State of the Art for the Evaluation of Resilience Measures

Fachveröffentlichung der
Bundesanstalt für Straßenwesen

German Federal Highway Research Institute, BASt

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22. November 2017

Report in the context of the BASt road infrastructure research program
FE 89.0320/2016

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Abstract

A significant challenge for decision-makers in infrastructure management consists in the assessment of the resilience of their infrastructural network (and the individual structures associated with it) as well as in the choice of suitable measures for ensuring or even increasing, where necessary, the strength of their network. Taking into account ever tightening resources in particular, it is essential, using suitable methods, only to implement those measures to increase resilience that are in a well-balanced ratio between the cost of the measures and the resulting benefits.

The objective of this research project consists in preparing a summary of the state of existing methods to assess the benefits and costs of measures to increase the resilience of road infrastructure. On this basis, it is intended to make recommendations on the selection of suitable procedures or methodical approaches. The current international state of application of resilience concepts in practical situations will then be demonstrated using case studies.

The studies are based on a comprehensive examination of literature in which both academic publications and technical reports, guidelines and standards have been analysed. A study of literature presents a critical reflection of the current international state of the art as regards methods for the assessment of resilience measures on structures and networks in the road traffic infrastructure.

Definition of resilience

Resilience refers to the ability of a system to be prepared for (potentially) damaging incidents, to factor them in, to avoid them, to overcome them and to recover from them as quickly as possible. Damaging incidents are unusual occurrences or processes of change caused by humans, technology or nature, having extreme or disastrous consequences.

Definition of resilience measures

Resilience measures are understood to include those structural, technical, planning and organisational measures on individual structures (e.g. bridges or tunnels) or the entire infrastructure network exceeding the specifications in the applicable regulatory texts (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). Resilience measures can be ascribed either to a structure or to an infrastructure network or a region.

Evaluation of resilience measures

The developed approach to the evaluation of resilience measures is based on established principles used, for example, in the context of risk analyses or in the evaluation of upgrade or new construction measures in traffic planning. The procedural steps have been adjusted as appropriate in line with the perspectives of structure- or network-specific resilience considerations. The following figure 1 outlines the procedure for assessing resilience measures.

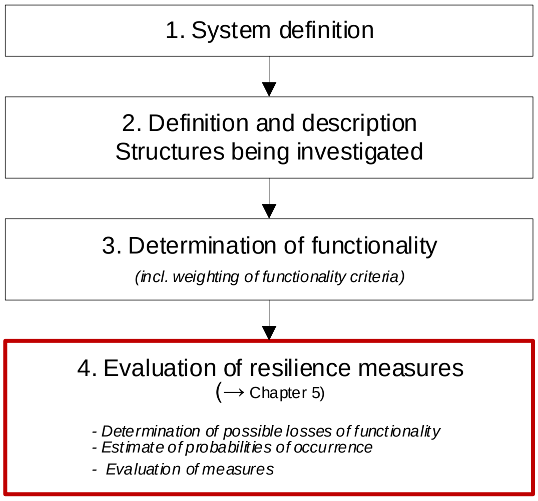

Figure 1: Flow chart showing the procedure for the assessment of resilience measures.

An international comparison reveals that, although there are some differences between individual countries, there are also significant similarities in methodical approach. A cost/benefit analysis is carried out most frequently and in many cases is supplemented with other criteria and expanded into a multicriteria analysis or a combination of cost/benefit analysis and multi-criteria analysis.

For resilience measures, the costs and effects – depending on the level of planning – should be estimated as accurately as possible. This applies to investments, reduced probabilities of damaging incidents, their impact on system functionality, the extent of the damage and how long the system takes to recover. Such estimates should enable the use of different evaluation methods at different levels of detail (down to the cost/benefit analysis). Where possible, uncertainties in assessment should be taken into account in the evaluation of the resilience measures. Where not all expected effects can be monetised, a comparative value/utility value or cost/effectiveness analysis can also be carried out. For a reliable evaluation of resilience measures, all three procedures should however then be used together. One finding of the investigations is, moreover, that the macroeconomic impact of measures in current projects and project specifications are not being taken into account in Germany.

Investigation of case studies

Using selected international case studies, the current state of application of the resilience concept in everyday infrastructure management practice will be shown.

In researching case studies, it became apparent that the concept of resilience is used today in many different academic disciplines. What, however, appears to be an accepted and established concept in academic theory is as yet however only seldom comprehensively used in everyday infrastructure management practice. Although evaluations of traffic measures are frequently carried out, they are not so much resilience measures, but have generally been created for new-construction and upgrade projects.

From the case studies analysed, it can be deduced, from a very general perspective, that the subject has already come to the attention of the decision-makers but its translation and implementation into the practical daily life of infrastructure managers is still very piecemeal and somewhat rare, and even then, it is hardly ever documented.

Recommendations

For the selection of suitable procedures and methods for the evaluation of resilience measures, it is recommended that the resilience concept as described in this report should be integrated into existing procedures rather than various new evaluation procedures being developed.

One innovative approach to resilience management that should take place in a first pragmatic step might take the form of a two-step process:

1) Net screening on a superordinate level (with analysis of low-level detail) to identify weak points in the system. The following questions should be examined: what elements of a system should be assessed as being particularly critical (criticality)? Where is there increased need for resilience due to a potential risk situation?

2) With the knowledge of the critical elements in the system (results from step 1, Net screening) specific, in-depth, more complex resilience analyses should be carried out at structure level. The decisive issues here are: where and to what extent is it worth investing in resilience? What system elements and damaging incidents should fall within the scope of the analysis? What are actually the most important functional components (to be evaluated)?

Future resilience management still to be established can be based on the evaluation procedures described. The scope of the determination of effectiveness increases in terms of inherent complexity and expense according to the extent of the resilience measure. Due to the time-consuming nature of monetising the individual components of system functionality, it is recommended only to resort to cost/benefits analysis evaluation methods in the case of rather more extensive (expensive) resilience measures. Evaluation of resilience measures with low cost consequences is also possible as an alternative, using the other methods (individually or preferably in combination).

Not least, a unified understanding of the concept and the use of standardised terminology is recommended: all those involved in infrastructure management should use the same terms with the same understanding of them in discussion of resilience measures. This report will lay the foundations for this.

Content

1 Introduction

1.1 Initial situation

Safeguarding the resilience of infrastructure in the event of damaging incidents caused naturally or by humans is increasingly important for infrastructure operators. It should be ensured, by suitable structural, technical or organisational measures, that the occurrence of the incident is avoided as far as possible or, in the event of an incident occurring, the availability and functionality of the infrastructure network affected remains intact for all user groups while the consequences of the incident are mitigated and the functionality of the system restored as quickly as possible.

One important challenge for decision-makers consists in the assessment of the resilience of their infrastructure network (and its associated individual structures) and in the choice of suitable measures to ensure the resilience of their network or, where needed even to increase it. Taking into account ever tightening resources in particular, it is essential, using suitable methods, only to implement those measures to increase resilience that are in a well-balanced ratio between the cost of the measures and the benefits thereby created.

