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Dynamic thresholds for the resilience assessment of road traffic networks to wildfires

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ABSTRACT

The severe effects of extreme wildfire events in recent years have shown that the fire suppression approach is not enough to solve the problem. An alternative to dealing with this issue is to accept the impossibility of eliminating wildfire hazards and focus on preparing systems to be more resilient. However, existing decision-making tools based on resilience present important drawbacks that make them inadequate for this task. This paper proposes a new approach and methodology for the resilience assessment of road traffic networks to wildfires that overcomes the main drawbacks, paying attention to the different functions of the system and the acceptance of a specific loss of performance. The latter is done through the introduction of dynamic thresholds that reflect the different requirements of the system under different wildfire conditions, including normal and extreme fires. The methodology is exemplified for five traffic networks. The results support the relevance of appropriate wildfire management through the adaptation of the natural and built environment to increase the capacity of the traffic networks to cope with wildfires.

1. Introduction

The severity of wildfires is affecting society as never before. In the last two decades, the damage caused by forest fires in the European Union amounted to more than US $60.5 billion, and more than 600 people (firefighters and civilians) lost their lives [1]. In 2020 alone, the burnt area in Europe was double that of the previous decade, and the 2021 fire wave was the second worst in the EU, with another 0.5 million hectares burned, according to the EFFIS report [2]. In 2020, bushfires in Australia caused the loss of more than 10 million hectares of forest and dozens of fatalities [3]. In the USA, wildfires in 2020 caused about $16.5 billion in damage to buildings and administrative costs, and hundreds of thousands of people were displaced [4]. The burnt area was more than 2.3 million hectares than the overall average in the previous decade and nearly double the previous year [5]. The same scenario applies to several countries around the world, as wildfires are already a recurring and growing threat to countries that were not previously considered at risk, such as those in Central and Northern Europe. The new type of wildfires caused by global warming and climate change is spreading faster and more intensely [2]. As a result of this emergent threat, experts agree on the need for moving from wildfire suppression to prevention, and the adoption of management policies focused on climate adaptation, education, and preparedness [6]. Thus, wildfire prevention is more often referred to as a top priority in local and international agendas. However, few efforts have been made toward wildfire prevention.

Within transport systems, road networks are considered one of the most critical and necessary for the functioning of society. Any damage or disruption to the roads in traffic networks can cause significant economic loss and have direct effects on disaster response, national defense, and the safety of citizens [7]. It is also one of the most exposed systems to climate change-related hazards given its spatial distribution. For that reason, it is paramount to align the policies around wildfire prevention with road network protection.

Risk management has been the dominant approach to infrastructure protection. However, it is becoming clear that risk-based approaches are not sufficient to defend critical infrastructure systems and their components in the context of current hazards [8]. This has led to research efforts on the resilience of infrastructure systems. It should be clarified that risk and resilience approaches are not mutually exclusive. Both concepts can be considered complementary although each one is applicable for different circumstances, depending on the analysis context and hazard understanding [9]. Holling [10] suggests that risk

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Notation

c	Wildfire category
d_{pq}^{g}	Geometric distance between OD pair pq
d_r	Travel distance of route r
$f_{j,k}$	Performance of target j and hazard level k
$g_{j,k}$	Compliance of target j and hazard level k
i	Link, i.e., continuous segment(s) of the road with similar physical and traffic characteristics.
pq	Origin Destination (OD) pair
r	Route, consisting of one or several links connecting an OD pair
t_i	Travel time associated with link i
t_{i0}	Free-flow travel time associated with link i
t_r	Travel time associated with route r
C_i	Capacity of link i
$FIRAT_{i,c}$	Fire approach time to link i under fire category c, in minutes
R	Resilience index
X_i	Users of link i
X_r	Total users of route r
$\mathcal{C}$	Set of wildfire categories
$\mathcal{N}$	Set of links
$\mathcal{PQ}$	Set of OD pairs
$\mathcal{R}_{pq,c}$	Set of routes connecting OD pair pq under fire category c
$\mathcal{R}_{pq,0}$	Set of routes connecting OD pair pq under normal conditions
$\emptyset$	Empty set
α	Parameter of the BPR function
β	Parameter of the C-logit Stochastic User Equilibrium model related to the users' preferences
γ	Parameter of the BPR function
θ	Parameter of the C-logit Stochastic User Equilibrium model related to the network dispersion

assumes identifiable hazards while resilience involves preparing for unexpected hazards. Risk assessment is based on the likelihood of the potential hazard affecting the system and the associated consequences. Whereas resilience assessment involves a more holistic perspective and focuses on the system's capacity to successfully handle the unexpected across different domains [11]. Thus, moving from risk to resilience leads to better results in preparing for unforeseen disruptive events. Given that the interest is in identifying the optimal strategies for preparing road networks for wildfires, including the new generation of extreme wildfires, resilience-based approaches seem more adequate.

Preparedness for wildfires has not received much attention in the scientific community in the field of road infrastructure. Moreover, the existing works do not consider the problem of the new wildfire regimes. Few approaches are available in this area, some of them analyze the system resilience based on the loss of connectivity of the network, such as [5,12,7], whereas other studies, such as [13,14] follow risk-based approaches. In any case, since these models are based on wildfire records and future forecasts, they are struggling to capture the current dynamics of extreme fires, which are very often far from expectations [15]. On the other hand, the existing approaches dealing with the resilience assessment of road traffic networks or other types of socio-technical systems present some important shortcomings, which will be discussed in Section 2. As a result, at present, it is not possible to establish a fair comparison between two interventions affecting traffic networks from the resilience viewpoint.

Within this context, this paper presents a novel approach to quantify the resilience of socio-technical systems that allows the comparison between systems subjected to different conditions. The approach is applied to the case of road traffic networks affected by wildfire hazards, focusing on the users. It allows the comparison of different interventions and strategies such as changes in vegetation policy and road distribution, aiming at improving the preparedness of road traffic networks for wildfire hazards. Therefore, it provides support in terms of decision-making and investment planning.

The novel approach integrates (i) different hazard levels, i.e., different wildfire categories, including normal and extreme wildfires, with a focus on the system capabilities. This means that it does not consider the likelihood of wildfire events that can be either naturally or intentionally caused, which brings unpredictability to the problem. This work follows on from Arango et al. [15], which propose a risk-based approach to study road traffic networks affected by different wildfire categories, no works study this range of wildfires (i.e., from normal to extreme wildfire events), (ii) different functionalities of the transportation system, such as safety, connectivity, reliability, and efficiency. Most of the studies on the resilience of traffic networks pay attention to only one functionality. For instance, connectivity [16–18], accessibility [19], reliability and recover ability [20] or evacuation capacity [21]; and (iii) different requirements for the traffic network depending on the wildfire category. It is reasonable that under an intense wildfire, the focus of the resilience analysis is based on the evacuation capacity. Nevertheless, the evacuation capacity is not informative about how the system responds to a low-intensity wildfire. To the best of our knowledge, there are no works introducing dynamic requirements.

The rest of the document is organized as follows. Section 2 provides a discussion of the main issues on resilience assessment and an explanation of the approach concept. The methodology formulation such as targets and thresholds are addressed in Section 3. The proof of concept is done through three case studies of basic networks and two complex networks from two cases of distinct exposure conditions, presented and discussed in Section 4. Section 5 covers the discussions of results, focusing on the comparison of networks, and finally, in Section 6 conclusions are presented.

2. Resilience assessment of socio-technical systems

This section elaborates on the need for novel approaches to assessing resilience. Although the discussion is around traffic networks, it can be extended to other types of socio-technical systems. According to the definition given by the National Research Council of USA [22], resilience is "the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events". Despite the increasing consensus around the definition of resilience, its operationalization has not been universally accepted yet. This has generated the development of diverse assessment frameworks with varying effectiveness and applicability ranges [23]. We have identified three critical issues related to the resilience assessment. At least one of these issues appears in most of the existing resilience assessment methods. Therefore, these limitations make the assessment frameworks partially or totally unsuitable for properly capturing the concept of resilience. Such issues may be the reason why there is no scientific consensus on how to assess resilience.

Issue 1. Case-specific resilience measures. It is quite common to find works assessing the resilience of traffic networks based on a specific scenario, with defined climatic, geographic, infrastructural, and socio-institutional characteristics, (e.g., [17,19,24–33]). They analyze if the traffic network performs adequately under the specific scenario and how to improve the performance if needed. However, it provides no information about the performance under other scenarios or conditions, which could be completely different. Thus, the system's resilience cannot be extrapolated based on just one or a few scenarios, usually covering overly critical conditions. It also prevents comparing different networks.

Issue 2. Resilience measures capture the state, not the process. A crucial difference between risk and resilience is that the first establishes a limit state (also a failure state or critical threshold) that the system under study cannot overpass. The resilience-based approach accepts the temporal degradation of the system's performance and focuses on the degradation process, not the state (i.e., degraded or not degraded). Many resilience assessments explicitly consider a fixed threshold to evaluate the system performance, adopted from risk assessments. The thresholds are associated with an inadmissible loss of performance of the functions of the system under study (e.g., [34,35,33,31]. However, the level of admissibility should depend on the hazard type -the desirable performance of a traffic network facing an extreme flooding event is not the same as facing a truckers' strike- and on the hazard intensity -a traffic network should provide a good service level in the context of a low-intensity wildfire, whereas under an extreme wildfire event (EWE), the network should guarantee the evacuation-. Therefore, thresholds may be set case by case, reinforcing Issue 1.

Issue 3. Resilience measures that only capture a small aspect of the system performance. The necessary consequence of a system that is *temporally degraded* is the existence of a recovery process. Thus, resilience implies recovery. For that reason, resilience is very often assessed through the only study of the recovery process (e.g., [36, 37,12,24,38–45]). Understanding resilience as only recovery is a poor interpretation of the concept of resilience; for instance, a system can have a poor response to an impact and still quickly recover. [36] assess the resilience of perturbation and recovery to distinguish between these two stages. As indicated by [46], resilience also considers robustness, redundancy, resourcefulness, and adaptability. Thus, resilience from the standpoint of the coping capacity of the system (i.e., use of skills and available resources to cope with a given event), should take into account preparedness and pre-disaster conditions in order to estimate the network capabilities to respond to disruptions.

2.1. A novel approach

This paper studies the preparedness of road traffic networks affected by different intensities of wildfire hazards. Given the emergent nature of the extreme wildfires, a resilience-based approach is of interest. Thus, the resilience assessment should focus on the capacity to cope with a disruptive event rather than the recovery process. It is also of interest to develop a methodology that allows the comparison across different traffic networks and hazard scenarios. This will permit the prioritization of different prevention strategies.

