tube, and HGVs are alerted, by VMSs, to leave the motorway to enter the alternative itinerary identified in the nearby road network; Scenario 5 in which the passenger cars traveling towards the North are diverted along the southbound tube used for traffic in two driving directions through the opening of the traffic by-passes after 10 min from the occurrence of the disruptive event in the northbound tube, while the HGVs, given the unavailability of an alternative route in the nearby road network, keep traveling along the northbound motorway using one lane of the northbound tube that is re-opened to traffic after 10 min from the occurrence of the disruptive event

travel speed of 130 km/h in Scenario 4a that is reached at a distance of 3, 3.2, or 3.3 km from Portal *b*, respectively); this means that downstream of the northbound tube, the maximum average travel speed in Scenario 5 is 10 km/h lower than that in Scenario 4a, and that the value of 120 km/h is achieved at greater distances from Portal *b* than those in which 130 km/h is reached in Scenario 4a.

These results confirm, from the point of view of the average travel speed on the motorway section containing a tunnel tube interested by a traffic accident, that additional advantages are obtained when HGVs leave the motorway and use an alternative route in the nearby road network.

5.3 Resilience Index

The functionality level of the tunnel system, when the northbound tube is partially or completely closed, was calculated as the ratio between the average vehicles' speed traveling northbound (i.e., from the Nodes A to D) after and before the occurrence of a traffic accident in the northbound tube (obviously, the functionality level was assumed to be equal to 100% in the absence of a traffic accident). The average travel speed under ordinary functionality conditions of the tunnel system remains constant along the entire length of the motorway section containing the northbound tube and is equal to 120 km/h (i.e., Scenario 0). After the occurrence of the traffic accident, the longitudinal spatial profiles of the average travel speed are not constant and are as reported in Figs. 5, 6, 7, or 8. For each longitudinal spatial profile of the average vehicles' speed, the corresponding subtended area (i.e., the integral of the average travel speed between the Nodes A and D) was computed; then, dividing the value of this area by the distance between the two mentioned nodes (i.e., about 21 km), the travel speed averaged over the length of the investigated motorway segment containing the northbound tube was obtained. The values of the travel speed averaged over the length were used to quantify the temporary functionality loss of the tunnel system due to the traffic accident in the northbound tube corresponding to each scenario analyzed. For example, when the northbound tube remains partially closed for 1 h and the alternative route in the nearby road network is still not used (i.e., Scenario 1), the travel speed averaged over the length is 101.5 km/h; this implies that the functionality level of the tunnel system is reduced to: 100 × 101.5/120 = 84.58%; while in the case of the complete closure of the northbound tube for 1 h with the alternative route still not used, assuming that the two traffic by-passes at the tunnel portals are opened within 10 min (i.e., Scenario 2a), the travel speed averaged over the length is 72.3 km/h, so that the functionality level of the tunnel system is temporarily reduced to: 100 × 72.3/

120 = 60.25%. It is to be said that the same procedure was also used to calculate the reduced functionality level of the tunnel system in all the other scenarios investigated.

However, to coherently use the definition of the resilience index reported in Sect. 3.6 where the variable time (t) was considered, the aforementioned travel speed averaged over the length of the investigated motorway segment containing the northbound tube was used to calculate the ratio between the average travel time required to reach a given destination from a specific origin after and before the occurrence of the traffic accident in the northbound tube. By reporting on the y-axis, the percentage values of the reductions in the functionality level of the tunnel system expressed in terms of the average travel time (i.e., $F(\%)$), and on the x-axis, the time instant t_0 when the traffic accident occurs in the northbound tube (i.e., 7:00 a.m.), the time instant t_a at which the functionality level is reduced to F_a, the time instant t_r when the disruptive event ends (i.e., after 1, 2, or 3 h from t_0), and the time instant t_h at which the system recovers the ordinary operating conditions reaching again its maximum functionality level (i.e., $F_0 = 100\%$), the functionality curves $F(\%)$ over time (t) was built, and consequently the resilience index was calculated: $R(t_h) = \frac{\int_{t_0}^{t_h} F(t)dt}{(t_h - t_0)}$. It is to be recorded that the resilience index can assume values between 0 and 1, and that a high resilience index indicates a low resilience loss.

