RESILIENCE INDICATORS FOR ROAD NETWORKS: THE ROLE OF ROBUSTNESS AND RAPIDITY

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ABSTRACT: With the increased complexity of urban systems, the need to protect the services of smart cities from disruptions by increasing their resilience to adverse events is more critical than ever before. The present paper aims at clarifying the meaning of system resilience by discussing its definitions and then accordingly proposes a set of resilience indicators for road networks. These indicators assess road networks ability to withstand adverse events without suffering a loss of function (robustness) and recover quickly (rapidity). Ultimately, both the conceptual discussion and the indicators presented could be of interest to researchers and practitioners developing their own resilience models and tools.

KEY WORDS: Resilience assessment, Resilience indicators, Road networks, Transport, Robustness, Rapidity

1. INTRODUCTION

With the increased complexity of urban systems, the need to protect the services of smart cities from disruptions is more critical than ever before. The road transport system is threatened by natural and man-made hazards that could result in casualties and significant economic losses. The resilience of road networks (i.e. their ability to sustain, resist and recover from shocks) is thus essential for society. However, the wide range of perspectives on resilience, which is now routinely used in different disciplines such as economics, ecology and engineering led to confusion over its definition and possible indicators. The present paper aims at clarifying the meaning of system resilience and accordingly proposes a set of resilience indicators for road networks. A discussion of the different definitions of resilience is presented in section 2. The conclusions of this conceptual discussion are then used to develop a set of resilience indicators in section 3, followed by a case study in section 4. Finally, section 5 provides some conclusions and recommendations.

2. THE CONCEPT OF SYSTEM RESILIENCE

The term resilience originates from the Latin word "resiliere" which means to bounce back [1]. The concept of resilience was extended to systems by Holling [2], as the ability of ecological systems to "absorb changes of state variables, driving variables, and parameters, and still persist." Since then, the word has been adapted and reinvented to refer to the capacity of systems to anticipate, sustain and recover from external shocks, as well as, the ability to cope with changes in general [3, 4].

The growing interest in resilience led to confusion over its concept as several authors, e.g. [1, 6], found a lack of consensus and rigor in the use of the term. For example, the concept of resilience overlaps other concepts such as robustness and reliability, often confused with resilience [6, 7]. To provide more clarity, the different definitions available have been surveyed. The review highlighted the concepts connected to the word resilience.
The framework introduced by Bruneau et al. [7] associates system resilience with the following notions: (i) reduced failure probabilities (ii) reduced consequences from failures and (iii) reduced time to recovery. The framework includes two historical definitions of resilience. The first one, attributed to Holling [2], refers to the

perturbation that can be absorbed before the system is displaced from one state to another. The second definition describes resilience as the speed of the system to return to its initial equilibrium [8].

Woods [5] identified four concepts associated with resilience in the context of complex systems:

- Resilience as rebound from trauma and return to equilibrium;
- Resilience as a synonym for robustness i.e. capacity to absorb perturbations;
- Resilience as opposite of brittleness, i.e. ability to extend adaptive capacity in the face of unexpected events;
- Resilience as network architectures that can sustain the ability to adapt to future events as conditions evolve.

The first two categories match the concepts of Bruneau et al. [7]. The third and fourth categories give more depth to the notion of "reduced failures probabilities" as they both aim at reducing the probability of future failures. However, one of them designates the extended adaptive capacity of the system, whereas the latter refers to the ability of the system to grow its adaptive capacity over time (thanks to management or regulation).

Finally, the three components of system resilience mentioned by Bruneau et al. [7] remain relevant today and are represented in the majority of the literature. A noteworthy evolution of these concepts is the extension of "reduced failure probabilities" to the capacity to adapt to future events and conditions. The confusion over the concept of resilience probably derived from the tendency of researchers to focus on one of these notions when addressing particular infrastructure systems [9]. System resilience as a comprehensive concept can thus be summarized with three pillars: reducing (i) consequences (ii) recovery time (iii) and future vulnerabilities.

3. RESILIENCE INDICATORS FOR ROAD NETWORKS

In the present paper, we propose to evaluate the resilience of road networks as a combination of two of the three pillars: reducing (i) consequences and (ii) recovery time. In other words, we assess road networks ability to withstand a given level of stress without suffering a loss of function (Robustness) and recover quickly (Rapidity). The indicators are computed for one specific hazard *s*.