To do so, it is proposed a novel approach to assess resilience. Based on the definition of resilience as the ability of a system to prepare, plan, absorb, recover, and adapt, the system's resilience is measured by its capacity to perform its functions as expected at any time. Thus, the system's performance is analyzed through its various functions. Some of the functions of a traffic network are safety, connectivity, and reliability. The level of importance of the functions is considered. The performance of the functions is evaluated against the corresponding admissible performance loss, which depends on the hazard intensity and the importance of the functions. This is done through dynamic thresholds. The dynamic thresholds allow the evaluation of different states of a degradation process caused by increasing hazard intensities. The non-compliance with a given threshold does not imply the system's failure. Hereafter, the functions are referred to as targets.

Fig. 1, depicts the difference between assuming a static threshold and a dynamic threshold to assess the performance of a system. The static threshold, represented by the horizontal dotted black line, divides the performance of the system into two blocks, namely, above the line (i.e., until point b) would be considered as acceptable performance, and below the line (i.e., after point b) would be regarded as an unacceptable performance. This is for any hazard intensity or hazards the system is exposed to. However, the dynamic threshold, represented by the red dashed curve, varies the level of acceptability according to the intensity of the hazard. As a result, in this representation of the dynamic threshold, the performance is divided into three blocks. The first part is which the system performs within the region of acceptable performance (until point a). A second part, between points a and c, in which the system performs below what is desired for those hazard intensities. And a third part, in which the system again performs within the region of acceptable performance, even at the highest hazard intensities (from point c onwards). The logic behind this approach is that the system cannot be asked to perform equally for all types of hazard intensities according to a single criterion. In most cases, the intensities encountered will be in the low to moderate range, but there are also cases where the intensities are the highest. The system does not necessarily have to be prepared to be unaffected with the highest hazard intensities; for economic reasons, the system cannot be asked to perform at the same level for all intensities. Hence, there is a need to consider dynamic thresholds. Consequently, the focus of this study is not on creating the concept of thresholds itself, but on how the concept is employed. This paper highlights the need for adopting a dynamic threshold. Fig. 1 also reinforces the importance of considering system performance over the full spectrum of hazard intensities. In this way, decision-making is made in a better informed manner.

The rationale behind the approach is the following; (i) The characteristics of a potential hazard are unknown, and it is paramount to ensure the critical functions of the transportation system regardless of the disruption duration or intensity. (ii) As noted by [47], the critical function of traffic networks is to allow the movement of people and goods, in terms of safety at the core level, of connectivity and reliability at an intermediate level, and of efficiency at an outer level. In this paper, the functions of traffic networks are defined based on the movement of people. These targets were selected after considering the indicators used in the scientific literature to measure resilience. Recent systematic reviews on resilience indicators are, for example [48,49]. Indicators such as connectivity, and reliability, are common in the context of transportation network resilience. Safety indicator is more recurrent in risk analysis. However, safety is indeed a key indicator to be considered also in resilience assessment. On the other hand, efficiency, which is more related to the assessment of network utility and performance, is considered important as a measure of network service in terms of its demand capacity and mobility. Most of the time, the indicators are used individually for resilience assessment. The selected targets capture the variability of traffic network requirements in the face of different hazard intensities. Therefore, using this combination of targets generates a more comprehensive and complete framework for resilience assessment. Additionally, the definition of the targets meets two essential requirements, (I) it avoids information overlapping, i.e., there is no redundant information derived from the overlapping of targets definitions; and (II) the targets are consistent and have continuity with each other, i.e., when a road is not safe (at the core level), other intermediate and outer levels are affected consistently. That is, if the OD pair becomes disconnected if there is no redundancy, the reliability drops to zero, and so does the efficiency of the system. Fig. 2 depicts the corresponding hierarchy of the functions. This means that in the case of a disruptive event, regardless of the hazard intensity, the most important target is the safety of the users. Depending on the hazard intensity, it can be desirable that the network is also reliable or even efficient. Efficiency is desirable under low-stress levels; however, the efficiency of the road networks is difficult to guarantee even under ideal conditions (without fires). For instance, in the event of a minor wildfire that is easy to suppress, it can be established that the network should be safe, connected, reliable, and efficient. In the case of an extreme wildfire event (EWE), i.e., a wildfire that makes suppression impossible and has severe and unexpected impacts [50], the major concern is the user's safety, in order to allow an adequate evacuation, regardless of the travel reliability or the efficiency of the network. Therefore, the hazard

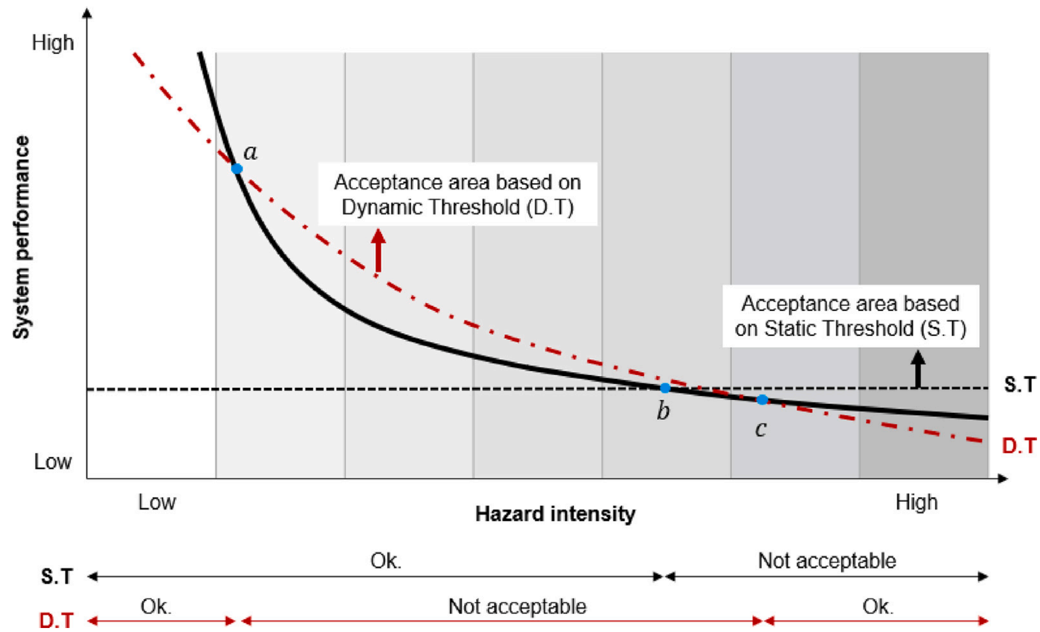

Fig. 1. Comparison between static and dynamic thresholds, S.T., and D.T., respectively, for resilience assessment.

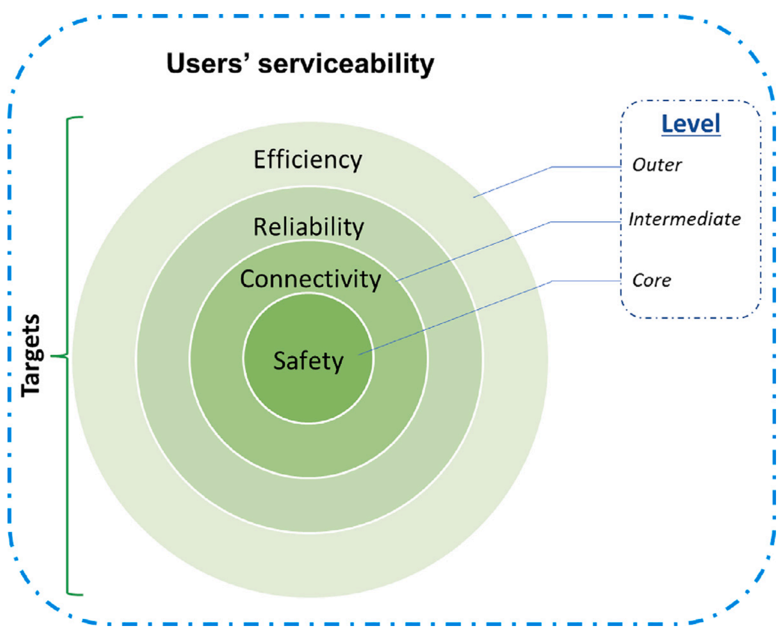

Fig. 2. Target levels for resilience assessment based on users' serviceability.

intensity defines the system's desirable performance. The performance is evaluated against the dynamic thresholds, in contrast to the static and unique thresholds typically associated with risk-based approaches. The full definition of the targets will be given in detail in Section 3.2.

Other targets, e.g., mobility, robustness, or resourcefulness, can be considered for the resilience assessment. The approach is the same, but it would be necessary to identify the level of importance of new targets.

(iii) The information provided by one scenario is insufficient to understand the entire traffic network performance. The proposed approach makes it possible to explore different scenarios, assessing how the different targets are affected by the various wildfire intensities. Since each network has different characteristics and preparedness degrees, their behaviors against distinct hazard intensities are also different. To exemplify the relevance of this, two networks are assumed. Their performance levels associated with the targets of safety, connectivity, reliability, and efficiency are presented in Fig. 3. In the face of a minor wildfire, Network 1 (Fig. 3.a) loses efficiency and part of its reliability compared to Network 2 (Fig. 3.b), in which only a little efficiency is lost. However, when comparing the same two networks against a higher-intensity fire, Network 1 performs better than Network 2. Network 1 (Fig. 3.c), although it loses its efficiency and reliability does not lose all its connectivity and guarantees the safety of the users. Whereas Network 2 (Fig. 3.d) loses its functionality even at the safety level. The example shows that determining which network is more resilient to wildfires is not straightforward. The idea of measuring the target's compliance with the dynamic thresholds allows such comparison, as will be explained in Section 3.