Figure 9a and b show the resilience index related to each scenario examined as a function of the duration of the traffic accident within the northbound tube (i.e., 1, 2, or 3 h), without and with the use of the alternative itinerary in the nearby road network, respectively. Specifically, it is possible to note that the resilience index increases (i.e., the resilience loss decreases) as the duration of the partial or complete closure of the northbound tube decreases (i.e., the highest resilience indexes are found when the duration of the interruption due to a traffic accident is 1 h in contrast to 2 or 3 h).

Greater resilience indexes correspond to the partial closure of the disrupted tube (i.e., Scenario 1) rather than the complete one (i.e., Scenarios 2a, 2b, and 2c). In the case of the complete closure of the northbound tube, the resilience indexes are higher when the intervention time of the emergency team to open the two traffic by-passes at the tunnel portals is 10 min (i.e., Scenario 2a against Scenarios 2b and 2c). By comparing Fig. 9a and b, it can also be noted that, both when the northbound tube is partially (i.e., Scenario 3 against Scenario 1) and completely (i.e., Scenarios 4a, 4b, and 4c compared to Scenarios 2a, 2b, and 2c, respectively) closed, higher resilience indexes might be obtained through the activation of VMSs that alert only HGVs to leave the motorway section before entering the tunnel and to use an alternative itinerary in the nearby road network.

It is to be stressed that, in the case of unavailability of the alternative route in the nearby road network, assuming that the emergency team re-opens within 10 min and for HGVs only at least one lane of the northbound tube that

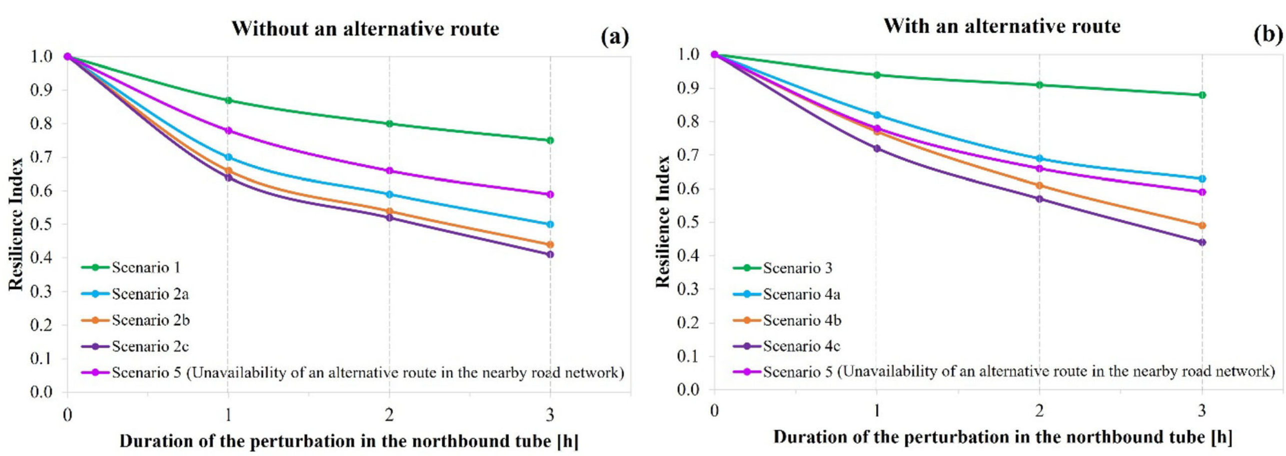


Fig. 9 Resilience index for the different scenarios analyzed as a function of the duration of the perturbation in the northbound tube: **a** without an alternative route, **b** with an alternative route. Scenario 1 in which the northbound tube is partially closed; Scenario 2 where the northbound tube is completely closed and the southbound tube is used for traffic in two driving directions through the opening of the traffic by-passes after 10 (Scenario 2a), 20 (Scenario 2b), or 30 min (Scenario 2c) from the occurrence of the disruptive event in the northbound tube; Scenario 3 that is similar to Scenario 1, but with only HGVs traveling northbound diverted along the alternative route; Scenarios 4a, 4b, and 4c that are similar to Scenarios 2a, 2b, and 2c, respectively, but with the activation of the alternative itinerary for only HGVs traveling along the motorway in the north direction; Scenario 5 in which the passenger cars traveling towards the North are diverted along the southbound tube used for traffic in two driving directions through the opening of the traffic by-passes after 10 min from the occurrence of the disruptive event in the northbound tube, while the HGVs, given the unavailability of an alternative route in the nearby road network, keep traveling along the northbound motorway using one lane of the northbound tube that is re-opened to traffic after 10 min from the occurrence of the disruptive event