3.1 Robustness indicator

As the main function of road networks is to allow people to reach their chosen destination within a reasonable travel time (TT) TT has been widely used in transport studies as a proxy for network performance. There is no consensual mathematical expression for road networks robustness. Several studies (e.g. [6]) employ the difference of the pre and post-event TT whereas others (e.g. [10]) use the ratio of the same values. To allow for comparison across different conditions and networks, we propose to use the Relative Change (RC) of the TT:

$$RC = \frac{TT_{disrup} - TT_0}{TT_0} \tag{1}$$

where TT_0 and TT_{disrup} are the undisrupted and disrupted travel times respectively. The expression of the network robustness is then:

$$Robustness = \frac{1}{1+RC} \tag{2}$$

This expression is chosen to scale the network robustness between 0 and 1. A robustness of 100% indicates that $RC=0$ i.e. despite the disruptive event the TT remains equal to the initial travel time (TT_0). The robustness then decreases as TT_{disrup} increases, reaching *50%* when $TTdisrup = 2\ TT_0$. The network robustness (*RO*) is computed by the weighted average of the robustness of all origin-destination (OD) pairs as follows:

$$RO = \sum_w k_w * Robustness^w \tag{3}$$

where $Robustness^w$ is the robustness of the OD pair w and k_w the weighting factor associated with w. The weighting factor reflects the importance of w compared to the overall travel demand.

$$k_w = \frac{d_w}{\sum_w d_w} \tag{4}$$

where d_w is the travel demand on w. The weighted average is used to provide a more accurate measure of the degraded network ability to meet the travel demand. Several resilience-assessment methodologies (e.g. [10-12]) use the total or average TT, which are less appropriate to account for OD disconnections and consequent demand leftover. When one of the OD pairs (w) is disconnected (i.e. destination D can no longer be reached from origin O), the models assume that the TT is infinite (i.e. takes a very high value), which arbitrarily increases the total (or average) TT. The robustness index may hence arbitrarily and unfairly decrease towards 0% although part of the demand is satisfied. In comparison, the weighted average ensures that the decrease of robustness due to w being disconnected is proportional to the importance of w.

3.2 Resilience indicator

The network resilience results from its instantaneous resistance to stress and its rapidity to recover from the consequences of the stress. The "resilience triangle" introduced by Bruneau et al. [7] in their seminal framework combines these two notions into one measure. In the context of earthquake resilience, they defined the loss of resilience as the integral over time of the quantity $100 - Q(t)$, where $Q(t)$ is the system performance expressed in percentage. As shown in Figure 1, a hazard causes a sudden drop in performance at t_0, and then the system gradually recovers its performance until t_1 when the system is completely repaired. The integral hence measures both the functionality lost and the time taken to return to pre-disaster levels of performance.

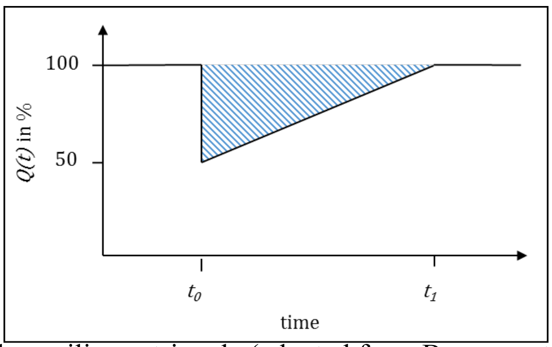


Fig. 1. The resilience triangle (adapted from Bruneau et al.[7])

Following the graphical interpretation introduced by Bruneau et al.[7], we define resilience as the integral of the road network robustness (RO) during the recovery process represented by the number of links repaired following the damage. It is assumed that all links are eventually repaired one after the other and that the ones which improve the network performance (i.e. the robustness indicator RO) the most are repaired first. This assumption implies that the network manager repairs one link at a time. Other repair processes and their influence on road network resilience will be considered in future works. The road network resilience to the hazard, s, is:

$$RE = \frac{\int_0^{Ns} RO(x)dx}{N_S+1} \tag{5}$$

where x corresponds to the number of links repaired and N_S is the total number of links damaged by s. The integral is divided by $N_S + 1$ to scale RE between 0 and 1. A fully resilient system would either (i) be very robust i.e. RO remains at 100% even when no links have been repaired or (ii) be very rapid to recover i.e. RO quickly increases towards 100% as links are repaired. In both cases, RE will be close to 100%. On contrary, a non-resilience network will exhibit a low robustness level slowly increasing with the number of links repaired.

