Rethinking transport
27–30 April 2020

TRA 2020 HELSINKI

Proceedings of 8th Transport Research Arena TRA 2020, April 27-30, 2020, Helsinki, Finland

Identification and prioritization of resilience measures for road infrastructures

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Abstract

This paper presents a methodology for the optimization of the response and recovery processes for an all hazard resilience management of road infrastructures after the occurrence of a disruptive event. The developed methodology enables road owners and operators to identify, assess and prioritize measures to improve the resilience of their infrastructures. A qualitative approach for measuring resilience is proposed, with a range of specific measures based on predefined resilience criteria and dimensions. The assessment process consists of a range of questions within each criterion, and to which scores are to be assigned. A practical handbook describing the developed methodology together with a simple software application is provided as a final output. The outcomes of this study help to achieve a more effective and efficient resilience management and action planning strategy.

Keywords: resilience management; resilience assessment; road infrastructure, disruptive events; impact assessment

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1. Introduction - Scope

Dealing with disruptive events is a major challenge for road infrastructure owners and operators. To maintain the functionality of the road infrastructure during disruptive events or to restore it as quickly as possible after such events, applicable concepts and methodologies are required, which enable a systematic assessment of the functionality of the road infrastructure. Based on that, adequate measures can be identified and prioritized e.g. based on their cost-effectiveness.

The aim of this research is to provide an application-oriented methodology on how to identify and prioritize measures which increase the resilience of road infrastructures. For the development of the methodology, based on an international literature and research project review, the most promising approaches for a resilience assessment and management in the context of road infrastructure management were taken into account. The suggested methodology is embedded into the context of a holistic resilience management concept. This concept describes the key elements of an iterative procedure, which must be run through for an effective and efficient resilience management. In order to establish the usability of the methodology, a handbook for resilience management and a software tool for practical implementation were developed.

1.1. Terms & Definition

Resilience can be described as the inherent capability of a system to absorb changes and disruptions of various kinds, to adapt to them and to retain its characteristic functionality. Resilience is therefore a system's characteristic and not a system state. In the present paper, the following definition of resilience is specified into account the definition in Scharte et al. (2014):

"Resilience is the ability to repel, prepare for, take into account, absorb, recover from and adapt ever more successfully to actual or potential disruptive events. Disruptive events are either catastrophes or processes of change with catastrophic outcome which can have human, technical or natural causes."

The resilience of a system can be assigned to five different sequential phases represented in the form of a resilience cycle in Fig. 1 according to Deublein et al. (2018) based on Thoma et al. (2014) .

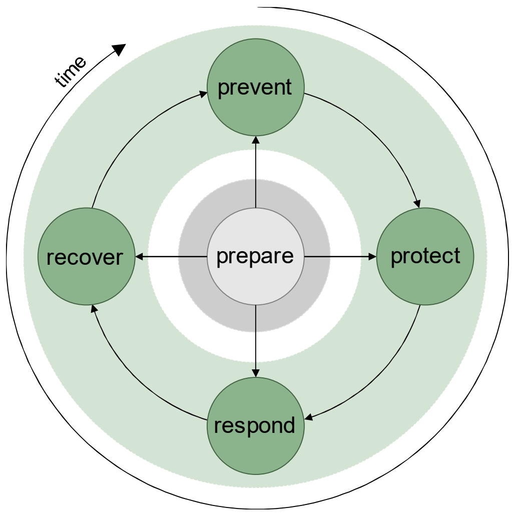

Fig. 1. Resilience cycle showing the five leverage points to increase the resilience of the system. Based on Thoma (2014), adapted by Deublein et al. (2018).

The first phase covers the preparation for disruptive events for example by implementing early warning systems (prepare). By reducing the underlying risk factors, the probability of occurrence of a disruptive event is decreased (prevent). If a disruptive event occurs, it is important that existing protective systems operate without defect and the negative impacts are minimised as far as possible (protect). By rapid, well-organized immediate measures, the extent of the damage resulting from the incident is reduced, and the functionality of the system retained as far as possible (respond). Finally, a resilient system is characterised by its ability to recover and adaptively learn from the event to be better equipped for future disruptive events (recover).