The subject of resilience is an important part of the long-term strategic focus of the research plans of the Federal Highways Research Institute (BASt).

1.2 The problems

As a starting point for in-depth future studies by BASt, this study will present the current state of research into the evaluation of resilience measures. In this work, depending on specific criteria, it is intended to verify what procedures for the evaluation of resilience measures are best suited to improving resilience in what situations and when.

The objective of this research project consists in the preparation of an overview of the current situation regarding methods for the assessment of costs and benefits of measures to increase the resilience of road infrastructure. Based on this, it is intended to make recommendations on the choice of suitable procedures and methodical approaches.

It is intended then to demonstrate the current international state of application of resilience concepts in practice using case studies.

1.3 Procedure

An investigation of the state of the art with respect to the evaluation of resilience measures is broken down into the following five main questions (Figure 2).

1. What does resilience mean?
2. What are resilience measures?
3. What procedure is suitable for the evaluation of resilience measures?
4. What methods are suitable for the evaluation of resilience measures?
5. Are there application examples?

Figure 2: Main questions in project handling

“Resilience” is a modern term that has many uses, not only in infrastructure management but also (and in particular) in many other disciplines. The objective of the first main question, therefore, consists in deriving from the existing multitude of definitions for resilience, one definition that is relevant and appropriate for the infrastructure management of road traffic systems.
A coherent definition of resilience measures can be derived on the basis of a consolidated understanding of the processes behind the term resilience. These measures are assigned to type categories in the context of the definition of resilience.

One central element of the investigations is ultimately to answer the main question as what procedure is most suited to the evaluation of resilience measures. In the context of these investigations, the most important part of the procedure for evaluating resilience measures is the selection and description of efficient methods for evaluation of the measures. Due to the extent and the significance of this 4th main question, the approaches to evaluation of resilience measures will be described in a separate chapter.
A selection of case studies is intended to indicate whether and how the theoretical considerations in the evaluation of resilience measures come to be used in current practice. To this end, selected studies are analysed, and suitable case studies identified and documented in summary using fact sheets. In the conclusion of the investigations, on the basis of the results of the above set of questions, recommendations are derived for the BASt, in order to be able to use methodical approaches to carrying out evaluations of resilience measures efficiently.

The studies are based on a comprehensive examination of literature in which both academic publications and technical reports, guidelines and standards have been analysed. A study of literature represents a critical reflection of the current international state of the art as regards methods for the assessment of resilience measures on structures and networks in the road traffic infra-structure. With the objective of creating an overview of the methodical approaches to the evaluation of measures most relevant to the BASt questions, the research into literature addresses in particular the question as to what methods of evaluation there are for resilience measures and what evaluation criteria are used.

The following chapters are organised in line with the main questions set out in Figure 2.

2 Resilience

2.1 Definition

Resilience can be simply 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 characteristic and not a system state [1]. It is greater, the better unusual damaging incidents can be overcome, disruptive impacts on the system anticipated and adaptive learning effects gained for the system [1]–[32].

In these investigations, the following definition of resilience is specified with the supporting experts from the BASt taking into account the definitions in [2] and [3]:

“Resilience is the ability of a system to be prepared for actual or potential damaging incidents, to factor them in, to avoid them, to overcome them and to recover from them as quickly as possible. Damaging incidents are unusual occurrences or processes of change caused by humans, technology or nature, having extreme or disastrous consequences.”

The resilience of a system can be assigned to five different sequential phases represented in the form of a resilience cycle in Figure 3 [1]:
The first phase covers preparation for the unusual damaging incidents for example by fitting early warning systems (prepare). By reducing the underlying risk factors, the occurrence of one or more incidents should also be avoided (prevent).

Figure 3: Resilience cycle in line with [1]

If an unusual damaging incident should nevertheless occur, it is important that existing protective systems operate without defect and the negative impacts are minimised as far as possible (protect). By rapid, well-organised 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 also characterised primarily by the fact that it is able to recover and adaptively gain a learning effect from the event in order to be better armed for future incidents (recover).

Development of resilience

The definition and application of the term resilience was originally used in psychology and reflected the ability of people to recover after an illness or other setbacks. Based on the Latin origin of the word resilience (*resiliere* = in the sense of a rebound or jumping back), a common core exists between the various academic disciplines that use this term: this relates to the successful handling by a system of a disruption or impact (a “shock” in the event of a damaging incident), in particular due to adaptive capabilities or opportunities to reduce vulnerability [11]. The disruptions are triggered by unusual damaging incidents and lead to direct and indirect consequences. The totality of the consequences is understood in general to be the extent of the damage to be expected as a result of an event. In the context of the resilience considerations here, the extent of the damage is represented by the loss of functionality of the system under consideration.

Discussions and definitions concerning the term resilience in the context of disaster management, the protection of critical infrastructure and social systems is often fundamentally linked to the manner in which a system reacts to one or more unusual damaging incidents and how this can be prepared for [24].

Damaging incidents are, for example, natural disasters caused by climate change, terrorist attacks or severe industrial accidents. Such events and their results (synonymous with the extent of the damage, consequences) represent serious threats to individual systems and modern societies. At the same time, rising complexity and increasing networking in society ensure that some systems are becoming more susceptible to what are known as “cascade effects”. As a consequence, (not only technical) systems should be designed to be as resilient as possible in order to enable societies and their relevant subsystems to minimise the damage caused by destructive events.

Resilience nowadays is considered to be a comprehensive, holistic problem-solving approach whose objective is to increase the general resistance and regeneration capability of (technical) systems. Here, it does not matter whether the threatened damaging incidents are already known of or are completely new and occur unexpectedly. Prevention and anticipation are therefore seen as essential components of resilience [31]. Resilience may also be understood to be the extent of adverse effects that a system can withstand, without transitioning into a different state of stability [1]. The central element of the resilience concept therefore is the capability of a system to self-rehabilitate, or, more precisely, to independently adapt and repair itself in the period after an event which affects it [33] [32].

Searching for a suitable definition of resilience, terms that are also closely associated with resilience, such as risk, vulnerability, robustness and criticality, are also often referred to nowadays. In order to be able to define the resilience concept in the context of infrastructure management in a traceable manner, it would seem important here to make a rational distinction between concepts sometimes closely related, and to present the overriding context.

