Evaluating Critical Infrastructure Resilience via Tolerance Triangles: Hungarian Highway pilot case study

Laura Petersen
Centre National de la Recherche Scientifique (CNRS)
&
The Worldwide Railway Organisation (UIC)
laura.petersen1@gmail.com

Johan Sjöström
Research Institutes of Sweden (RISE)
johan.sjostrom@ri.se

Eva Horvath
Magyar Közút Nonprofit Zrt.
horvath.eva@kozut.hu

ABSTRACT

While accepted as part of critical infrastructure (CI) resilience, no consensus exists on how to measure the exact minimum level of service or the rapidity of rapidly restoring services. The H2020 European project IMPROVER (Improved risk evaluation and implementation of resilience concepts to critical infrastructure) suggests to use the public's declared tolerance levels for both minimum level of service and rapidity of service restoration as criteria with which to evaluate if the resilience of a given CI is resilient enough. This paper demonstrates the development of a questionnaire-based methodology to determine public tolerance levels. It then tests this methodology via a pilot case study at IMPROVER's Hungarian Highway Living Lab. The paper argues that public tolerance levels are a reasonable choice for resilience evaluation criteria and demonstrates that the questionnaire-based methodology permits one to evaluate public perception in such a way as to compare it to technical resilience analyses.

Keywords

Critical infrastructure, resilience, questionnaires, tolerance triangle.

INTRODUCTION

Critical infrastructure (CI) resilience is defined by the H2020 European project IMPROVER (Improved risk evaluation and implementation of resilience concepts to critical infrastructure) as: "the ability of a CI system exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, for the preservation and restoration of essential societal services," which is adopted from the UNISDR (United Nations International Strategy for Disaster Reduction) definition. Thus, key parameters associated with CI resilience are both the ability to maintain a minimum acceptable level of service and the ability to rapidly restore full service in relation to a crisis event on the CI system. However, no consensus currently exists on how to measure these elements. Furthermore, once measured, how does one know if one's CI is resilient enough?

To answer these questions, IMPROVER has designed a framework: IMPROVER Critical Infrastructure Resilience Framework (ICI-REF), which proposes a relationship between CI resilience and CI risk assessment (Figure 1) (Lange et al., 2017). ICI-REF maps resilience management onto common risk management frameworks (such as ISO 31000). Within this framework, *resilience assessment* is made up of both *resilience analysis*, where the given level of resilience which a CI has (in response to an identified threat and within a given resilience domain if appropriate) is identified, and then *resilience evaluation* whereby the results of the *resilience analysis* are compared with some criteria to determine if the resilience is adequate or if further action is required to improve it.

The IMPROVER project has suggested to use the public's declared coping capacity as criteria for *resilience evaluation*. Indeed, previous work within the IMPROVER project has found that the general public, end users of CI services, appear to have reasonable expectations of CI operators in crisis times (Petersen et al., 2017a; Petersen et al., 2017b; Petersen et al., 2018a). The public's reputation for having too high of expectations appears unmerited; they are willing to cope in times of crisis. Further, this better aligns the idea of resilience to the purpose of CI, namely to deliver services to society. As an added bonus for CI operators, going beyond meeting needs to meeting expectations helps maintain reputation during a crisis (Barker, 2013).

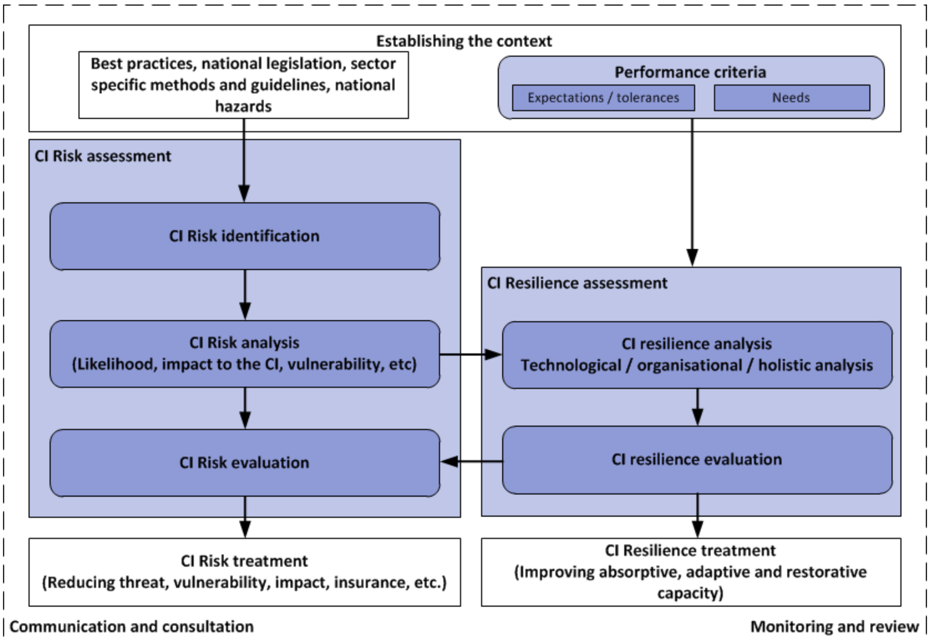

Figure 1 IMPROVER ICI-REF. CI operator risk and resilience management process (note that 'Communication and consultation' and 'Monitoring and review' are continuous processes which should interact with all other processes)

We propose to use a questionnaire survey in order to determine the public's perception of their own coping capacity in crisis times. Previous research has shown that people are good judges of their ability to deal with disturbance and change (Nguyen & James, 2013). The idea of people being able to accurately judge themselves has been used successfully in psychology, well-being and subjective resilience domains (Jones & Tanner, 2015). Furthermore, previous research into customer preferences and satisfaction has also used questionnaires to establish coping capacity in times of reduced service (OECD, 2001; Centre for Transport & Society, 2015; Transport Focus, 2017). The goal of the questionnaire then is to have a comprehensive understanding of the local population's expectations and tolerance levels. It is important to remember that it is the public's own views that are of interest here. While, as seen in Figure 1, within ICI-REF understanding the tolerances of the population falls under *establishing the context*, it is necessary that the questionnaire is designed in such a way that the results will be comparable to the results of the *resilience analysis* during the *resilience evaluation* part of the framework.

Within the IMPROVER project, a pilot test of such a questionnaire for a highway infrastructure was carried out. Similar work was carried out for a municipal freshwater network (Petersen et al., 2018b).

Public expectations for highways in crisis times

The relative importance of transportation infrastructure in ensuring emergency response, providing accessibility to other critical infrastructures for their recovery and in the day-to-day lives of citizens explains the high expectations for transportation infrastructure during and after a disaster (Petersen et al., 2017b). There is an expectation that a minimum level of mobility can be achieved, even if that requires a change in means of getting around (Petersen et al., 2018). Previous research has shown that the public is willing to tolerate reduced transportation service in terms of reduced capacity or frequency, diversion or alternative means for a period of months (Petersen et al., 2018). Recent research into public tolerance levels to a change in service of the Oresund Crossing due to the refugee crisis in 2016 using both questionnaires and a case study found that the public was willing to tolerate service disruption in times of crisis (Petersen et al., 2017a). Another recent study of the Oresund Crossing asked users "do you have a plan B?" in the case of service disruption and found that respondents felt capable of coping with short, medium, and long-term disruption scenarios (Dahlberg, 2017). When highways are no longer operable due to a crisis, the public appear to expect an offer of public transporation to be made available based on survey results from victims of both the 2011 Great East Japan Earthquake and the 2010-11 Queensland Floods (Regional Australia Institute, 2013; Nakanishi et al., 2014).