It is noted that the approach is suitable for evaluating distinct stages, e.g., during the disruptive event (i.e., the response stage) and

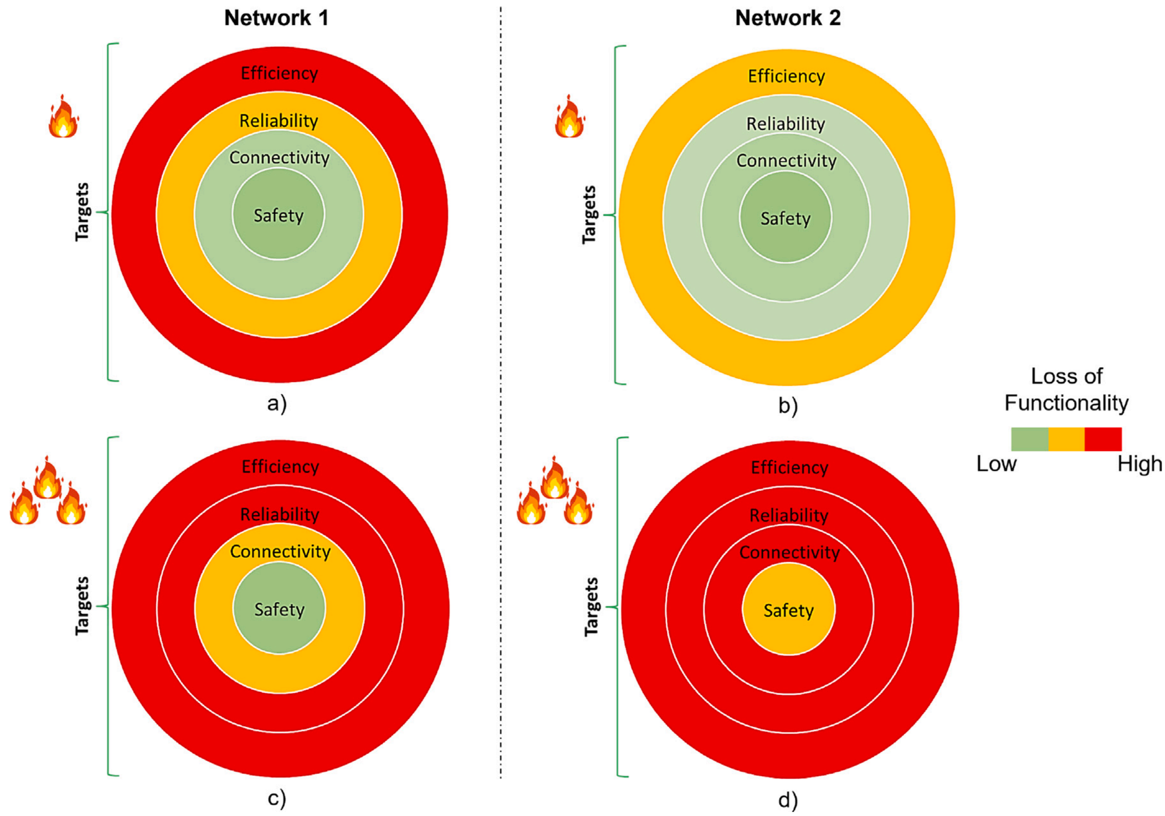

Fig. 3. Exemplification of resilience analysis, comparison between the performance levels of two networks affected by wildfire categories 1 (a and b) and 6 (c and d).

the recovery stage, with the appropriate definition of the dynamic thresholds. This approach allows analyzing the recovery process even in the presence of the hazard. Note that it is quite common to evaluate the recovery process once the system is not affected by the hazard anymore, however, in real cases, the recovery process starts even before the hazard is completely gone (e.g., COVID, economic crises, earthquakes with aftershocks, wildfires affecting large areas). Therefore, recovery should not be considered as an additional target, but a different stage. This paper is focused on explaining the methodology applied to the stage during the disruptive event. The recovery stage will be further analyzed in future works.

3. Methodology

This section explains how to use the presented approach to evaluate the level of resilience of the road traffic networks affected by wildfires. Three main elements must be defined, namely, different hazard intensities, targets organized at different importance levels, and dynamic thresholds associated with both the hazard intensities and targets. The combination of these elements provides stakeholders with more complete information on the traffic network's response to wildfires.

3.1. Hazard intensities

In this analysis, the hazard refers to wildfires, which are classified into 7 categories according to [50]; See Table 1. The classification is based on the feature of Rate Of Spread (ROS), which measures how fast the fire spreads depending on the burning sources. The fire categories go from normal wildfires, with characteristic ROS between 5 and 100 m/min, to extreme wildfire events (EWE) with characteristic ROS between 150 and more than 300 m/min.

Table 1
Wildfire categories according to [50].

Fire category	Normal fires				Extreme wildfires		
	1	2	3	4	5	6	7
ROS (m/min)	5–15	15–30	20–50	50–100	150–250	250–300	>300

3.2. Evaluation of targets

The considered targets are safety, connectivity, reliability, and efficiency with the hierarchy shown in Fig. 2. These targets have been considered to include the different domains in a resilience assessment. For a discussion on resilience domains, the reader is referred to [11]. Safety and connectivity address the physical domain, i.e., including network infrastructure and other physical components of the traffic network. Reliability and efficiency consider the operational domain by defining the preferences of travelers and, the social domain regarding road transport demand. The evaluation of the targets under different wildfire categories is conducted through the formulation presented below that considers both wildfire and traffic-related conditions, such as the number of users and travel time.

The traffic network is represented by a set of roads, $i \in \mathcal{N}$, that connects a set of Origin Destination (OD) pairs, $pq \in \mathcal{PQ}$. Hereinafter, roads are referred to as links for consistency with the terminology used in traffic studies. Links are unidirectional. Traveling from an origin to a destination pq is done through a number of possible routes, $\mathcal{R}_{pq}$. There are a number of users, X_r, associated with each route r. The route flows are calculated through the so-called traffic assignment models that distribute users through the traffic network accounting for the congestion level of each link. The higher the link congestion, the higher the link travel time, t_i. Then, users will choose the route with the shortest real or perceived travel time t_r, mimicking real behavior.

- **Safety**
Safety is based on the premise that users must not be exposed to hazards, ensuring safe road use and emergency response. This target is evaluated by a safety index, which compares the arrival time of a random wildfire to a road (link) with the link travel time. In other words, the time needed to travel through the link must be greater than the time needed for the fire to reach the link. For this purpose, the FIRe Approach Time, $FIRAT_{i,c}$, proposed by [15] is used. FIRAT is an exposure measure of the average time for a random fire under a fire category c to reach a specific asset, in this case, a road (link i). All the sources surrounding the link with the capacity to promote or suppress the fire are considered. FIRAT is calculated as the ratio between the Equivalent Fire Distance, EFD, and the ROS (ratio of spread) of a wildfire of a given category. The EFD combines the information of all the burning sources and fire extinguishers (suppression) around the analyzed link, providing an equivalent distance expressed in terms of a reference burning source. For instance, shrublands with a characteristic ROS of 25 m/min for fire category 1 located 1 km from a road are equivalent to grassland (ROS=50 m/min for fire category 1) located 2 km away. In that way, the two spread sources can be combined in terms of ROS. The FIRAT allows considering the mentioned categories of fire conditions. The interested reader is referred to [15] for a more detailed explanation of FIRAT formulation and application for a case study. A validation of the FIRAT assessment is provided in [51], in which, the method was applied to the case of Pedrógão Grande Portugal and contrasted with the official report of the 2017 extreme wildfire. It shows that the tool is capable of capturing fire behavior including extreme wildfire events. However, other types of exposure measures, vulnerability, or even risk could also be used as long as the measure can be expressed in units of time to be compatible with the proposed resilience methodology.
Accordingly, the safety index is calculated following Eq. (1).

$$Safety_{i,c} = \begin{cases} 0\ (unsafe) & if\ FIRAT_{i,c} \geq t_i \\ 1\ (safe) & if\ FIRAT_{i,c} < t_i \end{cases}, \qquad \forall i \in \mathcal{N}, \forall c \in C \tag{1}$$

where c indicates the wildfire category for which the safety index is assessed, of the set of wildfire categories to be evaluated, C. The link travel time, t_i, is compared with the corresponding $FIRAT_{i,c}$ for all the links of the set defining the network, $\mathcal{N}$.
Safety at a network level is assessed considering the portion of safe roads over the total roads in the network for each wildfire category, as expressed in Eq. (2)

$$Safety_c = \frac{1}{|\mathcal{N}|}\sum_{i\in\mathcal{N}} Safety_{i,c}, \qquad \forall c \in C \tag{2}$$

where $|\mathcal{N}|$ refers to the total number of links.

- **Connectivity**
The connectivity target assesses users' ability to move and identifies if there are disconnected areas in the network. A route r consists of a set of links that connect an OD pair, pq. When an OD pair has different alternative routes, the network presents redundancy. The network is considered successfully connected if all the OD pairs of the network have at least one operational route. The connectivity of a given OD pq is assessed as expressed in Eq. (3).

$$Connectivity_{pq,c} = \begin{cases} 0\ (unconnected) & if\ \mathcal{R}_{pq,c} = \emptyset \\ 1\ (connected) & if\ \mathcal{R}_{pq,c} \neq \emptyset \end{cases}, \ pq \in \mathcal{PQ}, \forall c \in C \tag{3}$$

where $\mathcal{R}_{pq,c}$ is the set of available routes connecting the OD pair pq under fire category c. When the safety condition is not fulfilled for a link, that is, $FIRAT_{i,c} \geq t_i$, it is assumed that the link is unavailable anymore, disabling the routes going through this link. The number of unsafe links tends to increase with each wildfire category because of the increase in wildfire spread velocity, reducing the connectivity of the network.
Connectivity at a network level is assessed considering the portion of active routes over the total routes of the network before the wildfire. That is,

$$Connectivity_c = \frac{\sum_{pq\in\mathcal{PQ}} Connectivity_{pq,c}}{\sum_{pq\in\mathcal{PQ}} |\mathcal{R}_{pq,0}|}, \qquad \forall c \in C \tag{4}$$

- **Reliability**
Reliability in transportation is related to the certainty and predictability of travel conditions [52]. This target accounts for travel time reliability. The definition considered in this paper follows the definition proposed by [53] who define travel time reliability as the feasibility of road users reaching a destination within a given travel time under the operating conditions. This definition of reliability may overlap with the concept of accessibility. Accessibility is defined as the ease with which road users can reach desired services from specific locations using the traffic network at a specific time (e.g., [54,55]). However, this idea is better captured by the definition of the efficiency target presented below.
Therefore, travel time reliability is evaluated for all the OD pairs of the network and all the wildfire categories. Thus, the reliability of an OD is calculated as the ratio between the minimum route travel time of all the routes available under normal conditions ($\mathcal{R}_{pq,0}$), and the minimum travel time under the fire category studied, as indicated in Eq. (5).

$$Reliability_{pq,c} = \frac{\min\{t_r;\quad r\in\mathcal{R}_{pq,0}\}}{\min\{t_r;\quad r\in\mathcal{R}_{pq,c}\}}, \qquad \forall pq \in \mathcal{PQ}, \forall c \in C \tag{5}$$

Note that the shortest route under normal operation may not be the shortest one under a given fire category, because the fire can either disable the optimal route or generate traffic redistribution, increasing its congestion. Nevertheless, given that users can have several alternatives to travel from an origin to a destination, it is relevant to compare the minimum travel time associated with the OD pair rather than comparing the routes pair-wise. The closer the ratio value is to unity, the more reliable the OD travel time is, or the closer to its ideal operating capacity. On the other hand, the closer the value is to 0, the less reliable the network is for a user. In the case all the routes of an OD pair are disconnected, thus, having $Connectivity_{pq,c} = 0$, the route travel time is assumed to be infinity, and consequently, $Reliability_{pq,c} = 0$.
Reliability at a network level is assessed as the average value of the reliability of all the OD pairs, that is,

$$Reliability_c = \frac{1}{|\mathcal{PQ}|}\sum_{pq\in\mathcal{PQ}} Reliability_{pq,c}, \qquad \forall c \in C \tag{6}$$

where $|\mathcal{PQ}|$ denotes the number of OD pairs.