Resilience measures can be assigned to one of the five phases of the resilience cycle shown in Fig. 1. Measures of the phase prepare are temporally decoupled, their purpose is to increase the understanding of the system and thus only have an indirect effect on the system's resilience as they reinforce the impact of measures in the other phases. E.g. the knowledge gained by advanced weather forecast models (prepare-measure) can improve the emergency planning (respond-measure). Measures, which can be assigned to the phases prevent, protect, respond and recover unfold their effect in a chronological order.

Resilience measures are understood to be those technical, planning and organizational measures on the individual structure (e.g. bridge or tunnel) or for the entire infrastructural network that exceed the specifications of regulatory texts in force (standards, design, codes etc.) (e.g. use of high-performance concrete in bridges where only conventional types of concrete are actually specified in the standards for the planning situation).

The development of strategies to implement or reinforce the resilience of a road infrastructure is based on known concepts for the identification and protection of critical infrastructures, risk concepts and management as well as emergency planning. In this context, Tierney and Bruneau (2007) refer to the 4R factors for resilience: these comprise redundancy, robustness, resources provision and response time. On the basis of Fletcher et al. (2018), it is assumed that an increase in traffic system resilience can essentially be achieved using the following eight strategies shown in Table 1.

Table 1. Strategies to increase resilience according to Fletcher et al. (2018)

Strategy	Short Description
Addition of redundancy	The addition of redundancies increases the resilience of a system in the event of an incident e.g. traffic flows can be diverted via one or more alternative routes.
Provision of backup components	The resilience of a system is increased by the rapid deployment of available backup system components in the event of an incident.
Provision of possible replacements	The desired process of functionality can be transferred from one system component to another (e.g. road -> rail).
Reduction of vulnerabilities	Adaptations in the construction of structures to eliminate or reduce their vulnerability in the event of damaging incidents
Increased improvisation capabilities	Resilience depends on the capability of a system for spontaneous improvisation. Improvisation capability is understood to be the adaptation of a process to an impact in real time.
Priority access to important resources	The system has priority access to critical resources (e.g. fuel, water, manpower), in order to restore functionality as quickly as possible.
System modeling	System functionality and the dependencies of the system on other systems are modeled. Knowledge of dependencies aids risk assessment.
Logistical back-up solutions	In particular, this includes planning processes in order to be able to deploy backup solutions as quickly as possible when required.

2. Methodology

A resilience management concept for a practical implementation was developed to guarantee the resilience of a system on a long-term basis through a holistic understanding of the interaction of the individual components of the resilience analysis and to increase the resilience if necessary. The resilience management concept was developed based on the current state of research (Coconea et al., 2018; RESILENS, 2016; AllTraIn, 2015; Hughes et al., 2014). These steps are outlined in Fig. 2.

The resilience management concept describes the iterative/cyclical procedure, which must be run through for an effective and efficient resilience management. At the same time the resilience management concept serves as important orientation for a target-oriented implementation and application of organizational steps, to examine the resilience of a system and increase it if necessary, by suitable measures. Further, interfaces to other, already existing management systems are pointed out, to produce a common increase in value. This facilitates the coordination and the efficient identification and implementation of actions to improve the resilience. The developed methodology suggests three iterative steps in order to identify the most cost-efficient measures.