However most previous research into public expectations/tolerances/satisfaction of transportation infrastructure does not investigate crisis times but instead "normal" times or planned works. Much research in this area has focused on user satisfaction with roadways by evaluating travel time, reliability of travel time, and delays in travel time (OECD, 2001). Unsurprisingly, the greater the delay experienced by the user, the worse the impact is on user satisfaction (Centre for Transport & Society, 2015). However, satisfaction surveys also demonstrate that the cause of the delay affects expectations, whereby accidents and "unexplained incidents" are mainly accepted by users as unforeseen events (Transport Focus, 2017), further demonstrating that people are willing to adapt after a crisis. Lastly, once a delay is communicated to the users, users are willing to accept it as part of their normal mobility, meaning that there is not a reduction in satisfaction due to the stated delay (Centre for Transport & Society, 2015; Transport Focus, 2017).

Hungarian M1 Highway Living Lab

The IMPROVER project uses Living Labs in order to study various aspects of CI resilience. Living Labs are a research concept that create an open-innovation ecosystem and use a systematic user co-creation process. This means the actors of a Living Lab are not simply subjects but also active participants in the research process. Thus, qualitative methods such as semi-structured interviews are carried out with the actors of the Living Lab. Living Labs have been the focal point of the scientific work carried out within IMPROVER and have been used to test various project methodologies, including the creation and implementation of tolerance questionnaires.

The M1 Highway is one of the most important highways in Hungary, serving the north-west part of the country (Figure 2). It is a transport infrastructure of importance at both national and European scale as it provides passenger and freight transport between the country's capital, Budapest, and two neighbouring capital cities: Vienna in Austria and Bratislava in Slovakia. The M1 highway is operated and maintained by Magyar Közút Nonprofit Zrt. (Hungarian Public Road Non-Profit Plc. - Közút). They were established in 2005, starting in 2014 were owned by the Ministry of National Development and since 2018 are owned by the Ministry for Innovation and Technology.

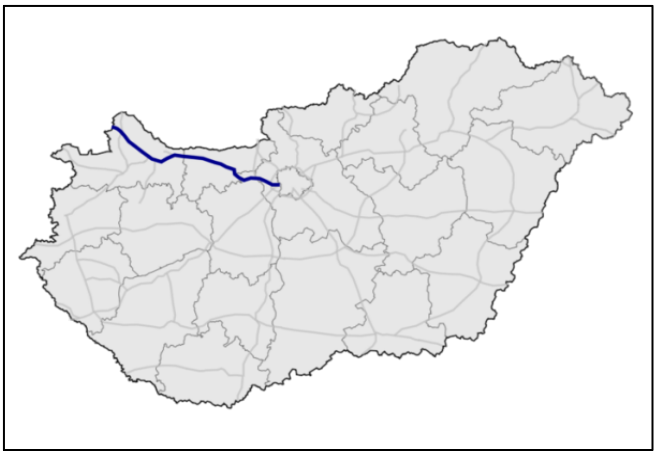

Figure 2 The IMPROVER Living Lab of the M1 Hungarian Highway shown in blue on the map

Several hazards may influence the highway network, including snowstorm, earthquake, flooding and collision leading to serious damage of bridges. A recent snowstorm that impacted travel on the M1 highway occurred on March 14, 2013 leading to a 3-day closure, where trucks were stuck, traffic was diverted to Road 1, the army had to intervene and evacuate cars, and which affected a total of 17,000 people. The effects of the crisis were heightened due to the combination of the storm occurring the day before a major Hungarian holiday, leading to an already increased rate of road traffic, and a swift change from spring-like weather to a winter storm. Another recent crisis event occurred on 19th May 2010 when flooding led to a 2-day closure of the M1 Highway, causing major traffic disruption, including cross-border traffic to and from Austria. The tender for restoration amounted to a total of 100 million HUF (ca. 437.000 USD at the time of the incident). (Honfi et al., 2018)

METHODOLOGY

Establishing the context

As stated in the introduction, if the results of the assessment of public expectations are incompatible with the resilience analysis, it will be difficult to use them as criteria for resilience evaluation. Thus, public perception of their own coping capacity in crisis times must be obtained in a way that is comparable to the technical performance measures of the service in question. In addition, the defined functionality and ways of measuring performance need to reflect one another. Within the IMPROVER project a resilience analysis using the IMPROVER Technical Resilience Analysis (ITRA) methodology is defined (Honfi et al., 2017). ITRA is currently being applied to the Hungarian M1 Highway Living Lab, however outside the scope of this paper. Through interviews with the living lab, it was discovered that highway performance is considered normal if, on the considered section, the highway is fully open for traffic and traffic flow is continuous without queuing. In such a case, the traffic demand is less than the actual capacity of the highway. As such, the main function of the M1 highway used for these studies was defined as being able to provide undisrupted traffic of passengers and goods, while ensuring user safety. The performance measure then to study this functionality was the travel time between selected origin destination pairs. Questions then were asked about the applicable performance measures of additional journey time and duration of additional journey time. Other factors influencing tolerance levels such as alternative routes and information provision were taken into account by inclusion in the detailed scenario (see below). In order to develop the questionnaire with a view to real world performance capabilities of operators, a combination of desk research and semi-structured interviews with the living lab operators were used.

The questionnaire was designed as an online questionnaire. The target population was adults aged 18+ who are users the M1 Highway, excluding professional users (i.e. lorry drivers). Convenience sampling was used. The questionnaire was registered with CNIL (French authority for digital privacy) and reviewed by the project's Ethics Officer. Respondents were informed of their right to withdraw from the project at any time and that the anonymised data from the questionnaire could be used in publications, presentations and reports. The questionnaire was published in English and Hungarian to best meet the linguistic needs of the user population. Unfortunately, despite the highly international character of the highway, researchers were unable to translate the questionnaire into German or Slovak. Data collection was held between 24 April 2018 and 10 June 2018.

The questionnaire began by asking respondents about their typical M1 highway usage and also investigated disaster preparedness, risk awareness and previous disaster experience of respondents. This is because expectations have been found to be influenced by these factors (Petersen et al., 2018).

Technological resilience is typically hazard dependent, having a strong link to risk analysis. Thus, in order for the results of the questionnaire to be comparable, the same hazard scenarios were considered here. Although the hazard assessment identified several potential scenarios, the two chosen for further study were a collision and a severe snow storm. These were chosen based on the interest of the operators via interviews. The collision scenario was important to Magyar Közút as they are responsible for the management of the Hungarian bridge stock, and the severe snow storm scenario was of great interest following the 2013 snowstorm crisis.

The following are the detailed scenarios that were presented individually to the respondents:

- Scenario 1: Imagine that a crash causes serious damage to a bridge on the M1 highway, leading to the closure of part of the M1 highway and prolonged delays. Users of the road will need to use deviations and will be informed ahead of time about increased travel times.
- Scenario 2: Now imagine that a heavy snow storm occurs in Budapest. Weather forecasting has predicted that there will be enough snow to impact traffic flows. Residents have been encouraged by local authorities to seek shelter and avoid traveling during the storm. Highway Operator crews have prepared the roads with salt and have used snowplows to keep the roads clear for as long as possible. However, now the M1 highway is no longer open, leading to prolonged delays.

After the presentation of a given scenario, the following two questions were asked. The first question was, "After [Scenario 1 or Scenario 2], how much additional journey time are you willing to tolerate when using a personal vehicle on the deviation route when travelling for…? Commute to work; Leisure (shopping, running errands); Holidays; Business trips." The times provided were: <20 minutes; 20 – 29 minutes; 30 – 44 minutes; 45 – 59 minutes; > 1 hour. This question aimed to capture the minimum level of acceptable service in regards to additional journey time.

The second question dealt with the duration for which an additional journey time would be tolerable. It asked, "After [Scenario 1 or Scenario 2], for how long would you be willing to put up with an additional journey time of…?" The time frames presented for the total crisis duration were different depending on the scenario. Based on the interview with Közút, the questionnaire recovery range for the collision (scenario 1) was proposed to be from less than 1 day to more than 1 month. The rather lengthy recovery time includes the reparation of the damaged bridge to allow for a full re-opening of the roadway. The recovery times of the snowstorm were based partly on the estimates provided by Közút, who since 2013 have increased their response-ability towards snowstorm, and partly on desk research of various recent snowstorms around the world that led to highway closure. In both cases, snowstorms appear to be cleared in a matter of days, and thus the snowstorm (scenario 2) additional journey time duration was proposed as being from 1 hour to 1 week. This question aimed to capture what the public expected in terms of "rapidity" of recovery.