was completely closed due to a traffic accident, as well as that the passenger cars use the southbound tube for bi-directional traffic within 10 min from the occurrence of the traffic accident (i.e., Scenario 5), Fig. 9a shows that higher resilience indexes might be found in Scenario 5 if compared to the corresponding scenario related to the complete closure of the northbound tube (i.e., both lanes are blocked) with the southbound tube used for bi-directional traffic by all the vehicles (i.e., passenger cars and HGVs) after the activation of the two traffic by-passes located at the tunnel portals within 10 min from the occurrence of the traffic accident (i.e., Scenario 2a). However, from Fig. 9b it can also be noted that the resilience indexes related to Scenario 5 are lower than those found in the corresponding scenario where an alternative itinerary in the nearby road network is used (i.e., Scenario 4a).

This confirms that additional benefits are obtained when HGVs leave the motorway using an alternative route identified in the nearby road network. In this regard, Table 3 shows both when the northbound tube is partially and completely closed, the percentage increase in the resilience index due to the activation of VMSs to divert only the HGVs on an alternative itinerary (i.e., Scenarios 3, 4a, 4b, and 4c) compared to the case in which they are not used (i.e., Scenarios 1, 2a, 2b, and 2c). From Table 3, it can be noted that the benefits due to the activation of VMSs increase as the duration of the disruptive event increases (i.e., passing from 1 to 3 h). For example, the percentage increase in the resilience index is 7, 12, and 17% for the partial closure of the northbound tube of 1, 2, and 3 h, respectively (i.e., Scenario 3 vs Scenario 1); while, when the northbound tube is completely closed for 1, 2, and 3 h with the opening of the traffic by-passes after 10 min from the occurrence of the traffic accident (i.e., Scenario 4a vs Scenario 2a), it is 14, 17, and 22%, respectively. Moreover, in the event of the complete closure of the northbound tube, the advantages due to the use of VMSs decrease as the time required to open traffic by-passes increases (i.e., passing from 10 to 30 min). A summary of the outcomes is also reported in Table 3.

6 Conclusions

The main aim of this work was to evaluate the resilience of an existing Italian twin-tube motorway tunnel in the case of a traffic accident occurring in one of its tubes and the efficiency of certain recovery strategies proposed to contain the reduction in the average travel speed of the vehicular flow along the transportation network containing the disrupted tube.

The scenarios investigated involved: (1) the tunnel system under its ordinary operating conditions (i.e., without any traffic accident and with both lanes of each tube used for unidirectional traffic); (2) the partial closure of the disrupted tube (i.e., only one lane is blocked and the entire vehicular flow entering the disrupted tube uses the other lane); (3) the complete closure of the disrupted tube (i.e., both lanes are blocked and the entire traffic entering the disrupted tube is diverted along the adjacent tube that is temporarily used for bi-directional traffic through traffic by-passes, located at the tunnel portals, that are assumed to be opened after 10, 20, or 30 min from the occurrence of the traffic accident); (4) the re-routing of only heavy goods vehicles traveling through the disrupted tube along an alternative route identified in the nearby road network and

Table 3 Percentage increase in the resilience index due to the activation of VMSs to divert only the HGVs on an alternative itinerary compared to the case in which they are not used

		Increase in the resilience index [%]		
		Closure of the northbound tube for:		
		1 h	2 h	3 h
Partial closure of the northbound tube				
Scenario 3 (with the VMSs for HGVs only) vs Scenario 1		7	12	17
Complete closure of the northbound tube	Time to open the traffic by-passes			
Scenario 4a (with the VMSs for HGV_S only) vs Scenario 2a	10 min	14	17	22
Scenario 4b (with the VMSs for HGV_S only) vs Scenario 2b	20 min	13	15	16
Scenario 4c (with the VMSs for HGV_S only) vs Scenario 2c	30 min	12	14	15

Scenario 1 in which the northbound tube is partially closed; Scenario 2 where the northbound tube is completely closed and the southbound tube is used for traffic in two driving directions through the opening of the traffic by-passes after 10 (Scenario 2a), 20 (Scenario 2b), or 30 min (Scenario 2c) from the occurrence of the disruptive event in the northbound tube; Scenario 3 that is similar to Scenario 1, but with only HGVs traveling northbound diverted along the alternative route; Scenarios 4a, 4b, and 4c that are similar to Scenarios 2a, 2b, and 2c, respectively, but with the activation of the alternative itinerary for only HGVs traveling along the motorway in the north direction suggested by VMSs placed at a certain distance upstream of the partially or completely closed tube. In this respect, the occurrence of the traffic accident in the disrupted tube was assumed to cause its partial or complete closure for 1, 2, or 3 h.