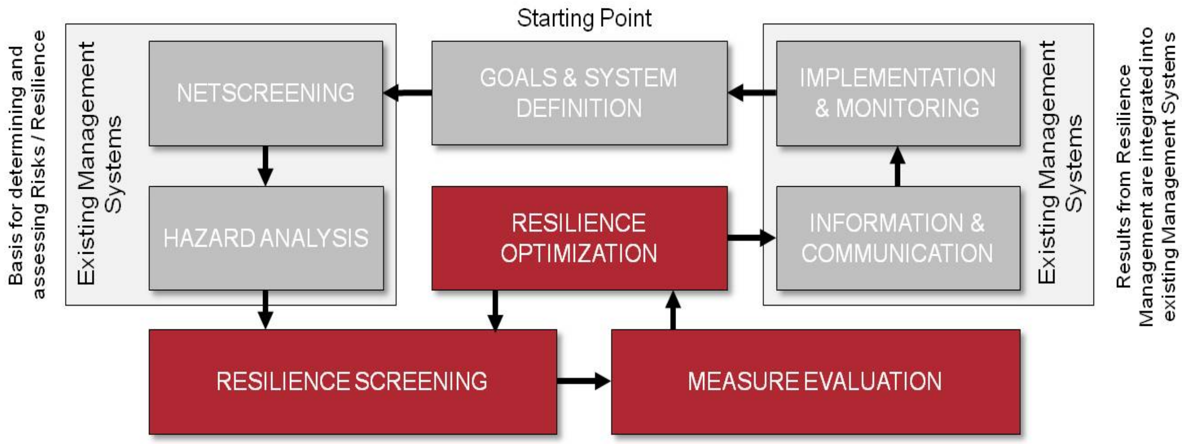

Fig. 2 Resilience management concept. The elements relevant for the proposed methodology are highlighted in red based on Deublein et al. (2018)

3. Results

Within the framework of this research, a methodology approach for the process elements: resilience screening, measure evaluation and resilience optimization is proposed. The proposed methodology consists of three steps (Fig. 3).

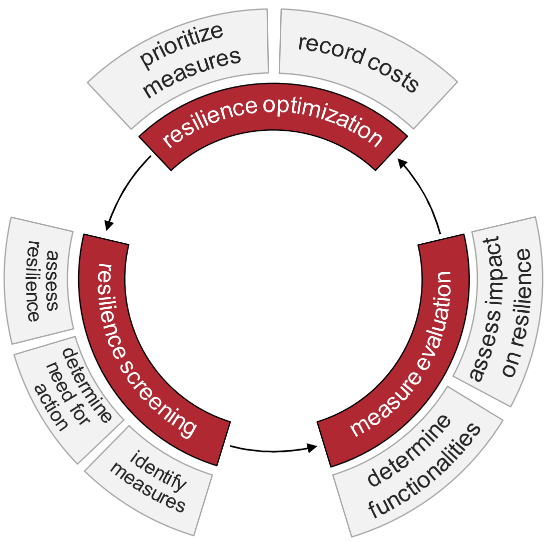

Fig. 3 Resilience management concept. The elements relevant for the proposed methodology are highlighted in red based on Deublein et al. (2018)

First, during the resilience screening (first step), the need for action is identified using a predefined set of checklist criteria. The result provides information to the decision makers about those fields of action, which show the highest potential for improvement. Based on that, explicit measures to improve the resilience are defined.

Second step, during the measure evaluation, the identified measures are assessed with respect to their impact on the system's resilience.

Finally, in the third step, the costs of the measures are recorded and set into relation to the (resilience) effectiveness of the methodology. Based on the cost-effectiveness, the measures can be prioritized. In the following, the single modules of the developed methodology will be described in detail.

3.1. Resilience screening

In the first step, a so-called resilience screening is conducted with the goal of examining the current state of the system with respect to its resilience. This step conduces to the identification of the need of action and thus to a limitation of the broad selection of potential resilience measures.

3.1.1. Resilience score

The first part of the resilience screening is the examination of the current resilience of the system based on a set of resilience criteria. The set of 17 criteria, which was predefined within the scope of this research, comprises organizational, financial, technical aspects. The criteria catalogues from a study in New Zealand (Hughes et al., 2014) and the European research project RESILENS (2016) were used as the basis for the development of the set of criteria.