Lastly, the questionnaire asked about demographic information, as culture, gender, education level and socio-economic status have also been found to influence expectations (Petersen et al., 2018). Chi-squared tests were performed to explore any significant differences across responses. For some chi-squared tests, responses were grouped together in order to have enough responses.

Dissemination Plan

Dissemination was also mostly online in both English and Hungarian. Közút showcased the questionnaire on their Facebook. They also shared it with other local authorities for them to also publicise it. IMPROVER publicised the questionnaire on their Twitter, LinkedIn, website and via their email list serve, and members of the consortium were encouraged to share it with relevant people. BME (Budapest University of Technology and Economics), the Hungarian IMPROVER partner, also published it on their Facebook and Twitter.

Figure 3 Online dissemination efforts. Right, the operator's Facebook post, Top-middle, BME's Facebook post, Bottom-middle, BME's Twitter post, Left, IMPROVER's Twitter post

Sample Characteristics

There were a total of 342 clicks on the questionnaire links (combined), which led to 116 respondents participating in the questionnaire. Filtering out respondents who had never used the M1 Highway or were professional users of the highway, in total the sample size became 68 respondents.

Due to the dissemination method, this self-selected sample was not broadly representative of the Living Lab. Sample characteristics showed that 72% of participants were male and 28% female. Most were highly educated, with 72% reporting that they have a bachelor's degree or higher qualification. Both young and old people appeared to be underrepresented in the study. Respondents aged 18-24 accounted for only 13% of the total sample and only 14% identifying themselves as aged 55 years and above. An overwhelming majority of the respondents reside in Hungary (88%), whereas around 60% of the Highway users are international users (Personal interview). Income groups were more varied (Figure 4). The majority of respondents use the M1 Highway for holiday travel (Figure 5). Due to this, a typical journal time for respondents is over one hour to two hours (Figure 6).

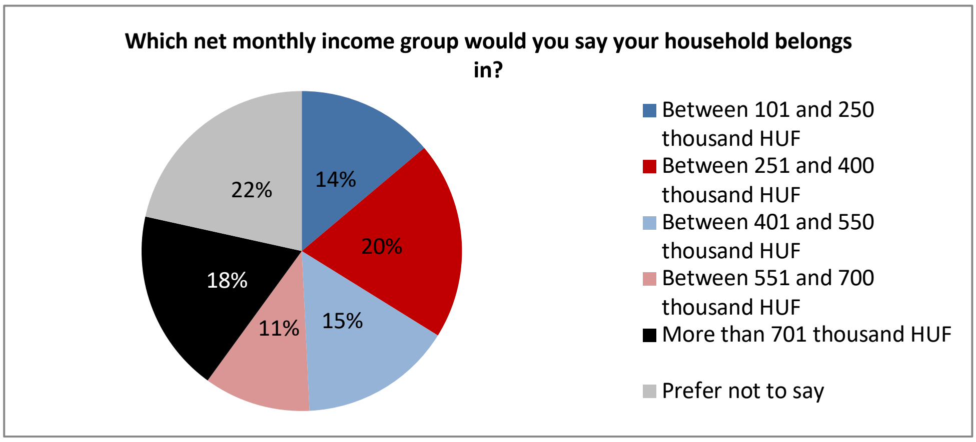

Figure 4 Monthly income group of respondents

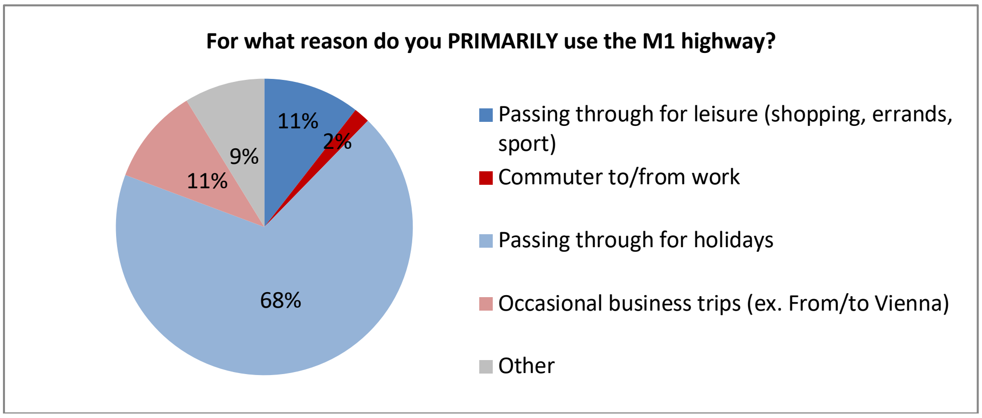

Figure 5 Respondents' primary use of the M1 Highway

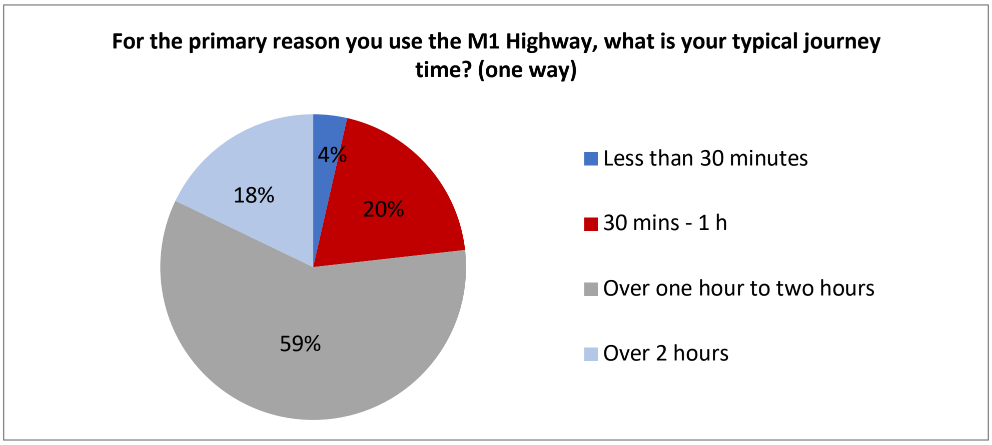

Figure 6 Respondents' typical journey time

Resilience Evaluation

As ITRA uses the idea of a resilience triangle shown schematically in Figure 7 (adapted from Bruneau et al., 2003), here we propose to transpose the results of the questionnaire into what we are calling "tolerance triangles" (Honfi et al., 2018).

Thus, a tolerance triangle is created by the accumulated percentages of respondents willing to tolerate a given service reduction for a given time frame. The next step would then be to compare the tolerance level to the resilience triangle, in order to perform the resilience evaluation and determine where public expectations are not being met (represented by the red area between the curves in Figure 7). Note that in Figure 7 the performance is plotted such that the increased positive value reflects better performance. In the case studied here we will use "additional travel time" as an indicator of performance. Since these are intuitively plotted as a positive number the triangles that are produced will be turned upside down with positive numbers during the aftermath of the incident and normal performance reflected by a value of 0, thus no additional travel time.

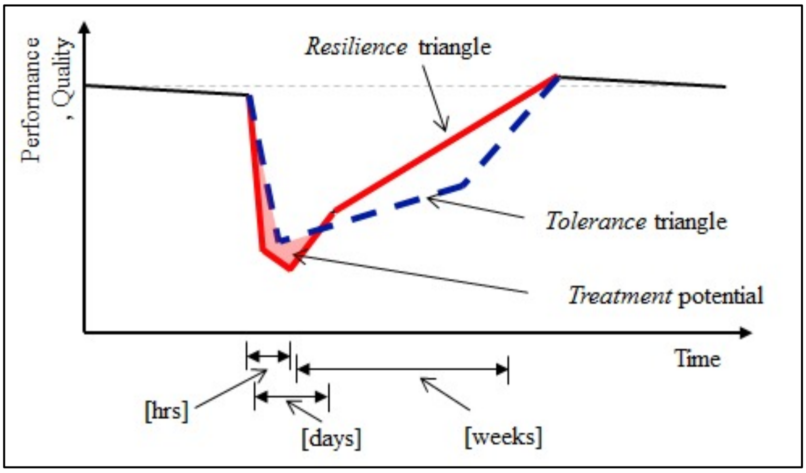

Figure 7 A schematic representation of a "resilience triangle" in red & a "tolerance triangle" in blue. From Honfi et al., 2018.