The impact area (i.e., that part of the network most affected by the perturbation caused by the traffic accident occurring in a tube), which was preliminarily identified by means of a traffic macro-simulation modeling, was found to have a length of 25 km and a width of 8 km.

The functionality level of the tunnel system, when the northbound tube is partially or completely closed, was calculated as the ratio between the vehicles' speed averaged over the length of the motorway section containing the disrupted tube after and before the traffic accident. Then, coherently with the definition of resilience in which the variable time (t) is explicitly considered, the mentioned travel speed averaged over the length was used to calculate the ratio between the average travel time required to reach a given destination from a specific origin after and before the occurrence of the traffic accident in the disrupted tube. Consequently, the resilience index related to each scenario investigated was computed as a function of the average travel time.

Specifically, the findings obtained showed that: (1) the best functionality level of the tunnel system, expressed in terms of average travel speed, as well as the highest resilience indexes, corresponded to the partial closure of the disrupted tube rather than the complete one; (2) further benefits may be found through the activation of VMSs that alert only HGVs to leave the motorway before entering the tunnel and to use an alternative route in the nearby road network; (3) the traffic by-passes should be opened as soon as possible (i.e., $\leq$ 10 min) to allow for the rapid use of the parallel tube for bi-directional traffic in the event of the complete blockage of the disrupted tube; (4) the use of one lane of the disrupted tube for HGVs only, in the case of unavailability of an alternative route in the nearby road network, is a better recovery strategy than the complete closure of the disrupted tube, although this measure is less effective than that in which the HGVs leave the motorway before entering the tunnel.

With respect to the benefits, expressed in terms of the percentage increase in the resilience index, due to the use of VMSs to divert only the HGVs on an alternative route compared to the case where they are not activated, the results showed that the percentage increase in the resilience index becomes greater as the duration of the disruptive event increases (e.g., it was found to be about 7, 12, and 17% when the disrupted tube is partially blocked for 1, 2, and 3 h, respectively; while, the maximum percentage increase (i.e., when the traffic by-pass is opened in a time equal to 10 min) in the resilience index is about 14, 17, and 22% when the disrupted tube is completely blocked for 1, 2, and 3 h, respectively).

The results of the paper provide additional points of view on the intervention time of emergency service teams, in order to reorganize the vehicular flow in the event of a traffic accident in a tube of a twin-tube motorway tunnel, and the effectiveness of VMSs to re-route traffic along an alternative route identified in the nearby road network. Therefore, it may represent a useful decision-support tool for enhancing the tunnel resilience and increasing the state of knowledge in the traffic analysis of a road network.

Although the authors are confident that they have carried out an appropriate resilience analysis using the average travel speed of vehicles as a metric, there are still some points that should be better examined to overcome certain limitations. The randomness of certain factors that play a role might also cause some uncertainties in the resilience analysis. Therefore, studies based on uncertainties in resilience should be carried out. Moreover, tunnel resilience should also be assessed in combination with safety that might be compromised by the occurrence of a fire as a consequence of a traffic accident involving, for example, the tunnel structural behavior (i.e., the concrete spalling [27]) or the vehicles that, having changed carriageway, use one lane of the parallel undisrupted tube to keep traveling (i.e., under bi-directional traffic conditions) or those that, having left the motorway before entering the tunnel, use the alternative route in the nearby road network, thus interacting with other vehicles. An additional extension of the paper might be to simulate a greater number of scenarios in which to modify the geometric characteristics of the tunnels (i.e., the length, the number of lanes, or the longitudinal slope [28]) and traffic conditions (i.e., peak hours of traffic flow, percentage of heavy goods vehicles) so to build a database large enough to perform an appropriate statistical analysis. Finally, since a disruption in a road tunnel might also propagate to other transport systems, the interdependency among different transport systems should also be considered.

Therefore, additional studies are needed to make further progress in the field of research on the road network resilience in the case of the partial or complete closure of a link.

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Data availability Data will be made available on request.

Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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