It is the task of an expert group, consisting of infrastructure owner, operators and other stakeholders, to assign a numeric score (S) of resilience on a scale of 5 (very high level of resilience) to 0 (very low level of resilience) to each criterion, each dimension and the entire system using a predefined rating scale. Each individual score can be weighted.

3.1.2. Need of action and identification of potential resilience measures

Based on the aggregated score of the resilience score, the need for action (a) can be determined in a second step and the broad selection of potential measures for the later and more complex measure evaluation can be limited.

In order to determine the need for action, the resilience scores (S) are transformed into action-indices α according to Eq. (1), using weighting coefficients for the single criteria c_c and the dimensions c_d according to Deublein et al., (2019).

$$\alpha = \frac{100}{5}(5 - S)c_c c_d \tag{1}$$

A high action-index score indicates a high need for action. The user can define the field of actions based on the action-indices of the criteria or the dimensions. Additionally, the need for action depends on the predefined threshold for the minimal acceptable action-index α. If the action-index α of a criteria or dimension exceeds the predefined threshold value, appropriate measures are provided by the software tool.

3.1.3. Identification of potential resilience measures

According to Fig. 1, the resilience of a system can be increased in the different phases by resilience measures. These measures can relate to individual structures (e.g. bridges or tunnels) or to the entire road network (bridges and tunnels and stretches of road) or a specific region. In Table 2 are exemplary potential resilience measures listed and identified by type of measure (planning/organizational, technical).

Table 2. Type identification and description of resilience measures on object level (e.g. bridge or tunnel) according to resilience cycle and system definition based on Deublein et al. (2016)

Phase / Description	Planning/ Organizational	Technical
PREPARE Preparatory measures implemented before the occurrence of an unusual, damaging incident. They serve to anticipate the occurrence of damaging incidents and to prepare the system for possible effects. Example: "early warning system" for continuous risk assessment and preparation for possible disasters.	Structure-specific emergency plans, exercises, preparations etc. exceeding the standard that enable fast, effective/efficient structure-specific intervention in the event of an incident, e.g. emergency exercises for a specific bridge System-level monitoring enabling fast, effective/ efficient traffic management at system level in the event of an incident, e.g. water level monitoring as input for forecasting models	Structure monitoring enabling, in the event of an incident, fast and effective/efficient structure-specific intervention e.g. identification of hazardous goods in the tunnel by means of a camera.
PREVENT Measures that reduce the probability of the occurrence of an unusual, damaging incident. Potential hazards are identified at an early stage and the associated risk factors reduced and resilience factors increased.	Organizational, structure-specific measures that reduce the probability of occurrence of an adverse event e.g. securing of as-built documents for a bridge	Technical, structure-specific measures that reduce the probability of the occurrence of an adverse incident e.g. extension of freeboard, detection of over-heating vehicles, prevention of access to bridges.
PROTECT Measures that have a protective effect at the time of the incident and reduce negative impact on system functionality (incl. direct protection of persons affected at the time of the incident). E.g.: ensuring the full functionality of the protective systems.	Organizational, structure-specific measures that take on a protective effect during the incident, e.g. a tunnel firefighting force.	Technical measures on the structure that have a direct effect in the event of an incident which are implemented before the occurrence of the incident, e.g. high-performance concrete on bridges, automatic fire-fighting system in tunnels. Stronger or more (redundant) pump systems in underpasses
RESPOND Measures which take effect immediately after the incident and which are intended, in the event of an incident, to maintain the functionality of the entire system (incl. protection of people not as yet affected, rescue and first aid to persons affected). Example: fast and functional immediate emergency measures.	Planning/organizational measures that take effect immediately after occurrence of the incident in order to maintain system functionality, e.g. efficient deployment of emergency services teams/disaster assistance e.g. tunnel communication.	Technical measures that take effect immediately after the occurrence of the event in a structure-specific manner in order to maintain system functionality e.g. automatic blocking devices, shortened emergency exit intervals in tunnels, special automatic bridge emergency call system.
RECOVER Measures implemented after the occurrence of the incident in order to restore system functionality within the shortest possible time and to improve it by comparison with the initial state through learning processes and experience.	Planning/organizational measures on the structure that are implemented after the occurrence of the incident in order to restore system functionality as quickly as possible, e.g. accelerated processing of construction permits.	Technical measures on the structure that are implemented before or after the occurrence of the incident in order to restore system functionality as quickly as possible, e.g. temporary exchange of non-functional elements.