Közút's performance (the red line in Figure 7) could be evaluated using many different performance criteria. The IMPROVER project has defined the M1 hazards and their probabilities, damage states associated to these and the implications that will have on the local situation for the highway. Thereafter, traffic simulations were performed for different traffic loads and damage states. The performance measures from these simulations are chosen as (1) value of transported goods, based on data by Közút and (2) increased travel time for a specified section of the highway. It is the second of these performance measures that this paper uses to compare with public expectations.

RESULTS

The full results are available in Table 1 in the Annex. The following sections present the results in more detail.

Disaster preparedness, risk awareness and previous disaster experience

Respondents are equally split in terms of disaster preparedness regarding having emergency supplies stocked in their private vehicles (Figure 8). Respondents mostly do not think that serious damage to a bridge will occur in the next year (49%) (Figure 9). However, there is great uncertainty (21%). For the snowstorm scenario, respondents are more unsure (32%), but overall believe it is more unlikely than likely (Figure 10). Respondents are almost equally divided between those who have experienced a disaster and those who have not (49% vs. 50%, with 1% choosing I do not know). For those that have, flood and snowstorm are the most commonly experienced, both of which have recently affected the M1 Highway service in the past.

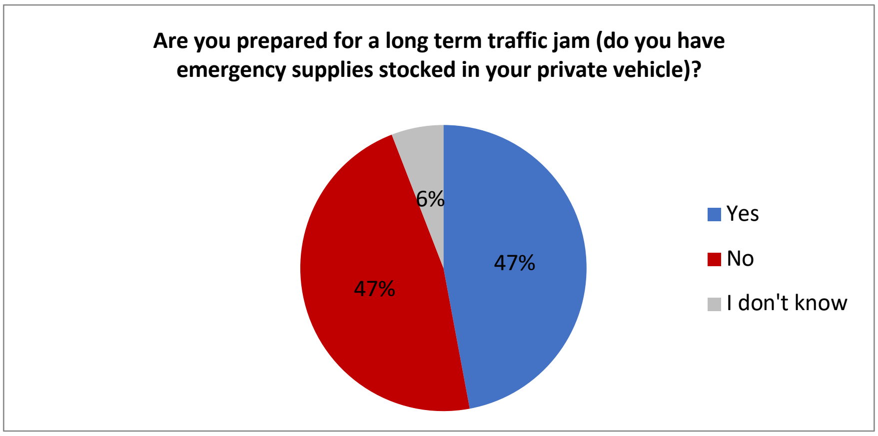

Figure 8 Respondent's declared disaster preparedness

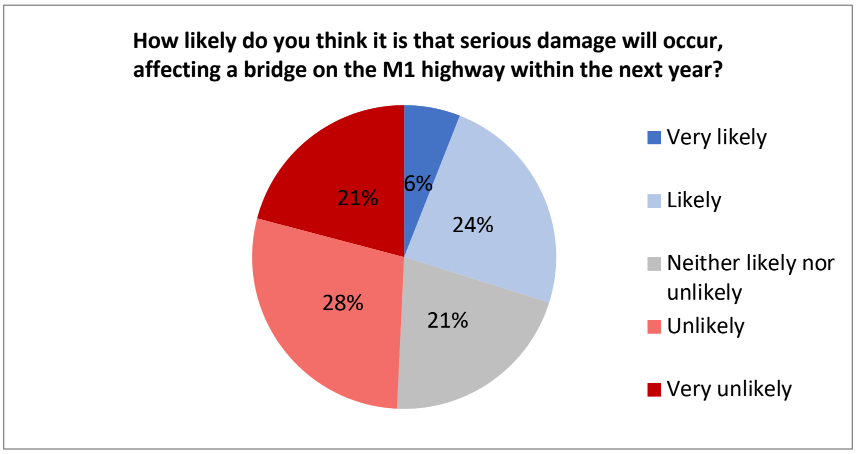

Figure 9 Risk perception: bridge damage

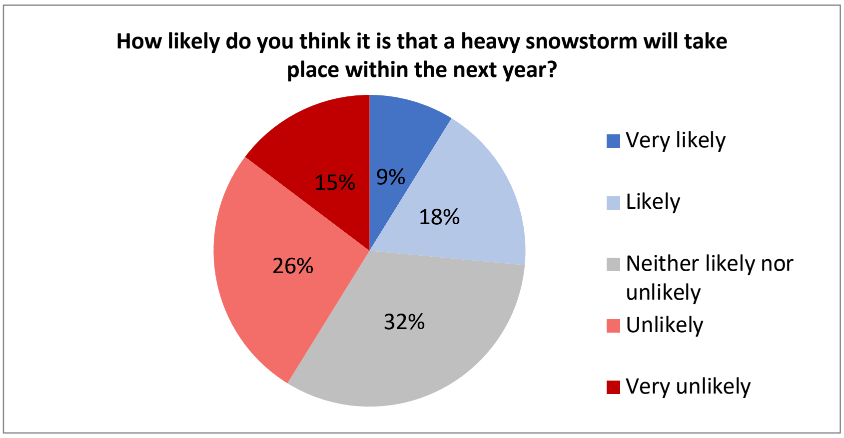

Figure 10 Risk perception: snowstorm

Tolerance triangles

Scenario 1

Additional journey time was asked in regards to four different possible reasons for taking the M1 Highway. Respondents using the highway for work related activities were less likely to tolerate longer delays ($X^2 = 831.39$, df = 12, $p < 0.001$). The related additional journey time tolerance triangles are presented in Figure 11. Duration of additional journey time was asked in regards to five different additional journey time scenarios. Unsurprisingly, shorter additional journey times are tolerated by more respondents for longer durations, however the statistical significance of this has yet to be verified ($X^2 = 1806.81$, df = 28, p=0). The related tolerance triangle is presented in Figure 12.

Scenario 2

Additional journey time was asked in regards to four different possible reasons for taking the M1 Highway. Respondents using the highway for work related activities were less likely to tolerate longer delays ($X^2 = 1341.45$, df = 12, $p < 0.001$). The related additional journey time tolerance triangle is presented in Figure 13.

Duration of additional journey time was asked in regards to five different additional journey time scenarios. Unsurprisingly, shorter additional journey times are tolerated by more respondents for longer durations ($X^2 = 1048.81$, df = 20, $p < 0.001$). The related delivery tolerance triangle is presented in Figure 14.