Integration into the risk concept

Resilience considerations fit neatly into the systemic risk concept shown in Figure 4. **Risks** are understood to be events that have an impact on a system which occur with a certain degree of probability (W) and in the event of their occurrence, can lead to a disruption of the system and failure of system components or of the entire system (consequences, extent of damage (A)). From a mathematical point of view, risk (R) is defined as the product of probability of occurrence and the degree of damage to be expected [35] [34] [36], [37]:

$R = W \times A$ {Formula 1}

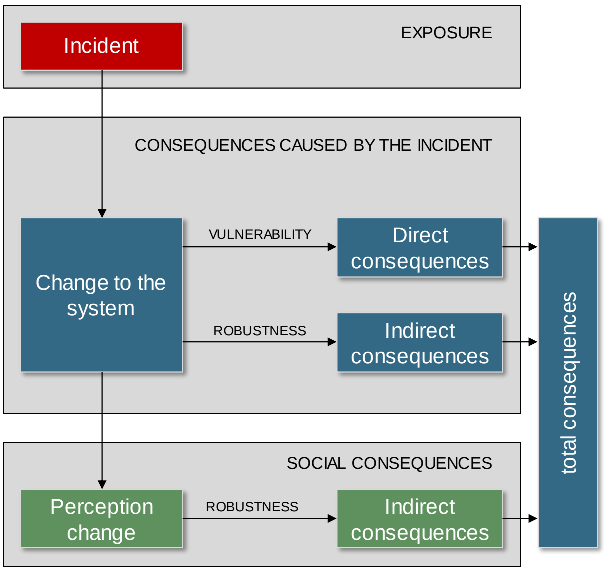

Figure 4: Representation of relations between an incident and its consequences according to [34].

Uncertainties in the assumptions, both for the probability of occurrence of certain events and for the extent of the damage to be expected, can be quantified using probability methods and taken into account in decision making [38].

With respect to Figure 4, it is assumed that every system is exposed to different short and long-term events. This is referred to as the exposure of the system. The events have an impact on the system and can lead to changes in system stability. This means that direct or indirect consequences are caused within the system.

In this connection, the term **vulnerability** describes the direct consequences (or damage) that occur due to the impact of an event on an individual system component. For example, the failure of a cable (=system component) of a suspension bridge (=system) due to strong winds (=event). The vulnerability of the bridge as a system is therefore defined using the failure probability of the system components. The vulnerability of the system can be quantified according to [34] as the proportion of the risks due to direct consequences on the overall value of the infrastructure system under consideration. All relevant exposure values within a defined period must be taken into account[1].

Measures for reducing the vulnerability of a system rely, by strengthening individual system components (on the principle of the weakest link in the

1 In some publications, the terms robustness and vulnerability are defined as complementary concepts (see for example [6]). In the context of structural engineering and (technical) infrastructure management, the authors of this study follow the definitions in the context of the risk concept in accordance with [34].

chain), on reducing their probability of failure and the direct consequences in the event of occurrence. [5], [21].

Robustness describes the capability of a system to withstand failures of individual system components without any loss of system functionality. Figure 5 shows the robustness of a system on the basis of the reciprocal value of absolute functionality loss at the time of impact (grey area). The greater the loss of functionality at the time of impact and shortly afterwards, the lower the robustness of a system.

Robustness is represented by the indirect consequences; with two different kinds of manifestation:
a) On the one hand, these are the aftermath of the direct consequences within the system after the impact of an incident. This means that robustness refers to the response of the system as a whole to the failure of one or more individual system components. If this consequential response is slight, the system can be designated as robust. An example of a robust system: the suspension bridge in the aforementioned example is constructed in such a way that failure of an individual cable will not entail the failure of the entire bridge.

b) The robustness of a system is reflected, however, also in the indirect consequences of a system change on society. This refers to those impacts the system change has on the functionality of the system in the social context. For example, it might be asked: will the functionality of the bridge be restricted by the failure of one suspension bridge cable? Can only a reduced volume of traffic now travel across the bridge, and will the consequences arising from this be expensive hold-ups and delays for professional and logistics traffic? Robustness can be quantified as the ratio of direct risks and the overall risks of the system. Within a defined period, all exposure variables (possible events) and the different potential states of damage to the system components must be taken into account [34].

With its proactive cyclical and holistic characteristic, the **consideration of resilience** extends beyond the conventional risk concept described previously. It includes the ability of a system also to survive the impact of as yet unknown, complex, unsafe, changing future incidents, and even to derive benefit from such for future system functionality [39] [40]. By contrast with resilience, the concept of robustness does not cover the capability to reorganise after an incident, but is rather seen as a static attribute of the system [1], [11]. The resilience concept opens up a new, previously little-discussed scope for action in decision-making. Resilience refers in particular to preparing for the consequences of damaging incidents which are not always known, keeping reduced functionality to a minimum and the recovery period as short as possible.

In relation to works of civil engineering, common exposure variables and their supposed impact on the system are covered by appropriate specifications for design or safety factors in the relevant standards and design codes. The probabilities of occurrence and the extent of the damage can be estimated (taking into account uncertainties). Damaging incidents that exceed the standard considerations will be affected by the concepts of robustness and resilience.

In connection with the “National strategy for the protection of critical infrastructures (KRITIS strategy)” of the Federal Ministry for the Interior, the traffic and transport infrastructure (in addition to energy supply, information and communication technology and drinking water supply and sewage system) is considered to be in particular need of protection [41]. Traffic infrastructure, due to its structural, functional and technical positioning in the overall system of society, has what is known as **systemic criticality**.

This refers in general to the relative degree for the significance of an infrastructure in relation to the consequences that a disruption or loss of functionality has for the security of supply to society with important goods and services [41].

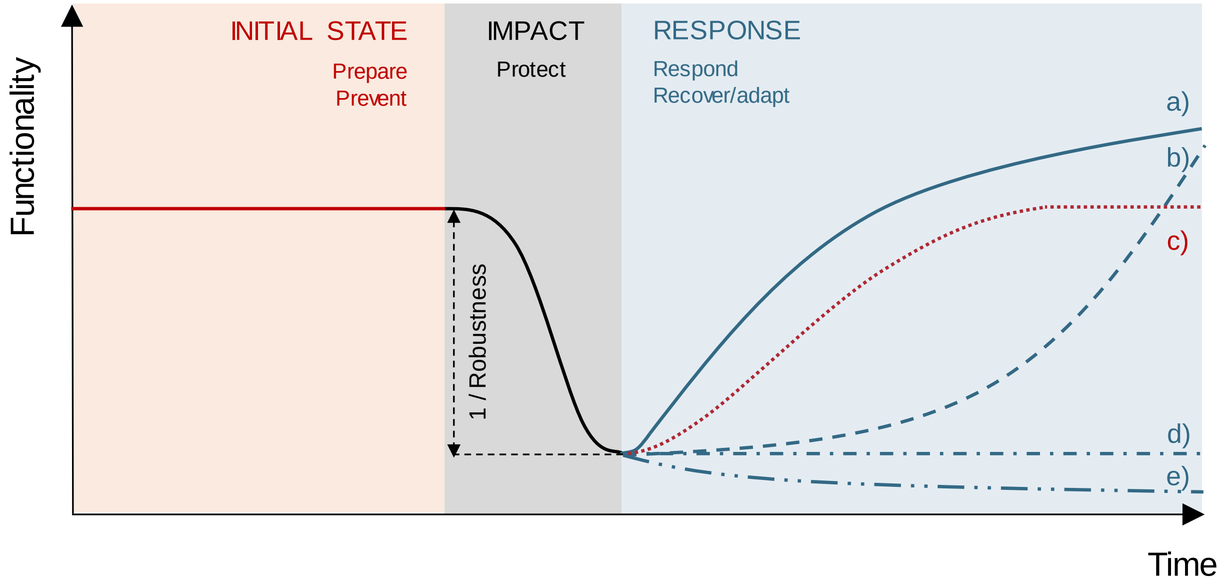

Figure 5: Initial state and response of a more (curve a, b and c) or less (curve d or e) resilient system before and after an impact on the system by one or more incidents (in accordance with [24]);