3.3 Rapidity indicator

Previous studies, e.g. [7,13], defined rapidity as the amount of time and resources required for the system to recover a minimum acceptable level of service (LOS). The problem of this approach is that the limit of the acceptable LOS is arbitrary and highly dependent on the system and its users. We propose to eliminate this arbitrariness with a new rapidity indicator computed in two steps, involving a temporary indicator based on a minimum acceptable LOS and the final rapidity indicator that aggregates the temporary indicators.

Temporary rapidity indicator: The network rapidity is measured by the minimum number of links that need to be repaired for the network to recover an acceptable LOS. This LOS is defined by a minimum targeted robustness level *p* that should be maintained. Using the road-network-resilience graph defined above, the rapidity measure *RA(p)* is obtained by the number of links repaired when *RO* becomes superior to *p*.

Final rapidity indicator: The temporary indicators are computed for different LOS. The network rapidity *RA* is now measured by the integral of *RA(p)* along *p* as follows:

$$RA = \int_0^1 RA(p)dp \tag{5}$$

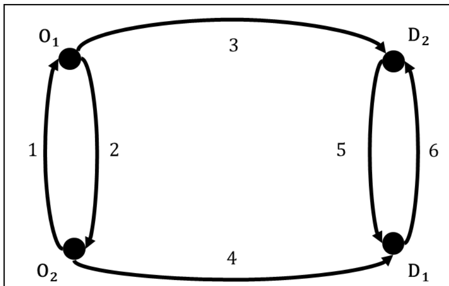
If the network can be repaired quickly, *RA* will tend towards zero (i.e. *RA(p)* will be close to zero regardless of *p*). On contrary, a network that cannot be repaired quickly will require repairing all the damaged links to recover an acceptable LOS, hence *RA* will tend towards N_s (the number of links damaged).

4. CASE STUDY

In this section, the resilience indicators are illustrated on a test network (Figure 2). Two assumptions are made: travel demand is fixed and the indicators are continuous. The first hypothesis is necessary to effectively compare the network performance under different scenarios. In reality demand is however dynamic as for instance policies can be implemented to inform and encourage drivers to delay their departure time after an event. A Python 3.6 code was used to compute both the traffic equilibrium and the proposed indicators.

4.1 The baseline scenario

The indicators are tested on a simple highway network with four nodes and six links [14]. For the sake of simplicity, the link-travel times are assumed to be linearly dependent on the link flow (Figure 2). The costs of travel (c_i) are in minutes and the flows (f_i) in thousands of vehicles per hour. Two OD pairs are considered: from O_1 to D_1 and from O_2 to D_2 with peak-hour demand for travel d_1 =4000 and d_2 = 5000 vehicles per hour respectively. The traffic assignment model used is a User Equilibrium that minimizes the TT of all road users. The results showed that two routes connect each OD pair and that the average TT per driver is 27.5 min.



Link	Cost of travel function
1	$c_1(f_1) = 2 + 4*f_1$
2	$c_2(f_2) = 1 + 3*f_2$
3	$c_3(f_3) = 8 + 2*f_3$
4	$c_4(f_4) = 10 + f_4$
5	$c_5(f_5) = 7 + 4*f_5$
6	$c_6(f_6) = 3 + 5*f_6$

Fig. 2. Test network

4.2 Disruption scenarios and impacts

Two types of disruption scenarios (i.e. consequences of hazards) are considered: single-link breakdowns (SLB) and two-link breakdowns (2LB). As road failures are rarely predictable, all possible scenarios were included. To model route unavailability, a very high cost of travel (10,000 min) is assigned to unavailable routes. SLB either blocked one route or two routes serving different OD pairs (Table 1). Hence, none of the SLB resulted in network disconnection as at least one of the routes connecting each OD pair remained available. Most of the scenarios of 2LB (8/15) caused the unavailability of two routes serving different OD pairs, which did not affect the network connectedness. The other scenarios blocked two routes serving the same OD pair or three routes, which, in both cases, disconnected one OD pair. Finally, the simultaneous breakdown of road 3 and 4 resulted in the unavailability of all routes (Table 1).

4.3 Results

The robustness indicator was computed for SLB and 2LB using equations (1-3). The results are shown in Table 1, where they are ordered in increasing number of routes unavailable and OD pairs disconnected, which can be used as an indicator of disruption severity. Table 1 shows that *RO* reflects the impact of the hazards on the network as it gradually decreases with the number of routes unavailable. Besides, the values spread in a large range (from 0.3% to 96%), showing that *RO* is suitable to compare several scenarios. The robustness indicator (equation 2) computed with the average TT is also included in Table 1 for comparison and contrary to *RO*, this indicator is unable to differentiate the cases where one or two OD pairs are disconnected. Hence, this confirms that the weighted average provides a more robust measure of the network ability to resist different hazards.