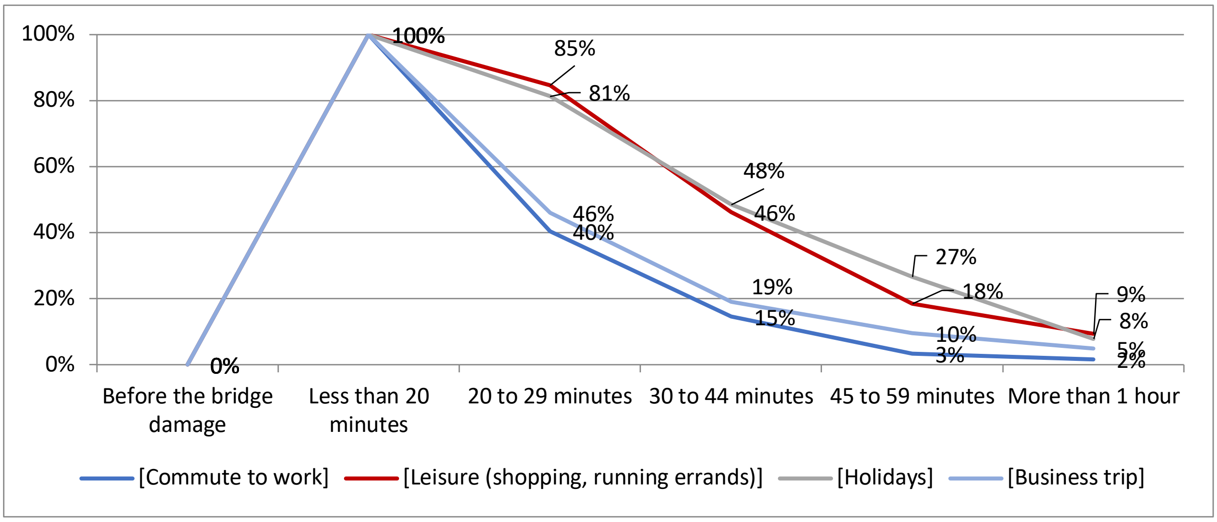

Figure 11 Additional journey time (bridge collision) tolerance triangles

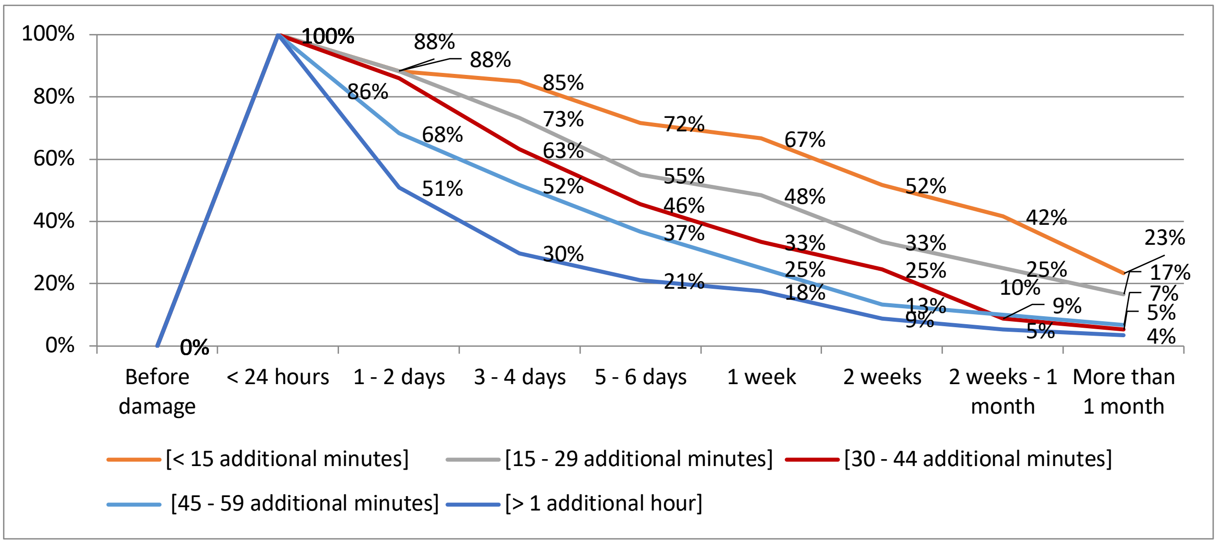

Figure 12 Duration of additional journey time (bridge collision) tolerance triangles

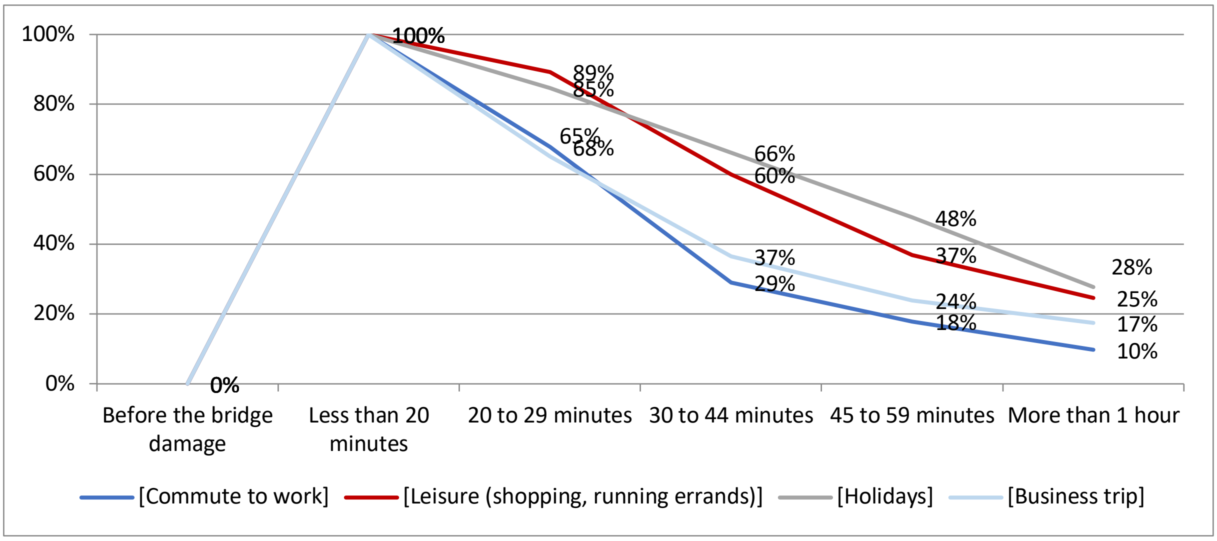

Figure 13 Additional journey time (snowstorm) tolerance triangles

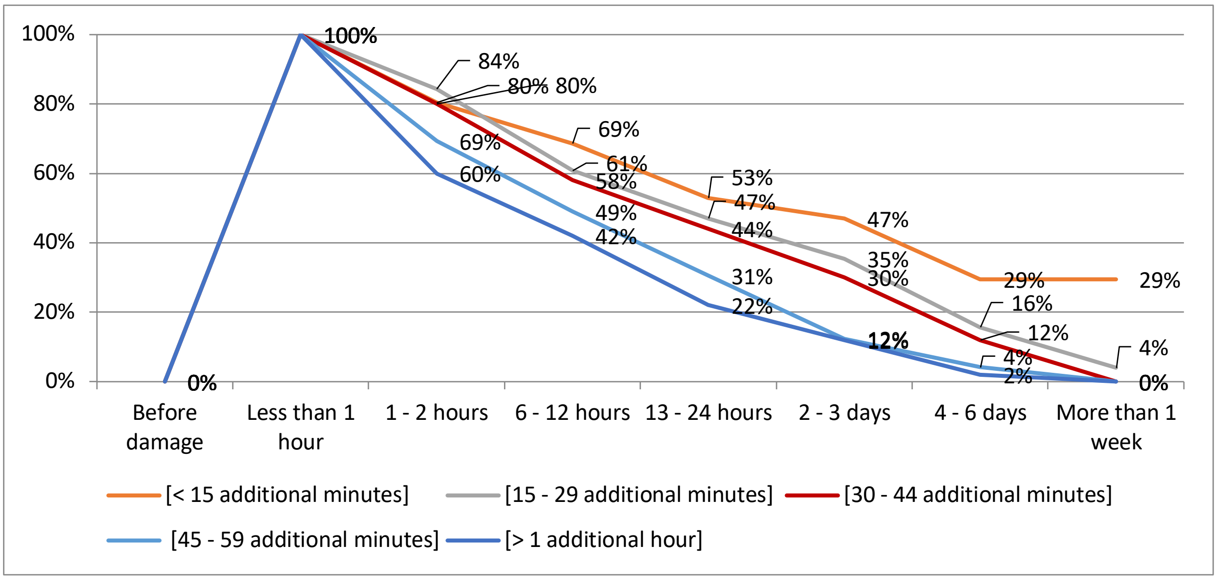

Figure 14 Duration of additional journey time (snowstorm) tolerance triangles

Resilience evaluation

Since most end-users will have unique tolerance to performance loss in infrastructure the tolerance of the public is a distribution which cannot be directly mapped onto a single curve of performance for a given scenario. The information in Figures 11-14 can shine light upon how tolerance varies among the end-users (i.e, does a minor fraction have a very low tolerance compared to the majority or are most end-users in agreement?). However, to be able to set targets one can describe the tolerance as e.g. that of the 75th percentile of the population or, as we will suggest here, as a weighted average of the whole population.