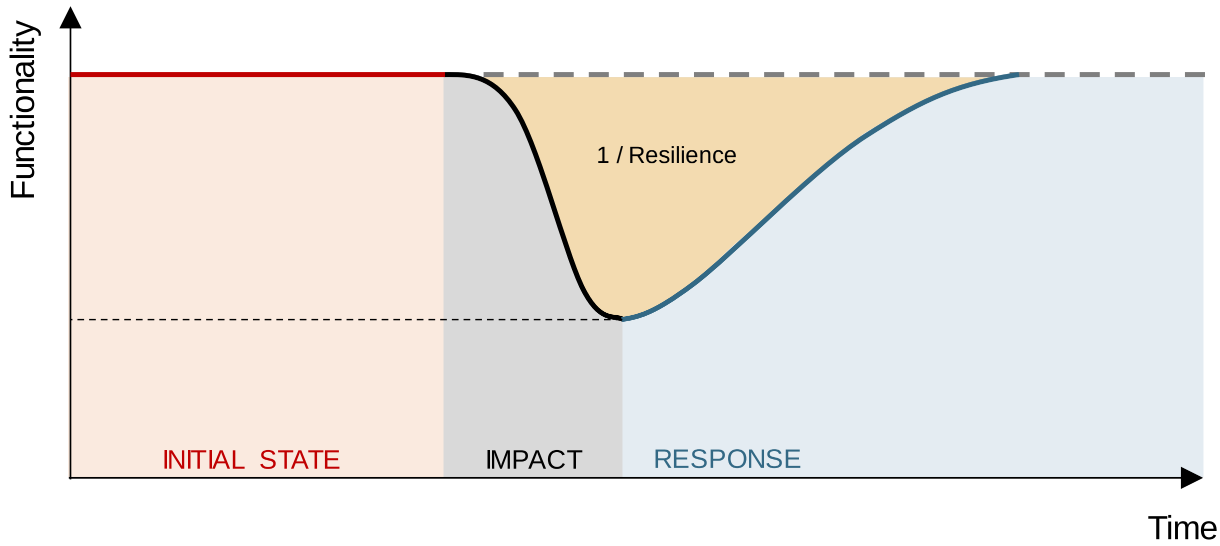

Figure 6: Determination of resilience as the integral over the area of functionality loss over time until restoration of complete functionality in accordance with [42].

An infrastructure in particular has systemic criticality if, due to its structural, functional and technical positioning in the overall system of the infrastructure areas, it is of particularly high interdependent relevance [41], [43], [44], [45]. For example, an individual bridge in the event of its failure can cause a very great regional loss of functionality of the “regional road network” system as lengthy journey times or delays in industrial logistics chains occur for users. A structure within the infrastructure is considered to be critical if the consequences caused by an incident to be expected with a certain probability (e.g. economic costs of a loss of functionality) exceed a predetermined limit for a risk acceptable from the point of view of infrastructure operators and/or policy or society.

Resilience in traffic infrastructure management

The representation of functionality of the road system over time is suitable for a description of resilience in the (road) infrastructure management before, during and after a “shock”-type impact from an unusual damaging incident. The functionality of the system can include very different elements. In the context of system definition, it must be specified how the functionality of the system is to be defined (e.g. capacity, safety, travel time etc.). Under normal conditions, according to Figure 5, the system is in a more or less stable initial state; the necessary functionality of the system is ensured. In order to maintain functionality as far as possible even during the impact from a damaging event or to minimise the impact as far as possible, preparatory and preventive measures may be taken, aiming at resilience of the system. Nevertheless, the system may suffer a loss of functionality.

Measures to directly protect the system at the time of a damaging incident contribute to such a loss of functionality being minimised. The short-term and medium-term response of the system after a damaging event indicates the level of resilience with which the system will actually respond to the impact. The time-specific component plays a decisive role here. Rapid recovery (from the impact of the shock) with regeneration to the original level (curve c in Figure 5) of functionality or even above that (curves a or b) in as short a space of time as possible reflects a high level of resilience. Although curve b) regains the original level of functionality, it takes a significantly longer period to do so – the resilience of a system with this functionality curve is significantly lower than a). Systems can be designated as not resilient if their functionality curves correlate to functions d) and e) in Figure 5.

Resilience describes the phased preparation and response of a system to disruptive influences due to damaging incidents. This results, for the determination of resilience in a system inevitably also in the need for the specification of a period within which the consequences of a disruption are investigated. This period must be sufficient in order also to take longer-term adaptation processes into account; otherwise, there is the risk that the assessment of resilience is restricted to a somewhat short-term consideration of impact or resistance [11]. On the other hand, long periods of consideration, by increasing the number of disruption factors, also increase the complexity of the resilience consideration. Comparison with a reference situation becomes increasingly difficult when the consideration periods are long.

2.2 Determination of resilience

The wide range of approaches to the determination or measurement of resilience is comparable with the number of different definitions of the term resilience. Building on the graphic definition in Figure 5 and in line with the approach to the quantification of resilience of the *US Department for Homeland Security* [28], determination or quantification of resilience has been represented as shown in Figure 6. Starting from the initial position with 100% system functionality, therefore, resilience can be represented and calculated as the area between the 100% functionality line (grey, dashed line) and the functionality line during and after the impact by a damaging incident until the recurrence of the initial state (yellow area). To simplify, it is assumed here that the functionality of the system is “only” regenerated up to the 100% line. According to curves a) and b) in Figure 5, however, the achievement of higher functionality subsequent to the impact is also feasible due to adaption and learning effects. The level of functionality loss depends on the robustness of the system. Expressed mathematically, this is the reciprocal integral of the functionality curve over time. Reciprocal because the greater the yellow area, the lower the resilience of a system [28].

3 Resilience measures

3.1 Definition

Resilience measures are understood to be those structural, technical, planning and organisational 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)[2].

The development of strategies to implement or reinforce the resilience of a traffic network is based on known concepts for the identification and protection of critical infrastructures, risk concepts and management as well as emergency planning in disaster prevention. In this context, Tierney and Bruneau (2007) refer to the 4R factors for resilience: these comprise redundancy, robustness, resources provision and response time [46].

On the basis of [14], it is assumed that an increase in traffic system resilience can essentially be achieved using the following eight strategies shown in Figure 7.

2 From the holistic perspective of a (social) resilience consideration, theoretically measures to improve human behaviour in extreme situations can also contribute to improving resilience and to the direct protection of the users of the infrastructure [11]. The focus of this study however is exclusively on technical, planning and organisational measures. For reasons of scope, there will be no presentation of educational measures in the context of this study.

3.2 Overview and type identification

According to Figure 3, the resilience of a system can be increased in the difference 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.

Strategy	Explanation
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 modelling	System functionality and the dependencies of the system on other systems are modelled. 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.