- **Efficiency**
The efficiency target gives a measure of the network service in terms of its demand capacity and mobility. For this purpose, the efficiency of the available routes of each OD is calculated as a function of its distance and users associated with that OD pair. It is assumed that the shortest route between two points (an OD pair in this case) is the most efficient for users because it allows faster trips. Thus, the closer the driving distance associated with an OD pair is to the minimum possible distance, the more efficient the route connecting the OD pair is. The minimum possible distance corresponds to the geometric distance, which means, in a beeline. Considering the number of users of a route is also relevant because even when a route is the shortest one, it is not

efficient if it has no users. In many cases, there are several routes connecting an OD pair. In such cases, the efficiency associated with an OD can be calculated as the average of the efficiencies of the routes weighted by the portion of users choosing each route. To calculate the efficiency associated with an OD pair under a given fire category, the formulation of Eq. (7) is proposed.

$$Efficiency_{pq,c} = \frac{1}{|\mathcal{R}_{pq,c}|}\frac{d^g_{pq}}{\sum_{r\in\mathcal{R}_{pq,c}} X_r}\sum_{r\in\mathcal{R}_{pq,c}}\frac{X_r}{d_r}, \qquad \forall pq \in \mathcal{PQ}, \forall c \in C \tag{7}$$

where $|\mathcal{R}_{pq,c}|$ denotes the number of routes associated with an OD pair under a given fire category. It is used to calculate the averaged values per OD pair. For all the available routes of a given OD pair, the ratio is calculated between the geometric distance, d^g_{pq}, and the route length, d_r. This ratio is weighted by the portion of users using each route, that is, $\frac{X_r}{\sum_{r\in\mathcal{R}_{pq,c}} X_r}$. As a result, for each route, the ratio $\frac{X_r}{\sum_{r\in\mathcal{R}_{pq,c}} X_r}\frac{d^g_{pq}}{d_r}$ is obtained. By reorganizing the terms, Eq. (7) is obtained. If the value of the efficiency index is close to unity, it means that the OD pair is efficient; values close to zero mean that it is not efficient.

Efficiency at a network level is assessed as the average value of the efficiencies of all the OD pairs. That is,

$$Efficiency_c = \frac{1}{|\mathcal{PQ}|}\sum_{pq\in\mathcal{PQ}} Efficiency_{pq,c}, \qquad \forall c \in C \tag{8}$$

The targets have been defined guaranteeing consistency and continuity between them. Connectivity is related to safety because if the traffic network is well connected with sufficient alternatives of evacuation paths, users will have the chance to evacuate. On the contrary, if a number of routes are disrupted in a poorly connected network, multiple areas could disconnect from each other, preventing people's evacuation, and leading to fatalities in wildfires. This is captured by Eq. (3). Once connectivity is lost in any part of the network (i.e., disconnecting any OD pair), it is not possible to guarantee travel time reliability for that OD, as captured by Eq. (5). Finally, a disconnected OD with no routes will result in zero efficiency as defined in Eq. (7).

3.3. Definition of dynamic thresholds

The definition of dynamic thresholds allows the evaluation of the target's performance depending on the varying importance of the target with the hazard intensities. The thresholds represent the desirable performance of a target for each hazard intensity and should be established by the stakeholders. Indirectly, the thresholds establish the level of importance of each target, because the more important a target is, the stricter the threshold is.

In this section, a guide is provided to help stakeholders define thresholds in each case. The guide is established based on the definition of the targets as summarized in Table 2.

Thresholds can assume values between 0 and 1 (i.e., 0 and 100%), where 1 requires the perfect performance of a specific target and 0 means that the loss of performance is fully accepted. For instance, a threshold of 1 for safety means that all the network roads are required to be safe and out of fire range, whereas a value of 0 means that it is accepted that the roads are within reach of the fire. Any value between 0.01 and 0.99 on safety means that only a percentage of safe routes is required, e.g., 0.8 means that 80% of the roads are required to be safe. The latter is recommended when other means of evacuation are available such as aerial evacuation (e.g., helicopters). Another example could be if the threshold value is 1 for reliability, it is requested that all trips between the different OD pairs are completely reliable in terms of travel time. A threshold value of 0.6 means that 60% of the trips are expected to remain reliable.

As explained, the thresholds (or the network's acceptable performance) will depend on the hazard intensity. For instance, for the connectivity target, two thresholds could be established, 1 for normal fires (categories 1–4, see Table 1 and 0.7 for extreme fires (categories 5–7), which means that full connectivity is expected under normal fire conditions, and at least 70% under extreme fire conditions. Also, a more gradual loss of efficiency can be acceptable.

3.4. Performance matrix and resilience assessment

By evaluating the targets for each hazard intensity, it is possible to form a matrix of the network performance of $M \times N$, with M targets and N hazard levels. Fig. 4 shows a generic performance matrix, whose components are denoted as $f_{j,k}$ for a target $j = 1 \dots M$, and a hazard intensity $k = 1 \dots N$.

When applied to the case of wildfires with the targets defined in Section 3.2, i.e., using Eqs. (2), (4), (6) and (8), the performance matrix for the four targets and 7 fire categories becomes,

$$Performance\ Matrix = \begin{bmatrix} Safety_1 & Safety_2 & \cdots & Safety_7 \\ Connectivity_1 & Connectivity_2 & \cdots & Connectivity_7 \\ Reliability_1 & Reliability_2 & \cdots & Reliability_7 \\ Efficiency_1 & Efficiency_2 & \cdots & Efficiency_7 \end{bmatrix} \tag{9}$$

The performance matrix also provides information to assess the performance of a target across different fire intensities, the so-called performance index (see Fig. 4). E.g., safety performance is obtained by calculating the average safety index obtained for the different wildfire categories.

Comparing the performance matrix with the dynamic thresholds provides the compliance matrix depicted in Fig. 5. Each component of the compliance matrix, $g_{j,k} = \{0, 1\}$ indicates if the system performance fulfills the dynamic threshold associated with a given target j and hazard intensity k. That is,

$$g_{j,k} = \begin{cases} 0 & if\ f_{j,k} < threshold_{j,k} \\ 1 & if\ f_{j,k} \geq threshold_{j,k} \end{cases}, \qquad j = 1 \dots M, k = 1 \dots N \tag{10}$$

Average values at the target and hazard intensity levels can be computed. When done at a target level, partial resilience indices are obtained. Thus, a partial resilience index provides the average compliance of a target for all fire categories. When averaging the results for a given hazard intensity, the capacity to cope with that wildfire category is obtained. For example, if the safety indices comply with the dynamic thresholds associated with the seven wildfire categories, then, the contribution of the safety target to the resilience index is 100%. In the same way, it is possible to quantify the capacity of the network to cope with each hazard category. This means, for fire category 1, if all the targets meet the respective thresholds, the capacity of the network is 100% to cope with that fire category. Finally, a global index of the traffic network resilience, R, can be obtained by averaging the scores of the compliance matrix. The calculation of the partial resilience indices and the resilience index based on the compliance matrix is depicted in Fig. 5.

It is noted that the different targets are aggregated without using weights despite their different importance (hierarchy). This is because their relevance has been introduced through the strictness degree of the dynamic thresholds.

The entire methodology is summarized in Fig. 6, specifying the inputs, process, and outputs.

4. Application to case studies

To prove the concept and demonstrate the validity of the framework, it is applied to different networks, including three basic traffic networks and one complex network. The intention is to show how the proposed methodology is useful to compare different network configurations and wildfire conditions.

Table 2
Guidelines for threshold definition.

Targets	Threshold		
	1	0.99–0.01	0
Safety	Ensures that all routes are out of fire range.	It is requested to maintain only a % of safe roads. This is recommended if other means of evacuation are available.	No road is safe from wildfires.
Connectivity	Guarantees all routes are active, i.e., no OD pair of the network is disconnected.	Only a % of active routes are required, but disconnected OD pairs are not accepted.	One or more OD pair is disconnected.
Reliability	Trips between all ODs are 100% reliable in terms of travel time.	A % of travel-time reliability must be maintained, even if there are some delays.	One or more ODs are not reliable at all in terms of travel time because they have been disconnected.
Efficiency	All routes in the network transport are used in a fully efficient manner.	A % of efficiency must be guaranteed.	The efficiency of the network is lost because it has been disconnected in some areas (OD pairs).

$$
\begin{array}{c|ccc|cc}
 & Hazard\ Level_1 & \cdots & Hazard\ Level_N & & Performance\ Index \\
Target_1 & f_{1,1} & \cdots & f_{1,N} & \rightarrow & \frac{1}{N}\sum_{k=1}^{N} f_{1,k} \\
\vdots & \vdots & \ddots & \vdots & & \vdots \\
Target_M & f_{M,1} & \cdots & f_{M,N} & \rightarrow & \frac{1}{N}\sum_{k=1}^{N} f_{M,k}
\end{array}
$$

Fig. 4. Performance matrix.

$$
\begin{array}{c|ccc|cc}
 & Hazard\ Level_1 & \cdots & Hazard\ Level_N & & Partial\ Resilience\ Index \\
Target_1 & g_{1,1} & \cdots & g_{1,N} & \rightarrow & \frac{1}{N}\sum_{k=1}^{N} g_{1,k} \\
\vdots & \vdots & \ddots & \vdots & & \vdots \\
Target_M & g_{M,1} & \cdots & g_{M,N} & \rightarrow & \frac{1}{N}\sum_{k=1}^{N} g_{M,k} \\
 & \downarrow & & \downarrow & & \downarrow \\
 & \frac{1}{M}\sum_{j=1}^{M} g_{j,1} & \cdots & \frac{1}{M}\sum_{j=1}^{M} g_{j,N} & \rightarrow & \mathbf{R} = \frac{\mathbf{1}}{\mathbf{M\,N}}\sum_{\mathbf{j=1}}^{\mathbf{M}}\sum_{\mathbf{k=1}}^{\mathbf{N}} \mathbf{g_{j,k}}
\end{array}
$$

Fig. 5. Compliance matrix and evaluation of the resilience index, R.