Thus, the tolerance curve for the bridge collision scenario, described as tolerable additional journey time as function of time after the incident, is the average of the different delay times shown in Figure 12 weighted by the percentage of people who stated that delay time as their maximum tolerance. The percentage of respondents that did not accept any of the proposed delay times are assumed to accept nothing but normal performance. This weighted delay time is calculated for each time after the incident.

$$\bar{t}_{Tol}(t_{incident}) = \sum_{I=1}^{X} \frac{n_i(t_{incident})}{N} \times t_{d,i},$$

where $\bar{t}_{Tol}(t_{incident})$ is the weighted average of tolerated time delay after a time $t_{incident}$ since the incident, X is the number of proposed time delays suggested in the questionnaire (the five curves in Figure 12), $n_i(t_{incident})$, is the number of respondents who stated the additional travel time $t_{d,i}$ as their maximum tolerance after time $t_{incident}$ from the incident and N is the total number of respondents. Note that this weighted average is lumped for all four different categories of travel (work commuting, leisure, …). The division between the different categories can easily be made but is not suitable for this low number of respondents.

The comparison of the weighted average tolerance in additional travel time and the estimated performance measure is shown in Figure 15 for the bridge collision. The performance curve is from Honfi et al. (2018) and is representative of a severe damage state due to a collision, a high vehicle rate of 1800 vehicles per hour and present-day resources and strategies. Figure 16 shows the equivalent data for the snowstorm scenario. The performance curve in this case is not estimated using the suggested tools for technological resilience analysis suggested in Honfi et al. (2017) but is an estimation of a realistic scenario based on the March 2013 Budapest snowstorm. Thus, it is important to keep in mind that the performance curves used here do not show the true performance of the system and are used here for illustrative purposes only.

With the tolerance curves derived here it is possible to evaluate the estimated performance for different resources available, different restoration strategies and different damage states. These evaluations will inform the decision makers on the sufficiency of the performance depending on these variables to partially guide the preventive work.

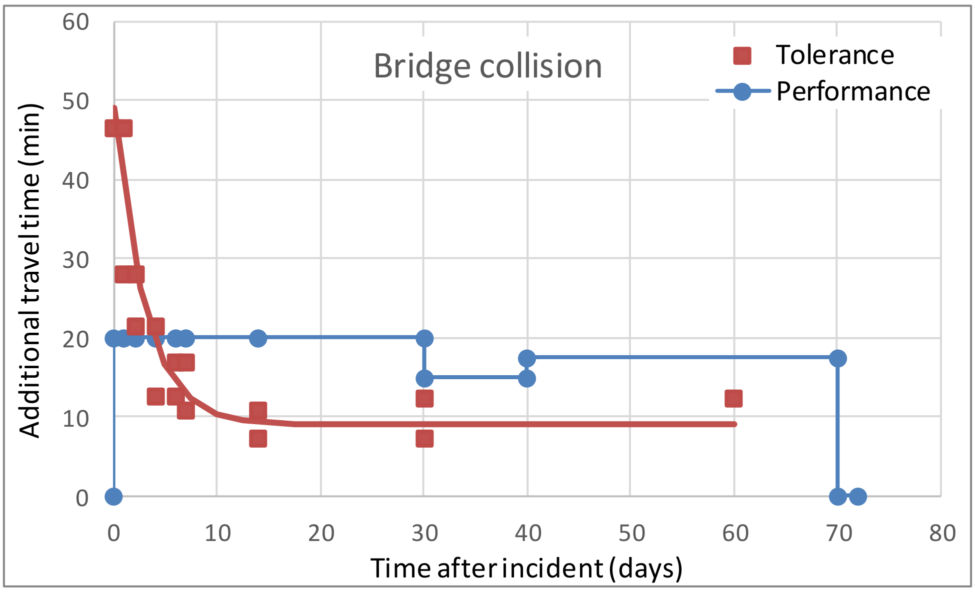

Figure 15 The performance measure of additional travel time (Honfi et al., 2018) evaluated against the tolerance curve for the bridge collision scenario. The red line is an exponential decaying representation of the tolerance data.

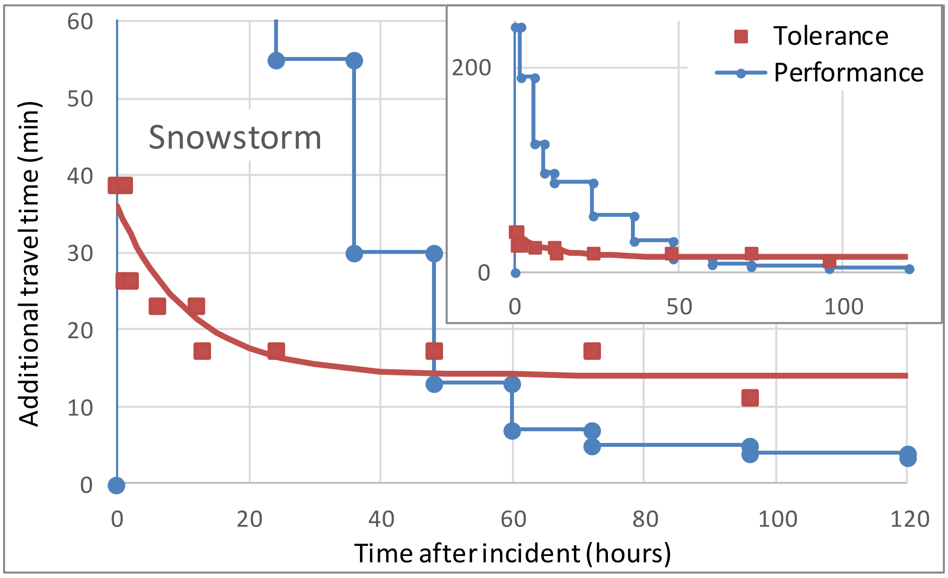

Figure 16 The performance measure of additional travel time evaluated against the tolerance curve for the bridge collision scenario. The inset shows the same data also for the period close to the incident.

DISCUSSION

Public expectations of service level and recovery time

The questionnaire results indicate that respondents are willing to tolerate service disruption in the form of additional journey times in times of crisis. For the four use-cases we presented, in both scenarios, the reason for using the highway highly affects the willingness to tolerate additional journey time. If traveling for work related reasons (commute to work & business trip), respondents were less willing to tolerate longer additional journey times. Thus, it seems that the minimum level of service expected from the public when it comes to work-related travel is between 20 and 44 minutes of additional journey time. When traveling for lesiure or holidays, respondents minimum level of service is an increased level of additional journey time then that of when travelling for work, ranging from 30 to 59 minutes. Unsurprisingly, the longer the additional journey time, the less long the respondents are willing to tolerate the new minimum level of service. For example, in Scenario 1, the majority of respondents are willing to have an additional journey time of 15 minutes for a period of 2 weeks, whereas for an additional journey time of 45 – 59 minutes, respondents choose only 3 - 4 days. The low risk awareness of respondents indicates that both scenarios would most likely be seen as “unforeseen” events, which could help explain why highway users are so willing to have reduce service levels.

Since most travellers in our study use the M1 Highway for holiday travel, the minimum acceptable level of service recommended is 30 - 44 additional minutes of travel time (chosen by 48% of respondents for scenario 1 and 66% for scenario 2). For this additional journey time, almost half of respondents (46%) consider 5-6 days with additional travel time to fall within a “rapid” recovery for scenario 1, whereas almost half of respondents (44%) consider 13 – 24 hours with additional travel time to fall within a “rapid” recovery for scenario 2. This clearly shows the importance of the crisis scenario on expectations, as the public have demonstrated their understanding that certain disasters require a longer recovery time.