Figure 7: Strategies to increase resilience [14]

Phase	Description	STRUCTURE *(bridge/tunnel)*		NETWORK / REGION	
		Technical	Planning/Organisational	Technical	Planning/Organisational
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 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	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 and early warning systems	Emergency plans, rescue practices, preparations etc. that enable fast, effective/efficient traffic management at system level in the event of an incident, e.g. clarification of roles and responsibilities, preparation of emergency management plans, identification of structure criticality
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	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	Organisational, structure-specific measures that reduce the probability of occurrence of an adverse event e.g. securing of as-built documents for a bridge	*No measures can be assigned to this combination*	Organisational, network-wide measures that reduce the probability of occurrence of adverse incidents, e.g. regional travel prohibitions, ensuring compliance of all structures with existing standards, avoidance of cascade effects
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.	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	Organisational, structure-specific measures that take on a protective effect during the incident, e.g. a tunnel firefighting force	Technical measures at network level implemented before the occurrence of the incident and which have a direct effect in the event of an incident, e.g. technical preparation of flood corridors or overflows with buffer zones	Organisational measures at network level that are implemented before the occurrence of the incident and which have a direct effect in the event of an incident, e.g. regular inspections of the structures; compliance with specifications; avoidance of cascade effects and dependencies (indirect consequences)
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.	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.	Planning/organisational 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 at system level implemented before the occurrence of an incident and which take effect immediately after the occurrence of the incident in order to maintain system functionality, e.g. network redundancy (alternative traffic routes and means of transport). Interfaces with other systems	Planning/organisational measures at system level implemented before the occurrence of the incident and which take effect immediately after the incident in order to maintain system functionality, e.g. networking of the different assistance organisations/bodies responsible
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	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.	Planning/organisational 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 at system level implemented after the occurrence of the incident in order to restore network-wide system functionality as quickly as possible, e.g. making available a new route e.g. upgrading of a track not previously accessible to traffic, construction of an alternative road, "floating bridge"	Planning/organisational measures at system level implemented after the occurrence of the incident in order to restore network-wide system functionality as quickly as possible, e.g. indication of alternative route, effective damage assessment

Figure 8: Type identification and description of resilience measures according to resilience cycle and system definition

The use of different methods is determined by the fact that, depending on the characteristics of a measure (or of a project), various requirements may be made of the evaluation method. To categorise the methods, therefore, in advance, potential resilience measures are brought together and identified by type. Type identification of resilience measures in Figure 8 takes into account both the time-related aspect of resilience definition (see also Figure 3 of the resilience cycle) as well as the principle of the aforementioned system differentiation.

4 Procedure for the evaluation of resilience measures

The procedure for the evaluation of resilience measures is based on pre-established principles as applied, for example, in the context of risk analyses or in the evaluation of (upgrade and new construction) measures in traffic planning (e.g. in accordance with the BVWP) [47]–[50]. The procedural steps in Figure 9 are modified as appropriate to take into account the perspective of structure or network-specific resilience considerations.

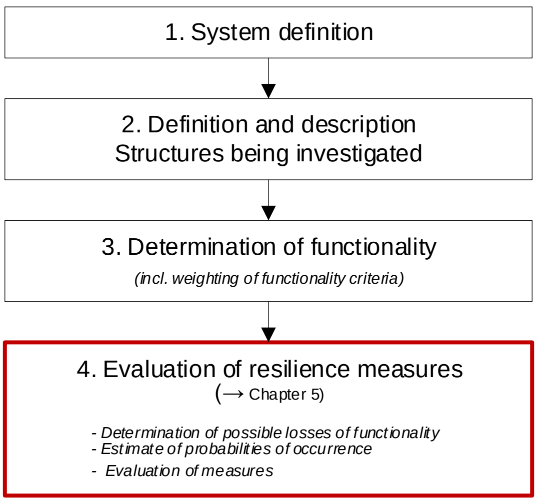

Figure 9: Principle of the evaluation procedure; Procedural step 4 is explained separately in Chapter 5.

According to Figure 9, the procedure for the evaluation of resilience measures comprises as the first step a system definition to specify the scope in terms of space, time and content of the considerations and assessment. On the basis of subsequent description and definition of the structures to be investigated, it is determined what type of structures are to be included in the resilience assessment with what relevance and/or criticality (see definition in Section 2.1) for the entire network. Specification of functionality in step 3 includes selecting criteria mapping the functionality of a system. The results of the first three procedural steps form the basis for the actual evaluation of resilience measures in procedural step 4. Here, using specific methodical approaches a (quantitative) evaluation of measures to ensure system functionality or to reduce negative event-specific impacts on the functionality of the system is made.

In the following chapters, the individual steps in the procedure for the evaluation of resilience measures in Figure 9 are explained.

4.1 System classification

One important first step consists in system classification suitable for the structure or infrastructure network to be analysed.

In order to discover the context in which the analysis of the structures to be investigated should take place, the constraints of the investigation in terms of space, time and content must be determined. Regarding resilience measures, the following points are to be taken into account in system classification:

Space constraints:

- Project perimeter: This normally refers to the area within which the measure will be implemented (e.g. measure on the individual structure or for the entire network).
- Impact perimeter: corresponding to an evaluation of new and upgrade measures, the perimeter must be chosen at least to correspond to that in which the resilience measures have an effect (e.g. in the form of a change in traffic volumes).

Time constraints:

- Resilience by definition takes into account a dynamic change in a system: due to a specific damaging incident, a (negative) impact /disruption to the functionality of a system takes place. After a particular period of time, the functionality of the system recovers once more and may exceed its original functionality due to adaptation. A measure influences this dynamic aspect. The evaluation must take into account the different trends in this time characteristic.

Content constraints:

- In the context of the content-based system constraints, among other things it must be determined to what structure or network types the resilience analysis is to relate. This also includes the question as to what damaging incidents are to be taken into account in the resilience analysis.

4.2 Definition and description of the structures to be investigated

The evaluation of resilience measures is based on a comparison between an initial or reference case and a planned case (several variants are possible). The reference case corresponds to the state of a system without the resilience measure to be evaluated. For the planned case – i.e. the condition of the system with the resilience measure implemented – the extent of the impact of the resilience measures to be evaluated on the probability and intensity of impact and the regeneration of the system after the impact must then be demonstrated by comparison with the reference case. Moreover, the expenditure (as a rule represented as costs) of the resilience measure must be clarified and demonstrated.

4.3 Functionality mapping

When the structures to be investigated have been determined, the components in respect of which the evaluation of the resilience measures is to take place must be defined. The totality of the components specified represents the functionality of the system (as a model).

An obvious solution in the context of road traffic infrastructures, for example, is to represent the functionality of a system (structure or network) simply using the availability of a certain traffic capacity. This one-dimensional functionality component, however, can be expanded into a multidimensional combination using other components.