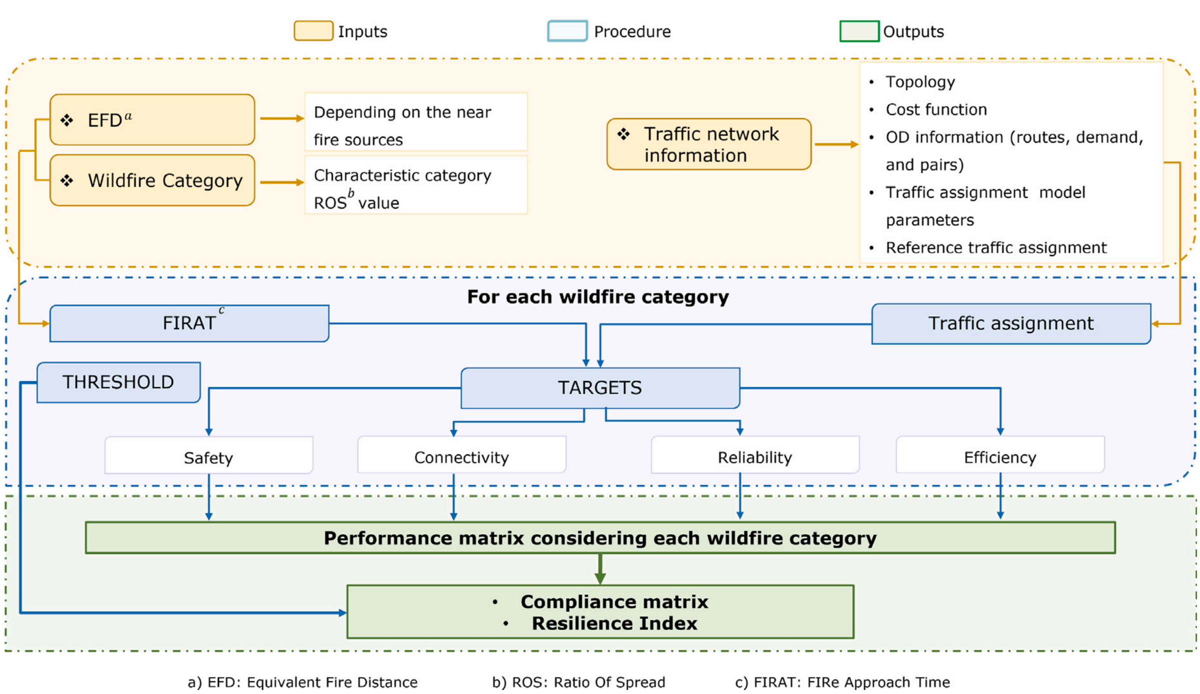

Fig. 6. Methodology for resilience assessment of a traffic network affected by wildfires.

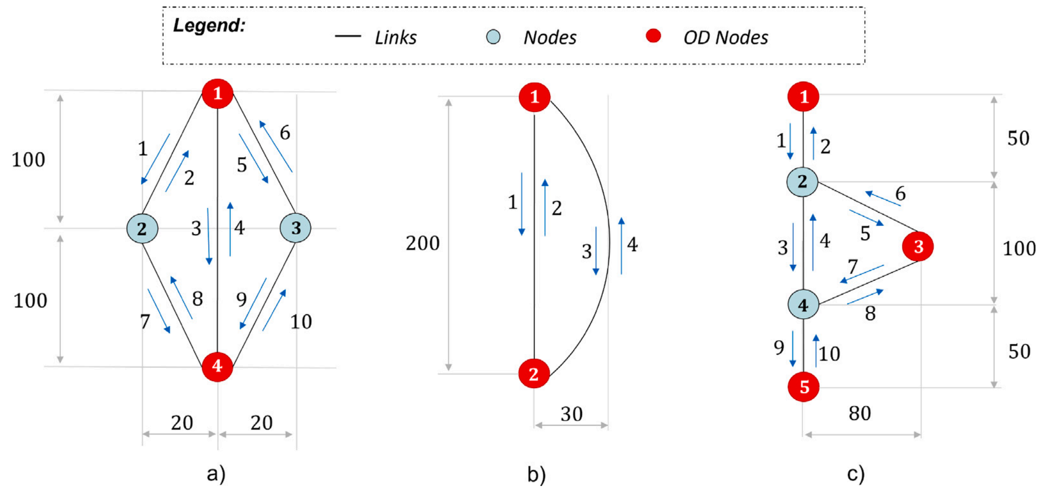

Fig. 7. Basic traffic road networks, units km. (a) four-node network, (b) two-lane network, (c) five-node network.

4.1. Comparison of basic traffic networks

4.1.1. Cases description

In this section three road networks of basic compositions, all different in terms of topological configuration, are presented. All three networks are subjected to similar fire exposure conditions. In this sense, it is possible to observe the change in the network's performance according to their configurations, i.e., how aspects such as redundancy are reflected in the transport networks' performance for the different wildfire intensities and resilience estimation. The first network, see Fig. 7.a, consists of two OD pairs, i.e., 1–4 and 4–1, with three alternative routes, for a total of four nodes and ten links. For practical reasons, it will hereinafter be referred to as a four-node network. The four-node network is redundant because it has different routes to connect the OD pairs, i.e., it has more options to reach the destination. The second traffic network consists of two OD pairs (i.e., 1–2 and 2–1) connected by two routes, i.e., two nodes and four links, as shown in Fig. 7.b. This second network hereinafter referred to as a two-lane network, is also redundant but not as much as the four-node network. The third basic network, hereinafter referred to as a five-node network, consists of six OD pairs (i.e., 1–3, 1–5, 3–5, and vice versa), five nodes, and ten links, see Fig. 7.c. It is the most critical network as it has some areas connecting the OD pair with no redundancy. Therefore, any disruption at links 1–2 and 9–10 would cause the network to fail.

4.1.2. Inputs and assumptions

The inputs assumed for the three cases consist of parameters related to wildfire and traffic conditions. Regarding the parameters related to the fire conditions, the equivalent fire distance, EFD, is assumed as shown in Fig. 8.

Fig. 8 shows the exposure classification of the links in terms of proximity to fire propagation sources (given by the EFD), represented by the color gradation from red to green. The links closer to propagation sources are represented by a red color line. To assign similar conditions to the three networks, the EFD assumes similar distribution of burning sources, as depicted by the tree and grass icons. The most exposed links of the three networks correspond to links {5, 6}, {3, 4}, and {5, 6}, respectively (see red lines in Fig. 8). The least exposed links, i.e., with more distant propagation sources, are links {7, 8}, {1, 2}, and {1, 2}, respectively. Subsequently, based on the EFD of each road and the ROS value associated with each wildfire category (see Table 1), the fire arrival time $FIRAT_{i,c}$ is calculated. The $FIRAT$ reflects the exposure degree of each link, i.e., the links closest to sources of fire propagation will be the first links to be reached by the fire.

The traffic is assigned using a traffic assignment model, such as the well-known Beckmann's user equilibrium model. In this paper, the C-logit Stochastic User Equilibrium (SUE) model [56] is used. It gives more dispersed traffic flow patterns when compared with deterministic models. The model parameter θ related to the network dispersion and β related to the users' preferences are assumed as 1.2 of 1, respectively (see [25]).

The inputs and outputs of this model are indicated in Fig. 9. The inputs include, (i) the network topology, i.e., nodes, links, and link lengths, which are assumed according to Fig. 7; (ii) a travel time function that provides the link travel time based on the saturation degree of the link. The formula proposed by the Bureau of Public Roads (BPR, [57]) is used, that is,

$$t_i = t_{i0}\left[1+\alpha\left(\frac{X_i}{C_i}\right)^{\gamma}\right], \tag{11}$$

where α and γ are parameters related to the road type. They are assumed as 1.2 and 7, respectively. The minimum travel time with no saturation conditions, t_{i0}, is calculated assuming a link free-flow speed of 50 km/hr; the link capacity, C_i, is 100 vehicles/hr/lane. X_i accounts for the hourly number of users of the link. (iii) The demand associated with each OD pair is 100 passenger car units per hour in each lane (pcu/h/lane) for four-node and two-lane networks and 50 (pcu/h/lane) for the five-node network.

In order to evaluate the targets defined in Section 3.2, the traffic assignment is conducted in an undisturbed state and assuming the seven wildfire conditions. Note that the wildfires will modify the inputs highlighted in blue color in Fig. 9.

4.1.3. Dynamic threshold definition

For the resilience analysis of the three basic networks, the dynamic thresholds of Table 3 are proposed. Assuming that the road network is the only alternative to guarantee the safety of users (i.e., the only evacuation means), a threshold of 1 (100%) is considered for the safety target for all the categories, i.e., unsafe roads are not desirable under any wildfire condition. It is not desirable to lose connectivity against wildfire categories 1 to 3. However, for categories 4 to 6, maintaining 50% of the initial connectivity is desirable; and 20% for categories 6 and 7. In terms of reliability, it is not desirable to lose travel time reliability against wildfire categories 1 and 2, accepting a gradual loss for the following categories. The thresholds for the efficiency target accept a gradual loss with each of the fire categories.

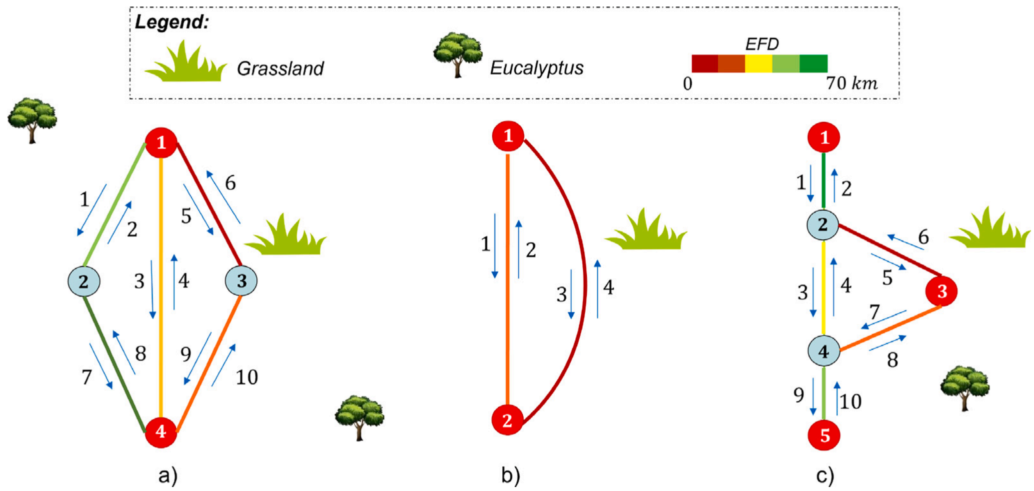

Fig. 8. Approximate representation of burning sources and EFD assumption for basic road networks, units km. (a) four-node network, (b) two-lane network, (c) five-node network.