For the two cases used here the tolerance levels are both below and above the performance levels for different time durations after the incident. For scenario 1 (bridge collapse), for the first few days after the incident the expected performance for this scenario is better than the tolerances of the end-users. However, five days after the incident the end-users expect less additional travel time than what is the expected performance from the resilience analysis (for this damage state, these resources and the given strategy). Contrary to the bridge collision scenario, the estimated performance during the early stage of the snowstorm scenario (scenario 2), which is 2 days for this scenario, does not meet end-users’ expectations. The very long additional travel times required just after a heavy snowfall is clearly not what the end-users expect. However, the public seem to tolerate small additions to the travel time for a longer period (> 2 days) than what is the estimated performance. While keeping in mind that these results are purely illustrative, they would permit one to advance to the next phase of ICI-REF, *resilience treatment*. For scenario 1, to better meet expectations for long-term recovery, a possible treatment could be the implementation of techniques for quick and efficient damage identification using e.g. structural health monitoring. For scenario 2, it may be beyond the capacity of the operator to meet public expectations. In this case, it is recommended to increase crisis communication during both the prevention and active crisis times. Indeed, information provision has been found to lead to more reasonable expectations of CI operators (Petersen et al., 2018; Buller, 2015).

Success of the method

Despite a low response rate, the questionnaire results demonstrate that it is possible to use this type of method in order to discern the tolerance levels of a given user population of a given CI. Indeed, starting from the same functionality and performance measures as the technical resilience analysis did not inhibit the ability of respondents to state their tolerance levels. Thanks to the use of Living Labs, the questionnaire was able to be developed with inputs from the Hungarian M1 Highway operators and study relevant crisis scenarios and realistic recovery timeframes. The operators at Közút have expressed positive feedback on the methodology and think that the results provide relevant knowledge. Of course, performing the resilience evaluation for all different damage states, recovery strategies and resource availabilities will be the true test of the method and ensure combability between the *resilience analysis* and the *establishment of the context* of the framework. This is part of ongoing work, pending the finalization of the resilience analysis. Thus, the ultimate success of the method is not yet entirely apparent. However, developing the survey in tandem with the resilience analysis parameters did not inhibit data collection and allowed the questionnaire to establish the public’s tolerance levels.

As stated in the methodology, in order for the tolerance questionnaire to be comparable to the resilience analysis, the questionnaire also had to be scenario-based. This is because ITRA is dependent on undertaking a risk analysis, which in general are scenario-dependant. Thus, the results are not generalisable to all types of crisis scenarios. However, to analyse resilience of a given CI, it is not necessary to be use a scenario-based method (i.e. to use a different method during the *resilience* analysis phase than ITRA), as certain performance changes will occur regardless of the type of incident that has occurred. In this case, while it should be possible to also use a questionnaire to determine public tolerances, our results demonstrate that the type of crisis does highly affect public expectations. This shows the value of using scenarios when evaluating tolerances, to more fully understand the population. Further, as previous research has shown that nationality plays a big role in public expectations of CI operators in crisis times (Petersen et al., 2018a), it is recommended to perform a questionnaire for each CI individually.

Limitations

Survey

Questionnaires as a research method have certain limitations that maybe overcome with purposeful survey design (Jones & Tanner, 2015). Indeed, when responding to a questionnaire, people often use snap judgement and may be influenced by emotional or contextual factors (Schwarz & Stack, 1999). For example, perhaps if the survey had been undertaken in winter, traffic delays would be more common and risk awareness for this issue would be higher. When it comes to using a questionnaire to ask about tolerances, question wording may influence responses, as research has demonstrated that when asked if they care about a given issue, people state concern for issues that do not exist (Herrmann et al., 1994). Another issue to consider is whether or not people answer in their own self-interest, claiming to tolerate less so as to not give the CI operators an excuse to perform any lower than absolutely necessary, or in a self-delusionary way, reporting that they are willing to tolerate more than they actually could handle. Another limitation to consider is that as disaster victims rarely passively wait around for someone else to take care of their needs (Quarantelli, 1998), stated tolerances may be for a level of reduced service that is higher than the actual minimum level of service that citizens are capable of tolerating. Another limitation is the sample method used does not allow for representativeness in the sample. The small sample size used here is also a limitation for the generality of the results. Further due to the dissemination method that focused heavily on Hungary, most respondents were Hungarian whereas about 60% of users of the M1 are international users according to Közút. Thus, the tolerance levels for all highway users cannot be said to be known.

Resilience evaluation

It should be mentioned that there are different ways of weighting the answers from the respondent. The method used here is to (1) average the accepted times of additional travel times for each duration after the incident. Another method could be to (2) average the duration after the incident for which the respondent will accept a certain additional travel time. For this specific case there are pros and cons to both methods. Method (1) can give non-monotonic results due to the way the precise question was presented. On the other hand, it represents all the answers better since the relative time of the largest delay time is not orders of magnitude larger than the smallest. Method (2) gives completely monotonic results but since the longest duration of time (>1 month) is so much larger than the smallest duration the final results are heavily reflecting only the answers related to the longest duration period. Both curves give similar results but method (2) cannot extend for much longer that 15 hours (for the case of bridge collapse). This could be improved in constructing a similar questionnaire in the future where the relative magnitude of the different alternatives should be spaced more evenly, or possibly that the respondent is free to write his/her own tolerance of duration without predefined alternatives.

One should also be aware of the fact that the performance measure and tolerances do not precisely reflect the same quantity. The tolerances are based on the respondent tolerance to additional travel time for their characteristic travelling (which differ in length, duration and position between the respondents). Performance is, on the other hand, defined for a fixed section of the M1 highway. Thus, 2nd order effect due to very long ques are therefore not taken into account but that could only be circumvented by performing the traffic flow analysis in a probabilistic manner having prior knowledge about the distribution of length, duration and sections of the highway used by all users… data that presently is not available.

CONCLUSION

This paper set out to establish a methodology using a questionnaire survey to determine public tolerance levels for CI service reduction in crisis times. The questionnaire was designed in such a way as to provide data that would subsequently be usable in the *resilience evaluation* step of IMPROVER ICI-REF. Using a living lab to test the methodology enabled it to ensure relevance to the CI operator. The questionnaire established that the public generally have reasonable expectations towards highway operators during both collision and snowstorm scenarios. However, the expected duration of traffic disturbance after a severe bridge collision is underestimated by the respondents. Additionally, the magnitude of the additional travel time for a short duration after a heavy snowstorm is not reflected in the tolerance of the public.

The minimum level of acceptable service was found to be dependent on the reason for travel, with work-related travel minimums being of a lesser additional journey time. In regards to rapidity of service restoration, as one would have thought, longer additional journey times were tolerated for shorter periods. These declared tolerance levels seem to fall within the response-ability of the CI operator, showcasing once again that the public have reasonable expectations of service levels in crisis times. Based on the main use case of our respondents (holiday travel), it is recommended to have a minimum service level of an additional journey time of 30 – 44 minutes and to rapidly restore normal performance would be restoring it within either 13 – 24 hours for snowstorm or 5 – 6 days for bridge collision. This pilot test then has successfully demonstrated the ability to use questionnaires as a means to discover public tolerances within the *establish the context* step of ICI-REF.

While the questionnaire results as first shown can provide a more general target, to successfully carry out a *resilience evaluation*, the results were then used to calculated the weighted average tolerance of the whole population. As such, the comparison of the tolerance criteria from *establishing the context* to the *resilience* *analysis* was demonstrated. As the *resilience analysis* is still ongoing work within the IMPROVER project, the performance curves used here do not show the true performance of the system. Nevertheless, they were useful as an illustration of the resilience evaluation methodology, demonstrating the compatibility of a tolerance questionnaire with resilience analysis.

Future work includes comparing the results of this questionnaire to the plethora of results from the *resilience analysis*, thus performing the *resilience evaluation* step of the framework for different decision parameters. Followed by the development of a *resilience treatment* plan for the Hungarian M1 Highway. Future work will also build on this methodology to perform a similar questionnaire-based study of tolerances in other IMPROVER Living Labs. Lastly, the IMPROVER project will develop a guide for practitioners on how to design and implement tolerance questionnaires.