In order to demonstrate the range of possible components to map the functionality of a system, the following (non-exhaustive) list documents possible components:

- Traffic capacity
- Intensity of injury to users
- Travel time
- Travel comfort
- Environmental pollution (e.g. CO_2 emissions)
- Economic losses/ gross domestic product

The objective of the evaluation of resilience measures lies in comparing expenditure (usually represented as costs) and effects of measures. This can only be successful if the effect of measures can be determined qualitatively (e.g. in the case of a utility values analysis) or quantitatively as a value comparable with the costs of the measures (e.g. cost/benefit analyses).

The increased resilience of the system is understood to be an effect of the measure; i.e. the impact of the functionality curve trend and the associated area size according to Figure 6. The change in the functionality curve in turn causes a change in one or more components used to map system functionality (e.g. increase in travel time in the event of an incident).

For each planned case (with resilience measure) and for the reference case, the effects on individual functionality components are to be forecast

This forecast can have various levels of detailed processing:

- Detailed quantification on the basis of models, forecasts and calculations (e.g. with traffic models)
- Estimate of impact
- Simple scoring system, e.g. with a points grading system (e.g. the measure should have a minor/medium/major effect). The extent of the impact can also be taken into account (high, medium low with the number of persons affected (many, few affected).

For the evaluation of resilience measures, it is important to be able to take into account the probability of an unusual damaging incident occurring, the consequential extent of the damage and the duration of recovery of the system to the initial level (or exceeding it). In estimating probabilities of occurrence, the extent of the damage to be expected and the time the system is expected to take to recover, additional uncertainties in the estimations can be represented using a probability calculation approach and taken into account in the decision-making. At the same time, this representation of uncertainties also serves strategic information gathering for example about individual uncertainties, where needed, by obtaining additional information (data, questionnaires, modelling).

The macroeconomic effects of resilience measures often play a central role. In common evaluation procedures (see Chapter 5.1), these are mapped using travel time savings and transport cost reductions for transport users. Monetised personal damages, medical costs, loss of earnings etc. are taken into account as standard to the same extent as impact on the environment. Figure 10 below, for example, shows the benefits and cost components of BVWP 2030 for the macroeconomic evaluation of measures. The following classification of effects has arisen in practical evaluations :

- direct effects of a measure (construction, maintenance, operation)
- direct – internal – effects of the measure (usually to transport users such as changes in travel times and operating costs of vehicles)
- Change in external effects due to the measure: effects on the natural environment or traffic safety.
- Indirect effect of the measure: e.g. productivity and employment effects due to better access to sales and procurement markets)

All represented components are monetised in BVWP 2030. Monetisation of the impact of measures enables direct comparison of the costs and benefits of measures (e.g. costs/benefits ratio in the context of a benefits/costs analysis). For evaluation methods to be explained later, differentiation is useful in the following monetisation approaches.

- Direct monetisation approaches (e.g. material damage to the structure)
- Indirect monetisation approaches (e.g. medical costs to injured persons)
- Immaterial monetisation approaches (e.g. willingness to pay to reduce pain and suffering)

The components corresponding to Figure 10 are also to be considered in mapping system functionality with resilience measures.

Benefit components	**Designation**	**Brief description**
Investment costs		Sum of all project-specific costs
Change in operating costs	NB	Change in the delivery or transport costs in the transport of people and goods
Change in travel time	NRZ	Benefits from changed transport time in the transport of people
Change in transport time benefits of the load	NTZ	Benefits from changed transport time in goods transport
Change in reliability	NZ	Project-induced benefits from changed reliability of traffic flows
Change in implicit benefit	NI	Implicit benefits due to increased mobility
Change in traffic safety	NS	Change in accident costs with regard to injury to people and damage to property
Change in noise pollution	NG	Benefits from project-induced changes in noise or sound pollution
Change in exhaust pollution	NA	Benefits from project-induced changes in exhaust pollution (air pollutants and greenhouse gas emissions)
Life-cycle emission of greenhouse gases from the infrastructure	NL	Total greenhouse gas emissions due to construction, maintenance and operation of the infrastructure project (“life cycle emissions“)
Change in local separation effects	NT	Reduction of local separation effects (delays and circuitous routes for pedestrians)
Benefits where there are competing modes of transport	NK	Effects of a project on benefits from the use of other modes of transport
Change in the operating and maintenance costs of the transport routes	NW	Benefits from project-induced changes in renewal and maintenance costs

Figure 10: Benefit and cost components of the evaluation methods of BVWP 2030 [51]

Effects on economic growth and employment are – as shown in the BVWP 2030 example – only very rarely included in the evaluation of (resilience) measures. There are various statistical and/or macroeconomic models (see Appendix 2) for testing the macroeconomic consequences of (resilience) measures. These, by contrast with England and Austria, however, up to now, have not been included in standardised evaluation methods in Germany. BVWP 2030 does not even include a corresponding evaluation component that was part of the earlier evaluation method, due to problems. The reasons for this are that the estimation of such effects is less certain and robust than those of other effects. There is also the risk of double counting, in particular as differentiation from existing benefit components (in particular travel times) is not clear and the methods for determining such effects are the subject of continual discussion [49]. Growth and structure effects of traffic measures are also to some extent ruled out of the argument, as transport infrastructure is widely available (ubiquity of transport infrastructure).

The mapping of the functionality of a system depends heavily on the system classification in terms of space, time and content. Depending on the project size and political framework, the effects of resilience measures on all aspects of sustainability and on all traffic types and modes of transport as well as on the economy as a whole can be taken into account.

It should be borne in mind that there are a large number of evaluation components for measures in the transport sector. These do not have to be reinvented for resilience measures. Experience has shown that determination of the effects as regards resilience (probability, extent and response due to effect over time) in practice represent a major challenge. Conversely, however, it should also be noted that resilience is not normally taken into account in the evaluation of measures in the transport sector. It does not represent a benefit component in itself. Therefore the extent to which resilience could be included in such processes as an evaluation component in its own right should be verified.

5 Methodical approaches to the evaluation of resilience measures

5.1 General

The spectrum of analysis and selection of methodical approaches for evaluating resilience measures is an important focus of these investigations. It is examined here whether the measures mentioned are appropriate or useful for resilient system functionality.

Various methodical approaches to the evaluation of resilience measures can be used to answer this question. They can be assigned to the following structure and will be described in detail in the following chapters:

1. Methods to determine expected functionality loss in the event of an incident.[3]
2. Methods to estimate the probability of the occurrence of damaging incidents.
3. Methods to evaluate resilience measures.

5.2 Determination of possible functionality loss

Expected functionality loss can be derived using the conceptual considerations in Chapter 2.2 by the area integral via the functionality curve (falling in the event of an incident and then rising again). However, prior definition of system functionality is essential for this estimate of functionality loss. This means that those (one or more) assessment components must be determined which affect the functionality of the system in connection with the resilience analysis: In other words, functionality as mapped in Figure 5 in the form of a curve corresponds to the function from one or more assessment criteria (e.g. traffic capacity, fatalities, gross domestic product).

5.3 Evaluation of probability of occurrence

Risk is determined in two stages: Firstly, an assessment is needed of system functionality loss in the event of an incident. On the other hand, the probability must be estimated, with which the damaging incident to be taken into account will take place or with which the damaging incident to be taken into account will have a negative impact on the system. The methods to assess the probabilities of occurrence are multiple and vary in statistical detail.