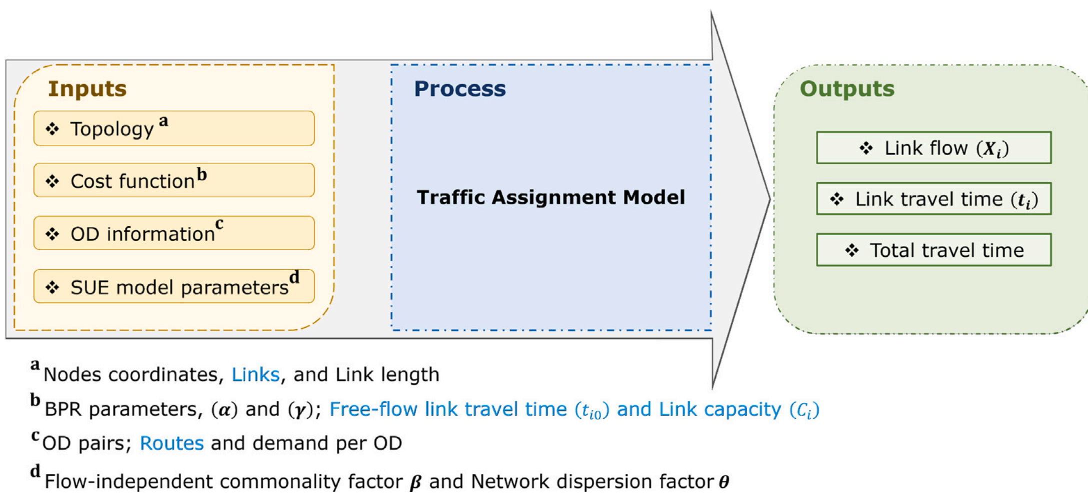

Fig. 9. Traffic assignment model. The inputs in blue color change with the hazardous level.

Table 3
Threshold definition by wildfire category for the case studies.

Targets	Wildfire category						
	1	2	3	4	5	6	7
Safety	1	1	1	1	1	1	1
Connectivity	1	1	1	0.5	0.5	0.2	0.2
Reliability	1	1	0.8	0.6	0.5	0.4	0.2
Efficiency	1	0.8	0.6	0.4	0.2	0.2	0.1

4.1.4. Results

Following the methodology explained in Section 3, the performance matrices of the three networks are obtained. Fig. 10 shows how the four-node traffic network degrades with increasing fire categories and the resulting performance matrix of the four-node traffic network. The red lines in the sketches on the top represent the links potentially reached by the wildfire. The performance matrix reveals that all the roads of the network are 100% safe from fire arrival for the three lowest fire categories. Under category 4, the network loses 20% of its original safety, as links 5 and 6 are reached by fire (see the sketches on the top). After this category, the network gradually loses 20% of safety with each fire category. In general terms, the average safety performance is 71% under normal and EWE. Because all the roads are safe for wildfire categories 1 to 3, the network connectivity also remains intact (100%) for these categories. For category 4, in which the fire reaches links 5 and 6, network connectivity is reduced to 67% of the initial connectivity because 1 out of the three possible routes is disabled. It is recalled that one route is disabled if the fire reaches any of the links that form it. This explains why for wildfire category 5, the network connectivity remains at 67%, although links 9 and 10 are also damaged. Under wildfire category 7 the network connectivity is completely lost. The best network performance is in terms of travel time reliability, with a performance index of 78%. It can be observed that the network reliability in terms of travel time is almost 100% for wildfire categories 1 to 5. In other words, the minimum travel time of the OD under these wildfire conditions does not suffer any significant variations with respect to the undisturbed state. The above implies that the total number of users can still travel from that OD without congestion, despite the disabled routes. This is due to the network redundancy and the high capacity of the roads concerning the number of users. Once the network loses its redundancy in category 6, the travel time reliability is reduced to 45% because of the increase in saturation. Finally, in category 7 with no routes available, the network completely loses the travel time reliability.

In contrast, the lowest performance index is efficiency, with an overall performance of 42%. Counter-intuitively, the efficiency of the network increases with increasing fire categories till category 6. This implies that the network is not optimized in terms of usage, with redundant routes that are longer than the geometric distance. As the

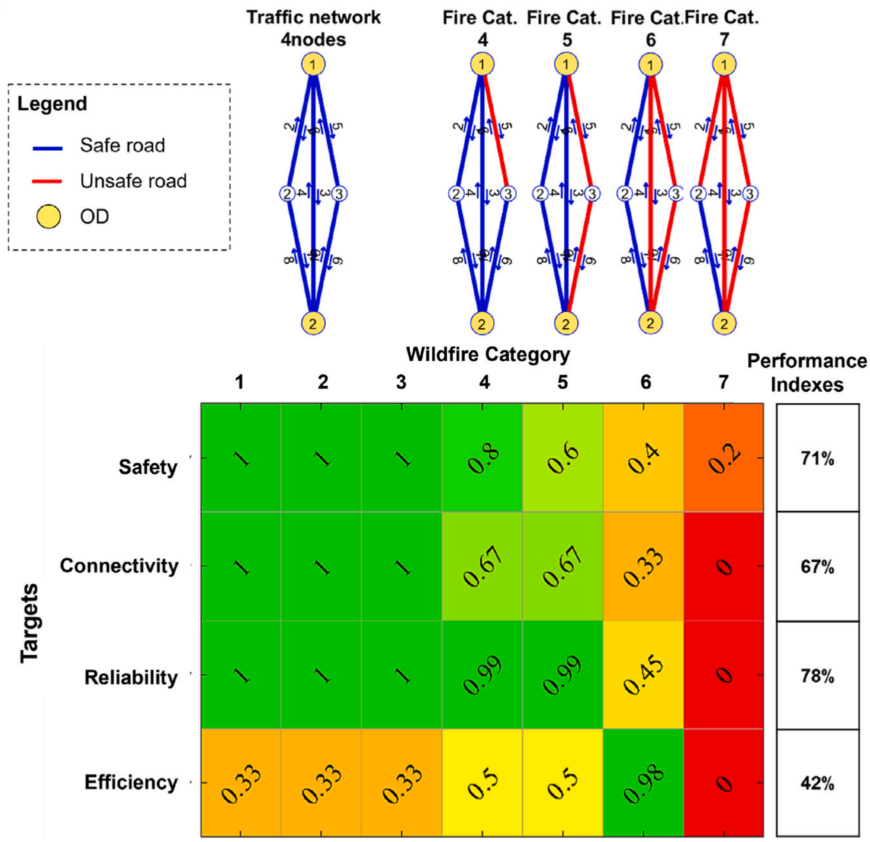

Fig. 10. Performance matrix four-node traffic network.

network loses redundancy, gains efficiency. This is evident when moving from categories 1 to 3 to categories 4 to 5, especially for category 6, where the only available route is close to the geometric distance. It is noted that the four performance indexes discussed cannot be combined in a unique value because they are related to targets with different importance. They may be weighted to capture the relative importance between them.

The compliance matrix is obtained by comparing the performance matrix of Fig. 10 with the dynamic thresholds of Table 3. The compliance matrix for the four-node traffic network is presented in Fig. 11, which shows that the resilience of the network is 64%. It is noted that even high values of the targets may not be sufficient to meet the required thresholds. For instance, given the importance of the safety target, the obtained safety index for category 4 (80%) is not acceptable according to the threshold definitions. The partial resilience index associated with the safety target is 43% because the safety index only fulfills the dynamic thresholds for the low wildfire categories. The partial resilience indices associated with connectivity and reliability are both 86%, as they fulfill 6 out of the 7 established thresholds. For the efficiency target, the partial resilience index is 43%. Analyzing the capacity of the network to cope with different wildfire categories, 75% of the targets perform as requested till wildfires of category 6, however, the network completely loses its functionality for a EWE of category 7.

The results of the two-lane network are shown in Fig. 12. This network has a resilience index of 39%, reflecting the importance of network redundancy to increase resilience. Indeed, the only difference between the analyzed four-node network and this one is that the two-lane network does not have the third route – the least exposed to wildfires – of the four-node network. It results in a loss of compliance for the targets of connectivity and efficiency under categories 4 to 6 and reliability under categories 5 to 6 with respect to the previous network analyzed. This is because links 3 and 4 are disabled with wildfires of category 5 onward, becoming a non-redundant network.

Regarding the five-node network, it has two critical branches with no alternative routes. Nevertheless, the exposure level of these branches is very low, with EFD close to 70 km (see Fig. 8.c). The level of performance and compliance of the network is shown in Fig. 13. When comparing the two-lane and five-node networks, the safety target of the latter is higher than the two-lane network, with an average performance index of 71% and 50%, respectively. A better performance for the safety target does not translate into an increase in the resilience index, given that it is not safe enough to increase the compliance level. Note that safety is a core function of the network and safety values under 1 arenot an option. As a result, the two-lane and five-node networks have the same level of compliance, and thus, the same resilience index.

4.2. Soiux Fall traffic network

Unlike the previous section where the networks were of different configurations for similar wildfire exposure, this section shows the application for the same network (i.e., same configuration) but different levels of exposure.

4.2.1. Cases description, inputs, and assumptions

To show the applicability of the approach to more complex networks, the resilience of the Sioux Falls traffic network, commonly used as a benchmark in transport studies, is assessed. The network is analyzed for two different exposure cases, as shown in Fig. 14. Color degradation is used to represent the degree of exposure, expressed in terms of EFD. Case 1 represents a network with a higher exposure level, i.e., it is closer to sources of fire spread. Instead, the network in Case 2

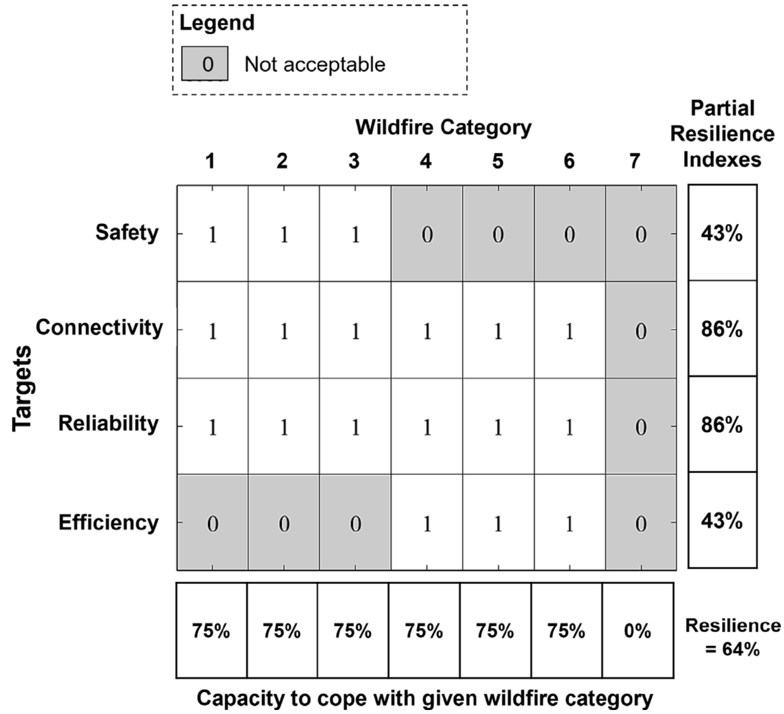

Fig. 11. Resilience assessment for the four-node traffic network.