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REFERENCES

Barker, B. (2013). New Focus for Weathering Storms: Customer Resilience. *In EPRI Journal*.

Bruneau, M., Chang, S.. Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K., Wallace, W., & von Winterfeldt, D. (2003). A Framework to Quantita-tively Assess and Enhance the Seismic Resilience of Communities. *Earthquake Spectra: November 2003, Vol. 19, No. 4, pp. 733-752*. DOI: 10.1193/1.1623497

Buller, A. (2015, July 10). Closing the Gap: Expectations versus Capabilities. *PA Times*. Retrieved from: http://patimes.org/closing-gap-expectations-capabilities/

Centre for Transport & Society. (2015). Independent Analytical Review for a Road User Satisfaction Survey. https://www.transportfocus.org.uk/research-publications/publications/independent-analytical-review-for-a-road-user-satisfaction-survey/

Dahlberg, R. Do you have a Plan B? Integrating adaptive capacities into infrastructure preparedness planning. *Journal of Contingencies and Crisis Management.* DOI: 10.1111/1468-5973.12203

Honfi, D., Lange, D., Malm, A., Mindykowski, P., Alheib, M., Bouffier, C., Cauvin, L., Willot, A., Ioannou, I., & Rød, B. (2017). Technological resilience concepts applied to critical infrastructure. *IMPROVER projet deliverable D3.2.*

Honfi, D., Lundin, E., Sjöström, J., Lange, D., Vigh, L. G., Petersen, L., Ioannou, I. (2018). Report of technological resilience concepts applied to living labs. *IMPROVER project deliverable D3.3.*

Jones, L. & Tanner, T. (2015). Measuring 'subjective resilience' using people's perceptions to quantify household resilience. Overseas Development Institute.

Lange, D., Honfi, D., Theocharidou, M., Giannopoulos, G., Reitan, N. K., Storesund, K. (2017). Incorporation of resilience assess-ment in Critical Infrastructure risk assessment frameworks, *In: Safety and Reliability – Theory and Applications,* ISBN 978-1-138-62937-0, p. 1031-1038.

Nakanishi, H., Black, J. and Matsuo, K. (2014). Disaster resilience in transportation: Japan earthquake and tsunami 2011. *International Journal of Disaster Resilience in the Built Environment. Vol 5 No. 4, Pp. 341-361.* doi: 10.1108/IJDRBE-12-2012-0039

Nguyen, K. V., & James, H. J. (2013). Measuring household resilience to floods: A case study in the Vietnamese Me-kong river del-ta. Ecology and Society 18(3): 13. 2013.

OECD. (2001). Performance Indicators for the Road Sector: Summary of the field tests. ITRD N°E 108267.

Peteresen, L, Fallou, L, Carreira, E., & Utkin, A. (2017a). Public tolerance levels of transportation resilience: a focus on the Oresund region within the IMPROVER Project. *Critical Information Infrastructures Security*, *12th International Conference, CRITIS 2017, Lucca, Italy, October 8-13, 2017, Revised Selected Papers*.

Petersen, L., Fallou, L., Reilly, P., & Serafinelli, E. (2017b). Exploring public expectations for aid from critical infrastructure operators. *Proceedings of the 52nd ESReDA Seminar Hosted by the Lithuanian Energy Institute & Vytautas Magnus University May 30-31, 2017, Kaunas, Lithuania, p. 68 – 81. EUR 28803, EN, Publications Office of the European Union, Luxembourg, 2017*, ISBN 978-92-79-73870-8. doi:10.2760/07157

Petersen, L., Fallou, L., Reilly, P., Serafinelli, E. (2018a). Public expectations of critical infrastructure operators in times of crisis. *Sustainable and Resilient Infrastructure*. doi: 10.1080/23789689.2018.1469358

Petersen, L., E. Lundin, J. Sjöström, D. Lange & R. Teixeira. (2018b). Creating comparable public tolerance and technical performance measures for critical infrastructure resilience evaluation. *Safety and Reliability – Safe Societies in a Changing World. Proceedings of ESREL 2018, June 17-21, 2018, Trondheim, Norway.* doi: 10.1201/9781351174664

Quarantelli E.L. (1998). Major criteria for judging disaster planning and managing and their applicability in developing societies. International Seminar on the Quality of Life and Environmental Risks held in Rio di Janeiro, Brazil.

Regional Australia Institute. (2013). From Recovery to Renewal: Case Study Reports. April, 2013. http://www.regionalaustralia.org.au/wp-content/uploads/2013/06/RAI-Natural-Disasters-Report-Case-Studies.pdf, last ac-cessed 21/04/2016

Schwarz, N., & Strack, F. (1999). Reports of subjective well-being: Judgemental processes and their methodological implications. in: Jones, L. and Tanner, T. (2015) Measuring 'subjective resilience' using people's perceptions to quantify house-hold resilience. Working paper 423. *Overseas Development Institute, London.*

Transport focus. (2017). National Road Users' Satisfaction Survey 2016-2017. https://www.transportfocus.org.uk/research-publications/publications/national-road-users-satisfaction-survey-2016-2017/

ANNEX

Table 1 Questionnaire results in number of respondents per answer.

Are you prepared for a long-term traffic jam (do you have emergency supplies stocked in your private vehicle)?				
Yes	32			
No	32			
I don't know	4			
How likely do you think it is that a heavy snowstorm will take place within the next year?				
Very likely	6			
Likely	12			
Neither likely nor unlikely	22			
Unlikely	18			
Very unlikely	10			
How likely do you think it is that serious damage will occur, affecting a bridge on the M1 highway within the next year?				
Very likely	4			
Likely	16			
Neither likely nor unlikely	14			
Unlikely	19			
Very unlikely	14			
Have you ever witnessed any disasters? A disaster would be an event that significantly affects the quality, quantity or availability of the transportation infrastructure				
Yes	33			
No	34			
I don't know	1			
After the serious damage to the bridge leading to the use of deviations, how much additional journey time are you willing to tolerate when using a personal vehicle or bus on the deviation route when travelling for…?				
	Commute to work	Leisure	Holidays	Business trip
Less than 20 minutes	37	10	12	34
20 to 29 minutes	16	25	21	17
30 to 44 minutes	7	18	14	6
45 to 59 minutes	1	6	12	3
More than 1 hour	1	6	5	3

After the serious damage to the bridge leading to the use of deviations, for your PRIMARY use of the highway, how long would you be willing to put up with an additional journey time of…?					
	< 15 additional minutes	15 - 29 additional minutes	30 - 44 additional minutes	45 – 59 additional minutes	> 1 additional hour
< 24 hours	7	7	8	19	28
1 - 2 days	2	9	13	10	12
3 - 4 days	8	11	10	9	5
5 - 6 days	3	4	7	7	2
1 week	9	9	5	7	5
2 weeks	6	5	9	2	2
2 weeks - 1 month	11	5	2	2	1
More than 1 month	14	10	3	4	2

After the M1 highway is no longer open due to snow, how much additional journey time are you willing to tolerate when using a personal vehicle on the deviation route when travelling for…?				
	Commute to work	Leisure	Holidays	Business trip
Less than 20 minutes	20	7	10	22
20 to 29 minutes	24	19	12	18
30 to 44 minutes	7	15	12	8
45 to 59 minutes	5	8	13	4
More than 1 hour	6	16	18	11

After the M1 highway is no longer open due to snow, for your PRIMARY use of the highway, how long would you be willing to put up with an additional journey time of…?					
	< 15 additional minutes	15 - 29 additional minutes	30 - 44 additional minutes	45 – 59 additional minutes	> 1 additional hour
Less than 1 hour	10	8	10	15	20
1 - 2 hours	6	12	11	10	9
6 - 12 hours	8	7	7	9	10
13 - 24 hours	3	6	7	9	5
2 - 3 days	9	10	9	4	5
4 - 6 days	0	6	6	2	1
More than 1 week	15	2	0	0	0