To support the identification of potential measures, a contingency table was developed which assigns a number of potential measures to each criterion. Based on the outcome of the examination of the criteria as well as other system-related boundary conditions, measures can be selected by the expert group, which are then in the next step assessed regarding their effect on the system's resilience.

3.2. Measure evaluation

The measure evaluation consists of the determination of the system's functionalities as well as the examination of the impact of each measure on the system's resilience.

Based on Bruneau et al. (2003), the loss of resilience can be described mathematically as follows:

$$Loss\ of\ Resilience\ = \int_{t_{event}}^{t_{recoverd}} F_{max} - F(t) \qquad (2)$$

To assess the measures regarding their effects on the system's resilience, the resilience of a system is regarded as the loss of functionality over time. The impact of a measure on the resilience is characterized by its effect on the total loss of functionality $\Delta F = F_{max} - F_{min}$ and its required time to recover after a disruptive event $\Delta t = t_{recovered} - t_{event}$ (Fig. 4). The smaller the maximal loss of functionality and the shorter the duration until the functionality of the system has recovered after a disruptive event, the higher the system's resilience.

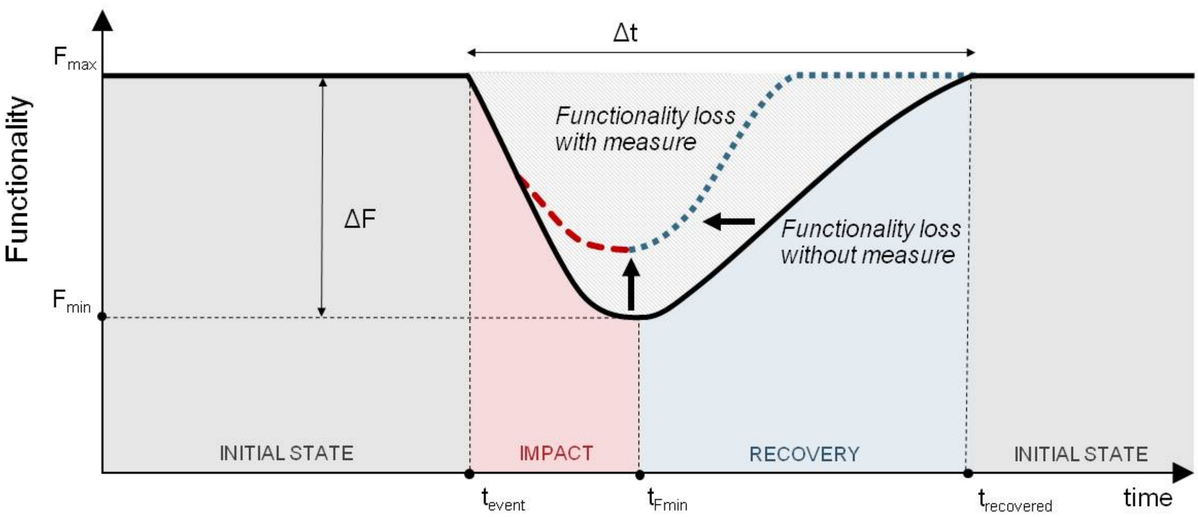

Fig. 4 Effect of the measures in the "respond" and "recover" phases on the functionality of the system - represented by black arrows

A measure decreases the maximal loss in functionality ΔF and the time until the system has recovered Δt. The quantification of the relative loss in ΔF and Δt due to a certain measure has to be estimated for each sub-functionality *f* and for each critical element in the system, which was identified during the netscreening as proposed in Figure 1. Different methodologies for the identification of the critical elements can be used based on Anastassiadou et al. (2016), AllTraIn (2015), Haardt et al. (2014).