The description of the methods to determine probability of damaging incidents and to take into account the associated uncertainties is not the subject of these investigations. This refers, for example, to risk-based approaches and procedures. For

[3] *In the opinion of the authors, the resilience analysis prioritises the determination of expected functionality loss in the event of a damaging event and therefore is listed as the first step in the analysis. In the event of pure considerations of risk, analysis steps 1 and 2 are often carried out in reverse order.*

the evaluation of resilience measures, the following requirements result:

a) Damaging events to be considered must be defined (e.g. severe weather, terrorist attack),

b) their probability of occurrence must be estimated[4] and

c) whether and the extent to which the resilience measure to be assessed affects the probability of occurrence must be described.

However, estimation of such probabilities is only rarely the responsibility of the infrastructure operators themselves, as groundwork is provided either by the authorities (e.g. maps showing risks to the natural environment or network-wide accident risks), or such probabilities are determined with the assistance of experts.

5.4 Methods for the evaluation of resilience measures

Nowadays, there are a large number of methods and procedures for the evaluation of resilience measures. This depends, among other things, on resilience measures being in place in respect of different damaging incidents such as natural catastrophes (flood, storm etc.), premature ageing of infrastructure due to extreme environmental conditions etc., and these too are evaluated on the basis of different specialist disciplines. The methods have in common that they are largely based on a comparison of the costs invested in measures and the resulting benefits for society. Although bases of calculation may differ widely, which means that various results could be determined or various recommendations be made, one important difference, for example, is the extent to which the "benefit concept" is understood or the extent to which the effects of the measures are monetised.

In the first instance, the most frequently occurring evaluation procedures taken into account in literature are described in comparison with one another below.

These are:

- Descriptive assessment (DA)
- Comparative value analysis (CVA)
- Utility value analysis (UVA)
- Cost/effectiveness analysis (CEA)
- Costs/benefit analysis (CBA)

4 Where appropriate taking into account uncertainties

CVA, UVA and CEA are also designated as multi-criteria analysis (MCA) methods [48], [52]. The various MCA procedures are distinguished by the fact that they do not use any one overriding criterion. Cost/benefit analysis by contrast has an overarching objective, i.e. increasing societal welfare defined by various environmental and social criteria. Ultimately therefore, a large number of criteria and indicators are used in all procedures. [53] [54] [47].

Descriptive assessment

In descriptive assessment, the effects are described in exclusively qualitative terms. There is no evaluation (grading or points system) of the effects.

Comparative value analysis

In comparative value analysis, the effects expressed in points, physical or monetary measured variables or scores (comparative values) are allocated in such a way that the effects are comparable with one another.

Utility value analysis

The comparative values described above form the basis of utility value analysis. In utility analysis, in order to be able to undertake an overall evaluation, the comparative values or target contributions are added together including the corresponding target weighting.

As comparative value and utility value analysis build on one another, the procedures are described jointly here.

The effects are determined (c.f. Figure 11, step 1) and these effects are allocated a points score on a unified (scoring) scale (step 2) using utility functions both in comparative value and in utility value analysis. It does not matter here whether the scale goes from +3 to -3 or from +1000 to -1000. It only has to be used in the same way for all indicators so that for example with grading the range of marks goes from 1 to 6.

The objective of utility value analysis is the determination of an overall utility value for each planned case/resilience measure. For this, all indicators are given a weighting (as a %) by which the comparative value is to be multiplied. Where an indicator cannot be evaluated, it is nevertheless given a weighting but no changes are indicated by comparison with the reference case. This prevents the evaluated indicators from receiving a higher weighting due to the non-evaluation of others. The products formed from the comparative value and the target value (sub-utility value) are added together using all indicators. The result is the decision-making indicator, the total utility value (c.f. Figure 11, step 3)

There is no generally recognised procedure to determine the utility functions (c.f. Figure 11, step 2). Although this conceals the risk, due to scaling, of ratings being used in the method that have the effect of hidden, implicit weighting. In order to ensure the greatest possible transparency in this method, the benefit functions are openly indicated in accordance with principles that are as unified as possible, easily understandable and traceable and not defined using typically ideal or hypothetical assumptions.

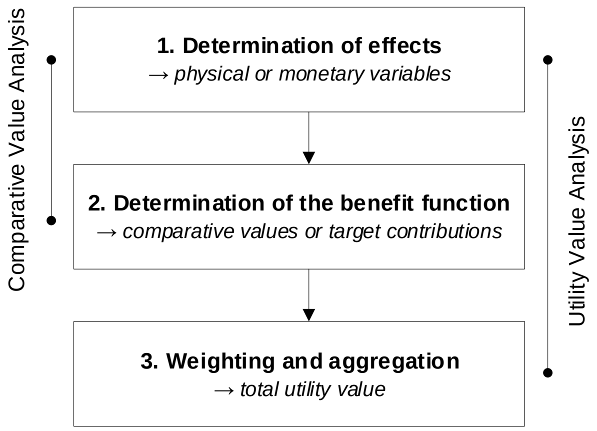

Figure 11: Procedure for comparative value and utility value analysis

The greatest challenge lies in scoring the descriptive indicators. In this case, it is the responsibility of the assessor alone to say what is a 1 or a 6 in his or her opinion.

Relative or absolute utility functions can be defined for all indicators with physical measured variables. These are relative if variants are only compared with one another and evaluated. The best variant is given maximum points, the worst the lowest score. In-between, the interpolation is linear. Because no absolute values are taken into account in this procedure, slight differences are therefore evaluated as equal in size and major differences using a different indicator.

An absolute evaluation only takes place if the limits of the utility functions are defined in “absolute“ terms. For example, the benchmark values on the scale can be achieved by a 10% improvement (corresponds to maximum points) or deterioration (corresponds to minimum points) of the reference case. Interpolation is linear in-between. The following cases deviate from this rule, however:

- The correlations are non-linear: for example, the harmful effect in the case of noise is not linear but logarithmic. The utility functions and the end points on the scale are to be determined on a case-by-case basis.
- For example, where benchmark values of the benefit function are determined as deviations from 3dB(A), which corresponds to a doubling or halving of the sound energy.
- Minimum standard or legal specifications already met in the reference case. The plan cases achieve, with regard to an indicator, changes greater than 10% by comparison with the reference case. If however the reference case itself achieves the target (e.g. compliance with limit values), the scale should be determined e.g. at 100% change by comparison with the reference case in order not to weight such changes too heavily.

In the case of indicators with monetary measured variables, the MONAQ approach (monetary equivalence approach) should be taken into account. This assumes that a change by 1 million euros per year always results in the same amount of points. The infrastructure result serves as a basis for determining the change in score: The minimum score corresponds to the annual infrastructure costs (debt service and maintenance costs) arising from the investment of a (hypothetical) maximum variant e.g. of 50 billion euros. The annual infrastructure costs following on from this (debt servicing and maintenance) amount to around 2.4 million euros. On the basis of this amount, a ratio of “utility points per 1 million EUR” can be formed. On a scale of 100 points (e.g. from -50 to +50 points), there result around 48 million euros per year for a utility point. This value is carried over onto the remaining monetary indicators. This ensures that the evaluations of the monetary indicators are in line with the cost/benefit analysis. If this is not desirable because e.g. a critical attitude is taken towards the monetisation of accidental damages and of CO2 emissions, physical measurement units for accidents or emissions can be taken as a basis as above for other physical measurement units.