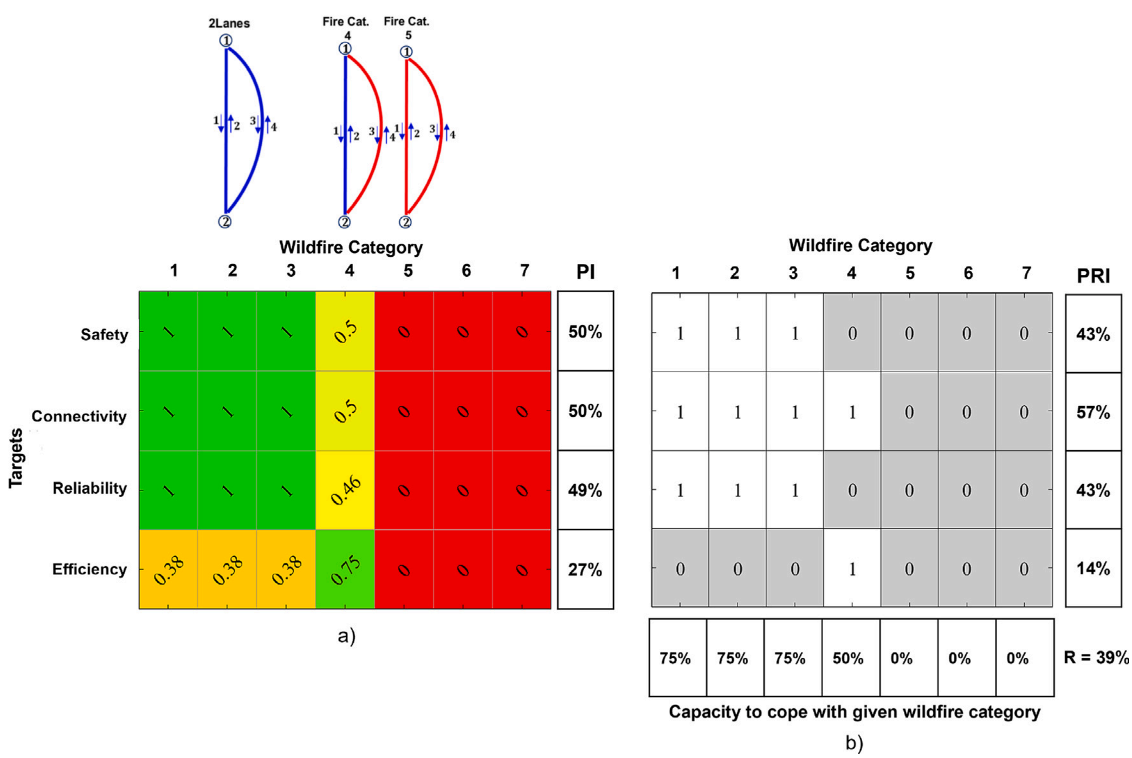

Fig. 12. Degradation evolution with increasing wildfire intensity, compliance matrix, and resilience assessment for two-lane traffic network.

is less exposed due to the existence of several water masses, and thus, with larger EFDs. i.e., red links are those closer to propagation sources, and dark green links to those less exposed.

The network consists of 76 links and 24 nodes. A total of 20 ODs pairs are considered (see pink circles in Fig. 14), connected by 6 routes each, with a demand per OD of 60 users/h. Other assumed traffic parameters are $\alpha = 1.2$, $\beta = 1$, $\gamma = 5.2$ and $\theta = 1.2$. The assumed dynamic thresholds are the ones shown in Table 3.

4.2.2. Results

Fig. 15 presents the performance matrices for both wildfire exposure conditions. The influence of the exposure conditions is evident.

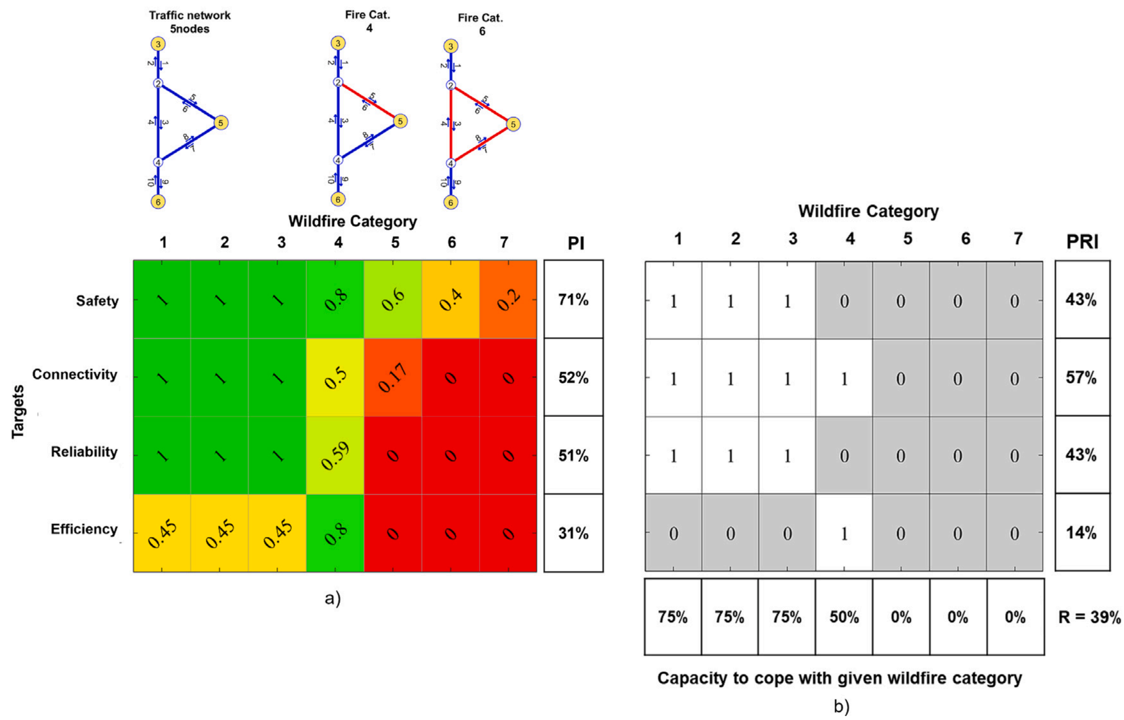

Fig. 13. Degradation evolution with increasing wildfire intensity, compliance matrix, and resilience assessment for Performance matrix of five-node traffic network.

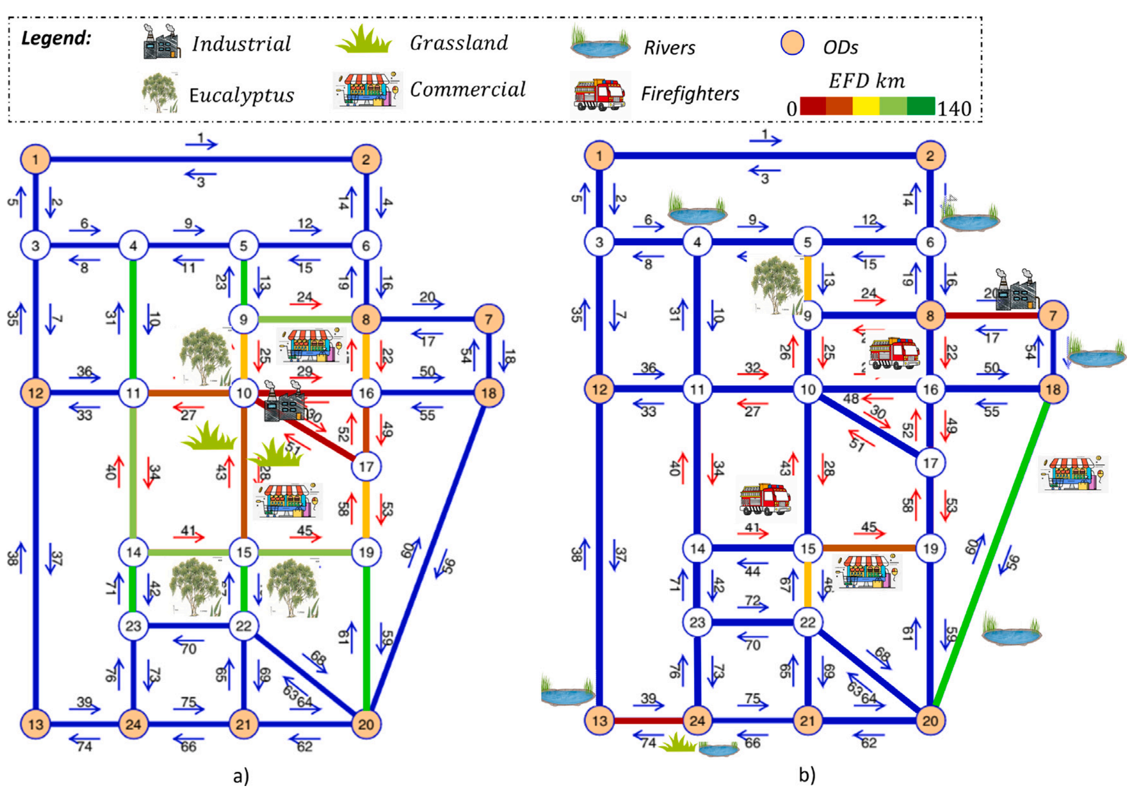

Fig. 14. Exposition level to wildfires assumed for the Sioux Falls traffic network. (a) Case 1. (b) Case 2.

Increments of 11%, 32%, 33%, and 60% are observed for the safety to efficiency targets, respectively, due to the existence of wildfire barriers and less aggressive burning sources in the surroundings. The network in Case 1 starts to lose functionality at the intermediate and core levels from wildfire category 3 (see Fig. 15.a), whereas in Case 2, the same level of loss occurs from wildfire category 4 onward (Fig. 15.b).