The overall functionality of a system can be described by several sub-functionalities (Table 3). For a road infrastructure system these could be travel time, operational costs or pollutant emissions. Aim of the measure evaluation is to assess for each measure its impact on the loss of functionality and the duration until the functionality has recovered. This is done for each sub-functionality using a rating scale. The values for the loss of functionality and the duration of recovery are combined and aggregated over all sub-functionalities. The aggregated value represents the impact of each assessed measure on the system's resilience and thus the effectiveness of the measure.

Table 3. Exemplary sub-functionalities and their weight regarding the overall functionality for a road system. The weighting is based on BMVI (2016)

Funtionality	Sub-Functionality (*f*)	Weight (%)
Economical (70%)	Travel time	35
	Road network capacity	10
	Operating costs	15
	Separation effect on settlements	5
	Value added effects	35
Safety (20%)	Road safety	100
Ecological (10%)	Air pollutant emissions and greenhouse gas emissions	40
	Noise pollution	30
	Impairment due to constructure work	20
	Landscape (natural scenary)	10

3.3. Resilience optimization

For the prioritization of measures their effectiveness is set into relation to the costs. Therefore, the yearly costs of the measures must be estimated considering the investment and maintenance cost as well as the lifespan of the measure. In addition to the cost-effectiveness other criteria such as the implementation time or the realization probability can be considered. The final prioritization of the resilience measures includes the compilation of a ranking list by the expert group. The best evaluated measures or combinations of measures are those which, after careful consideration of the aspects described above, have the largest impact in terms of increasing the system's resilience. The suggested approach comprises the prioritization of individual measures which can be triggered subsequently or in combination.

4. Case study

In the conducted case study, the measure evaluation was tested for an exemplary and simplified study area shown in Fig. 5.

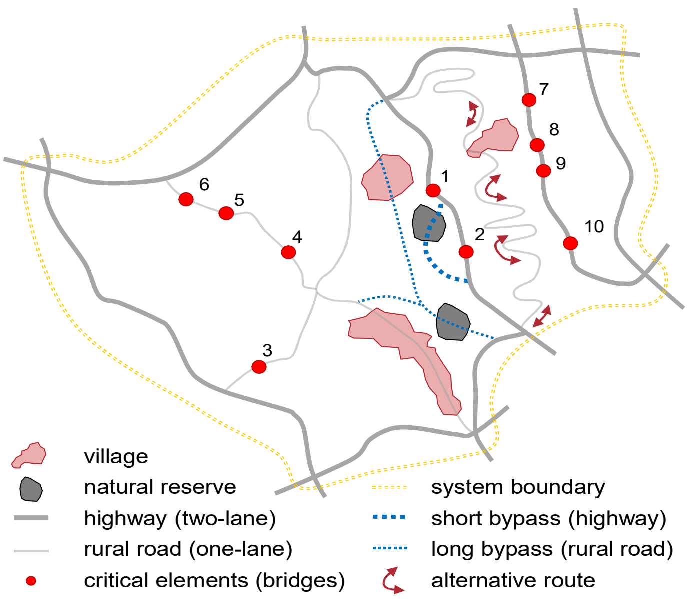

Fig. 5 Simplified study area. Existing of several highways and rural roads, three villages and two natural reserves. Ten critical bridges have been identified as critical elements. In case of a failure of element 1 or/and 2, most of the road users would use the marked alternative route.

To demonstrate the working principle of the measure evaluation, two exemplary measures have been assessed. A short, two-line bypass, surrounding the critical element 2 and a longer, one-line bypass surrounding the critical elements 1 and 2. For reasons of simplicity the functionality of the system is represented by only five sub-functionalities: travel time, road network capacity, operating cost, separation effects on settlements, and road safety. For each sub-functionality and each critical element, the impact of the measure on the loss in functionality ΔF and the time Δt until the system has recovered its full functionality is assessed. The impact of the measure on ΔF and Δt is separately assessed using a rating scale, ranging from +3 to -3. The two values are then combined into a single value.