Table 1. Variations of the network robustness (*RO)* under single-link and two-link breakdowns

No. of routes unavailable	No. of OD pairs disconnected	Single-link breakdowns	Two-link breakdowns	Range of network robustness (RO) (%): [min, max]	Range of Robustness using the average TT (%): [min, max]
0	0	-	-	100	100
1	0	1, 2, 5, 6	-	[79.2, 96.0]	[75.7, 96.0]
2	0	3, 4	1&2, 1&3, 1&5, 2&4, 2&6, 3&5, 4&6, 5&6	[56.8, 82.6]	[56.8, 80.4]
2	1	-	1&6, 2&5,	[51.8, 60.8]	[0.5, 0.6]
3	1	-	1&4, 2&3, 3&6, 4&5	[29.6, 42.6]	[0.5, 0.6]
4	2	-	3&4	0.3	0.3

Moreover, the difference of magnitude of the average values of the indicators, i.e. *RO=77%, RA= 0.23 links, RE=89%* for SLB and *RO=53%, RA=0.63 links*, *RE=76%* for 2LB, captures the difference of impact on the network of the two different types of events (SLB and 2LB). Hence, the indicators should be useful to compare the impacts of different hazards as well as the resilience of different networks to these hazards.

For the sake of brevity, only the charts describing the average values of the indicators for 2LB are presented. The evolution of the network rapidity (*RA)* with respect to the targeted robustness level is shown in Figure 3 (a). This figure could be of particular interest to decision-makers to help them visualize how the cost of maintaining a certain LOS increases with this LOS. For example, in the case of 2LB, maintaining the robustness level at 60% requires repairing 0.60 links in average, whereas a more demanding level like 80% would require repairing 1.13 links. The road network resilience graph showing the evolution of the network robustness (*RO)* against the number of links repaired is shown in Figure 3 (b). The instant loss of functionality of the network due to damage is described on the leftmost bar, while the following bars show how functionality is recovered with the amount of repair done.

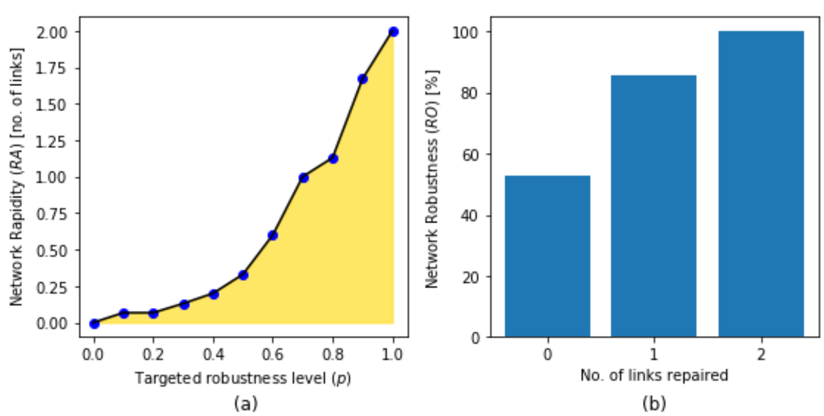


Fig.3. (a) Average network rapidity to recover from two-link breakdowns depending on the targeted robustness level and (b) Average network resilience to two-link breakdowns

4. CONCLUSIONS

The aim of this paper was to clarify the meaning of system resilience and accordingly propose a set of resilience indicators for road networks. The review of the different uses of the term "resilience" showed that system resilience can be summarized with three pillars: reducing (i) consequences, (ii) recovery time, (iii) and future vulnerabilities. On this basis, we developed and tested a set of indicators suitable to assess road networks resilience as a combination of their ability to reduce consequences (robustness) and recover quickly (rapidity). The robustness indicator employs a weighted average of the TT on all OD pairs to provide a robust measure of the degraded network performance compared to measures based on the average TT. Furthermore, the rapidity and resilience measures have the advantage of not requiring defining an arbitrary acceptable LOS (often used in previous studies). Future studies could consider developing a measure addressing the third pillar to complement this set of indicators and explore their applicability to full-scale road networks. Ultimately, both the conceptual discussion and the indicators presented in this article could be of interest to researchers, industry professionals and policy-makers aiming to develop their own resilience models and tools.

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