Contrasting the performance scores with the thresholds (see Fig. 16), the better exposure conditions of Case 2 increase the

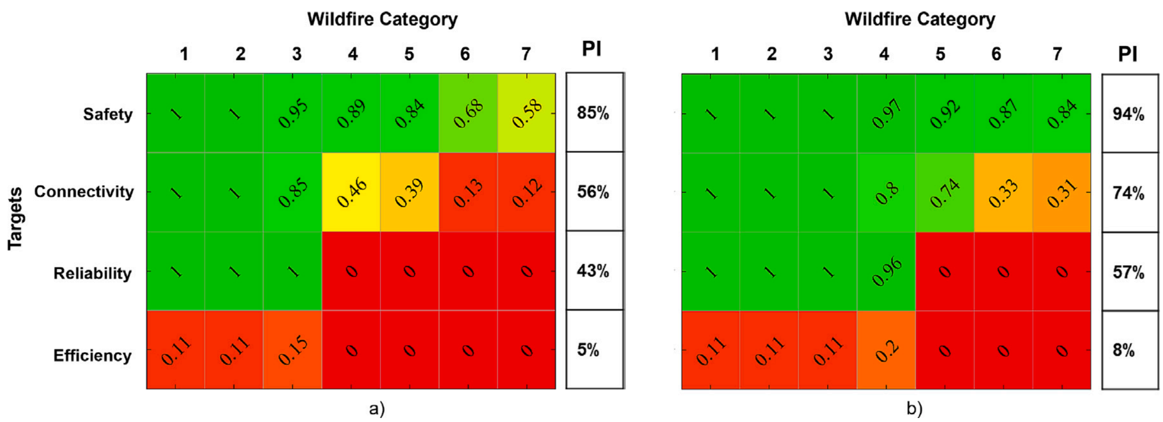

Fig. 15. Performance matrices of Sioux Falls traffic network for (a) Case 1 and (b) Case 2.

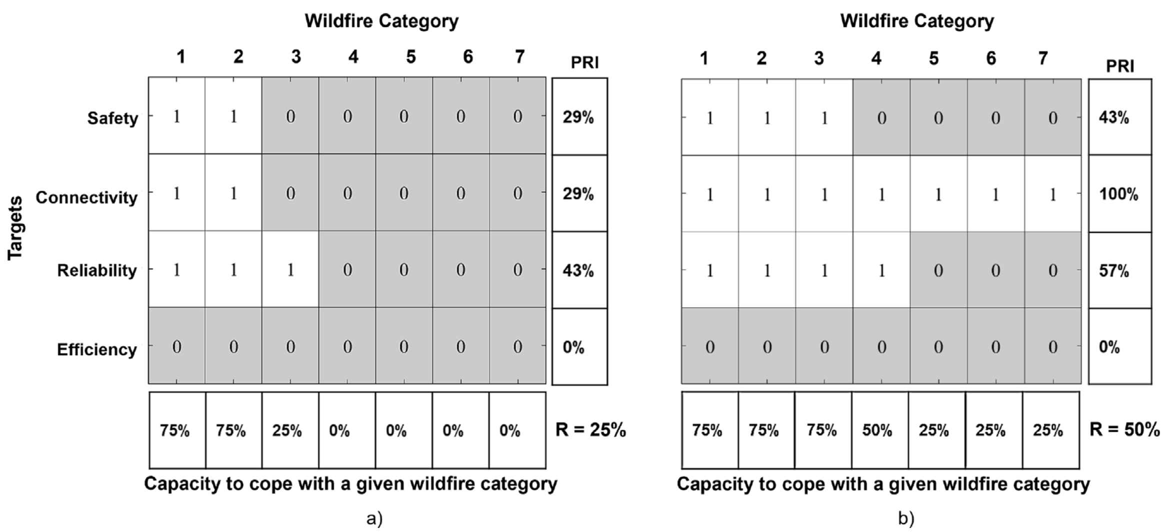

Fig. 16. Compliance matrices of Sioux Falls traffic network for (a) Case 1 and (b) Case 2.

level of compliance 48%, 245%, and 33% for the safety, connectivity, and reliability targets, respectively (Fig. 16.b). The compliance level for efficiency, which is zero, does not improve. As a result, the network in Case 2 is twice more resilient as in Case 1. Reducing the exposure level guarantees compliance with the thresholds of the connectivity target for all the wildfire categories, while in Case 1 (Fig. 16.a), it was fulfilled till category 2.

When looking at the average compliance level per wildfire category, both networks have a satisfactory capacity to cope with wildfires of categories 1 and 2; however, it drastically drops in category 3 for Case 1, being unable to fulfill any of the targets for higher categories. The network in Case 2 presents a more gradual loss of the capacity to cope with higher wildfire categories, without losing its functionalities completely even for extreme wildfire events. These results support the relevance of appropriate wildfire management through the adaptation of the natural and built environment to increase the capacity of the traffic networks to cope with wildfires. The proposed methodology allows the assessment of adaptation policies that directly influence the exposure conditions of the analyzed system, such as the implementation of wildfire barriers.

5. Discussion

To facilitate the discussion, the performance, compliance, and resilience indexes for all the networks previously discussed are summarized in Table 4.

The proposed methodology allows a more holistic analysis of the traffic network. For instance, using the FIRAT measure to evaluate safety allows the introduction of social factors (e.g., land use), physical factors (e.g., buildings, road, and energy infrastructure), environmental factors (e.g., type of vegetation, rivers), and coping capacity of the communities (e.g., the existence of fire stations and other barriers). All the targets depend on the hazard intensity and the mentioned social, physical, and environmental factors. In addition, the safety and reliability target depends on the travel time, which in turn depends on the road capacity, traffic demand, and network redundancy. The connectivity target depends on the topology of the network. Finally, the efficiency target reflects economic and environmental factors that penalize unnecessarily long roads and redundancy, which result in higher maintenance costs, CO2 emissions, among others.

The Sioux Falls network is interesting by its high redundancy level. The high redundancy positively impacts connectivity and reliability, however, penalizes the efficiency of the network. Nonetheless, this is not so clear when comparing the four-node and two-lane networks. Although the first is more redundant than the latter, its performance index for efficiency is higher. Note that the performance indexes capture the average performance of a target that degrades with increasing hazard intensity. Given that some critical links of the two-lane network are not safe after wildfire category 4, it loses connectivity and thus the efficiency drops to zero at very early stages. As a result, the performance index for the efficiency of the two-lane network is lower than initially expected. Note that the different scales of the networks are not a problem for allowing comparisons between them.

Table 4
Comparison between different traffic networks.

	Targets	Networks				
		four-node	two-lane	five-node	Sioux case 1	Sioux case 2
Performance index	Safety	71%	50%	71%	85%	94%
	Connectivity	67%	50%	52%	56%	74%
	Reliability	78%	49%	51%	43%	57%
	Efficiency	42%	27%	31%	5%	8%
Partial Resilience index	Safety	43%	43%	43%	29%	43%
	Connectivity	86%	57%	57%	29%	100%
	Reliability	86%	43%	43%	43%	57%
	Efficiency	43%	14%	14%	0%	0%
Resilience index		**65%**	**39%**	**39%**	**25%**	**50%**

In the case of safety, the associated partial resilience index is mainly influenced by exposure conditions. In fact, having more redundancy can negatively affect the compliance index for safety. Assuming a threshold of 1 for all the wildfire categories, no link can be reached by fires. Thus, given that more redundancy is achieved by adding links, the probability of having an unsafe link increases, reducing the partial resilience index. However, if the threshold is slightly loosened, redundancy could increase the compliance index for safety. This discussion highlights the complexity of the resilience evaluation of traffic networks, with many intricate relations, discouraging the analysis of just one aspect, such as connectivity or redundancy to derive meaningful conclusions.

Resilient assessments based on scenarios are also discouraged. For instance, scenarios under fire categories 1 to 4 would suggest that the Sioux Falls network of Case 2 is very resilient. However, if the studied scenario is under category 7, the conclusion would be that the network is not resilient. The resilience assessment conducted in this paper suggests that the Sioux Falls network Case 2 has a limited capacity to cope with wildfires, scoring only 50% in the resilience index. Moreover, it can be easily compared with the network of Case 1, which scores only 25% in the resilience index.

6. Conclusions

This paper proposes a new approach to assess the resilience of a system in its capacity to cope with different hazard intensities. A methodology based on the approach has also been introduced to assess the resilience of road traffic networks to wildfires, from normal fires and extreme wildfire events. The assessment is conducted assuming that the system under study has distinct functions with distinct importance levels. The performance of the functions is evaluated against different requirements that vary with changing hazard intensities. The lack of compliance with a given requirement does not imply that the system fails as typically considered in risk-based approaches. The methodology has been verified using three simple and one complex traffic network under different wildfire conditions, demonstrating that the framework applies to any type of configuration and level of complexity. Although applied to traffic networks and wildfires, this methodology can be applied to other systems, e.g., energy transmission networks, and be extended to other hazard types, by defining the appropriate targets, hazard degrees, and dynamic thresholds.

The approach overcomes the key issues associated with the operationalization of resilience, that is, (i) it does not estimate the resilience of the system by analyzing a scenario with a given hazard intensity, occurrence probability, or ignition point, but it analyses the system's response to the entire spectrum of hazard intensities and focuses on the exposure level resulting from the nearby fire sources and barriers. Regardless of where a fire starts, the nearby fire sources and barriers will modify the progress of the fire. (ii) The system is not assumed to fail; instead, is compared against expectations regarding system performance under the changing hazard conditions, i.e., it pays attention to the degradation process of critical functions with increasing hazard intensities. (iii) It does not derive conclusions on the resilience of a system based on one only indicator, such as travel time increase. It integrates multiple aspects. For instance, the redundancy of the network affects its safety, connectivity, reliability, and efficiency, the road capacity affects its safety and reliability and the number of users affects its reliability and efficiency. Therefore, the proposed approach paves the way for resilience operationalization.

The approach is useful to support decision-making on adaptation policies. Different strategies can include the modification of the (i) natural or built environment by introducing changes in the fire sources and barriers and (ii) traffic management, e.g., by constructing new roads, improving the capacity of the existing ones, or closing some of them under wildfire events. The proposed methodology allows for the comparison of these strategies in terms of their capacity to improve resilience.

Given that the focus of this paper is on the traffic networks' preparedness to cope with wildfires, the system's capacity to recover has not been addressed. The recovery stage will be explored in future works. The evaluation of this stage can require adding new targets, such as the time needed to recover as a function of the hazard intensity. Also, the implementation of the methodology for a real traffic network will be addressed in future works. Special attention will be paid to the integration of different stakeholders' perspectives when defining the dynamic thresholds.

CRediT authorship contribution statement

Erica Arango: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Maria Nogal:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Ming Yang:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Hélder S. Sousa:** Writing – review & editing, Supervision, Funding acquisition. **Mark G. Stewart:** Writing – review & editing, Validation, Supervision, Methodology. **José C. Matos:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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