Without the measures it is assumed, that the road user takes the alternative route marked in Fig. 5 in case of a failure of the critical element I or/and II. The alternative route is significantly longer than the original route. An implementation of measure m_I decreases the loss in travel time to nearly zero in case of a failure of element II, wherefore the measure is assigned 3 points for the decrease in the loss in functionality ΔF. However, the measure has no impact on the time Δt, until the critical element is restored. Also, it has no effect on the system in case of a failure of the critical element II or any other critical element in the system. An implementation of measure m_{II} has an effect in case of a failure of critical element I or/and II. However, although the loss in functionality is decreased, the travel time is still longer than without a failure of one of the critical elements. The measure m_{II} therefore gets assigned 2 points. Similar thoughts can be carried out for the other functionalities. The exemplary results are given in Table 4.

Table 4. Exemplary results for the study case. Impact of the measures on the sub-functionalities and the critical elements and total impact of the measures under consideration of the weighting factors suggested in Table 3.

Sub-functionality	Critical element	m_I	m_{II}
Travel time	I	0	2
	II	3	2
Road network capacity	I	0	2
	II	3	2
Operating costs	I	0	2
	II	3	2
Separation effect on settlements	I	0	2
	II	3	2
Road safety	I	0	2
	II	3	2
Total impact		**15**	**20**

Under consideration of the weighting factors the values for the single measures shown in Table 1 can be combined into one value, representing the total impact of the measure on the system's functionality (Table 5). To finally prioritize one of the measures, the annual costs as well as other considerations have to be taken into account, as described above.

5. Conclusions

Systemic consideration of resilience is currently a very broadly and intensively discussed subject in traffic infrastructure management internationally. However, a closer look reveals, that the topicality of this term refers primarily to scientific studies, whereas the term resilience has only rarely been encountered in the circle of potential users (e.g. traffic authorities, traffic management institutions). This does not mean that these user groups do not consider aspects of resilience in their daily work. On the contrary, many measures, procedures and management approaches in the sense of resilience are already being discussed and implemented today. New in this context is the striving for a systemic increase in value by an efficient, decision making with respect to the system's resilience. This is achieved by combining existing measures and approaches in a consistent resilience management, considering all stakeholders. The conceptual and methodological solutions of this research project will build a bridge between the scientifically very established state of research on technical and engineering resilience assessment in the application-oriented everyday life of infrastructure managers.

The developed methodology serves decision makers in road infrastructure management as an objective basis and support in the identification and prioritization of measures to increase system resilience. It enables an assessment and prioritization of measures regarding their impact on the system's resilience and contributes to establish a more efficient response and recovery process during and after disruptive events. The goal is based on the interest of road infrastructure operators to minimize the functional, temporal and thus financial consequences of disruptive effects on the system (triggered by disruptive events). It is important to intelligently combine existing methods and approaches for the consideration of disruptive events and to generate added value from them. To achieve this, the methodology is embedded in an overall concept of a resilience management. Thus, existing methodical approaches and management systems can be used, interfaces and connection points can be obtained and finally a higher resilience can be achieved. Last but not least, the generic concept of the methodology can also be applied to other critical infrastructure system such as the energy, and/or water sector.

Acknowledgements

This work is carried out within the framework of the BMVI Network of Experts "Knowledge – Ability – Action" (https://www.bmvi-expertennetzwerk.de) of the German Federal Ministry of Transport and Digital Infrastructure as part of the research project entitled: "Quantification and prognosis of the availability and safety of road infrastructure during extreme events", which is a component of the topic "Increasing the reliability of transport infrastructures" coordinated by the Federal Highway Research Institute (BASt).

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