Cost/effectiveness analysis

For the utility value analysis, all comparative values are multiplied with the target weighting and added together. This gives a total utility value, which enables statements to be made as to what variant is the most advantageous. Using a scale that indicates the variations from the reference case, statements can also be made as to whether the variants are better or worse than this reference case.

If the investment, operating and (discounted) annual costs are not taken into account in utility value analysis but the utility value, across all indicators relating to investment costs, the cost/benefit ratio is obtained which is suitable as an efficiency measure ("how many benefit points are obtained for each euro spent?"). In this case, this is a cost/effectiveness analysis.

Cost/benefit analysis

The most frequently used method to evaluate measures is the cost/benefit analysis. The economic cost/benefit analysis investigates the planned cases to be evaluated taking the increase in welfare under a macroeconomic monetary evaluation as a main target. For all criteria taken into consideration, the measures-related changes must be quantified and these changes are to be monetised. The cost/benefit analysis is based on the opportunity cost principle. When a supply concept is created, the resources used for this purpose are no longer used for other public or private purposes. With regard to the effects after any such realisation, resources may be saved or greater consumption can result (e.g. energy consumption). Costs are therefore seen both as negative benefits and prevented positive effects of relevant alternatives, with benefits corresponding to negative costs. Costs are, therefore, always opportunity costs (lost benefits from alternative uses) and benefits corresponding to benefits from opportunity (lost costs from alternative use). A measure-dependent additional consumption of energy therefore represents both costs and negative benefits because the resource of energy cannot be used alternatively (e.g. to heat homes); measure-dependent reductions of energy consumption, conversely, represent benefits or negative costs as the energy is now available for alternative uses.

Consumption of resources is considered in the cost/benefit analysis where it can be monetised. Here, for instance infrastructure, personnel, rolling stock, environment or time are considered to be resources. In the context of "targets" those indicators are represented that are monetarised in the context of the German Federal Transport Plan (Bundesverkehrswegeplan) and so taken into account in the cost/benefit analysis [55].

For the evaluation of the effects, valuation bases used are in monetary units (e.g. EUR per tonne of CO_2 emitted or EUR per staff hour) and the measure-dependant changes by comparison with the reference case multiplied by it.

The changes in the consumption of resources are determined in the context for the realisation and the useful duration of the project. For the economic effectiveness calculation, a real (inflation-adjusted) social discount rate is taken as a basis. Discounting the values for the individual years (cash values) and their addition gives the cash value (capital value) of the project.

The sum of the cash values over all indicators gives the cost/benefit difference. If the cost/benefit difference is greater than zero, the measure is economically useful. The offer concept with the highest cost/benefit difference should be favoured from an economic perspective.

The result of a cost/benefit analysis gives information to the decision-maker as to whether the realisation of a measure is worthwhile from an efficiency perspective by comparison with the reference case. Using the cost/benefit analysis, various measure variants can also be compared with one another or prioritised. This enables financial resources to be employed where the economic benefit is greatest.

Mapping of resilience in existing evaluation methods

In principle, existing evaluation methods e.g. for the evaluation of new and upgrade measures in transport are also suitable for the evaluation of resilience measures. In Germany in particular this includes the following approaches:

- Federal Ministry for Transport and Digital Infrastructure BMVI (2006): Standardised evaluation of investment in local public transport).
- Federal Ministry for Transport and Digital Infrastructure BMVI (2014): Final report on FE project 96.0974/2011: Thorough examination and further development of the cost/benefit analysis in federal transport planning evaluation methods.
- Federal Ministry for Transport and Digital Infrastructure BMVI (2016): Federal plan on transport routes 2030.
- Forschungsgesellschaft für Strassen- und Verkehrswesen FGSV (1997): Recommendations for economic feasibility studies on roads) (the updating of the EWS is in progress but not yet published)

It has been shown in an international comparison that, between the individual countries, although there are some significant differences, there are also important similarities in the methodical approach. A cost/benefit analysis is the most frequently used and in many cases is supplemented with further criteria and extended into a multicriteria analysis (CVA, CEA, UVA) or a combination of cost/benefit analysis and multicriteria analysis.

In practice, various methods are used for the evaluation of projects and measures. The greatest difference between the evaluation methods is in the appropriate level of detail and thereby in the associated requirements for the persons responsible. Additional differences may, for example, arise due to the selection of the period under consideration or various system limitations and definitions of the functionality of a system.

Figure 12 contains a comparison between methods based on the literature examined and our own experiences. The aforementioned selected methods are compared with one another.

The focus for the selection of methods relevant to this research project depends on the following questions:

- Is the method basically applicable to all measures in the sphere of road infrastructure and modes of transport?
- What preconditions (data, know-how, etc.) are required for application of the methods?
- How high is the level of complexity and the degree of standardisation in the application of the methods?
- How can the practical applicability of the methods be assessed?
- How reliable, traceable and justifiable are the method-specific results? What uncertainties exist regarding application?

These questions form the framework of the comparison between evaluation methods in Figure 12 and can be answered in relation to resilience measures in summary as follows:

- All methods taken into account can be used for an evaluation of resilience measures in the sphere of road infrastructure.
- The cost/benefit analysis represents the highest requirements with regard to data demand and the knowledge of chains of effects and dependencies between systems and their modelling. With relation to the resilience measures, the requirements continue to rise as probabilities have to be assessed for effects on functionality and the extent of damage.
- The descriptive assessment of resilience measures can be applied, due to their low level of complexity, without major conditions, with qualitative estimates such as investments (low/medium/high) and extent of damage (low/medium/high). This aspect is qualified, however, by the fact that, due to a lack of formal development and framework, using descriptive assessment to make a complete and correct argument about a number of indicators is indeed a complex task.
- The BVWP and the EWS represent standardised procedures for cost/benefit analysis. For the other processes there is no standardisation (e.g. for points rules, utility functions etc.). These are redefined in every case.
- Practical relevance from the user’s perspective diminishes from qualitative descriptive assessment through to a more complex cost/benefit analysis.
- From the perspective of the decision-makers however, this is completely reversed because, in the case of a cost/benefit analysis the results figures have a “familiar dimension” in the form of monetary units or a factor, and expenditure in the form of cost of measures can be compared to the same extent. For decision-makers the results are therefore easier to understand and convey and can be seen at a glance.
- Due to standardisation, the lowest uncertainties are in cost/benefit analysis even if the uncertainties are greater with respect to data availability and modelling predictions. However, it is “Better to take a good estimate than bad advice” in such cases.
- For comparative value analysis, utility value analysis and cost/effectiveness analyses, the advantage emerges that more functionality components and thereby more effects can be taken into account than is the case with cost/benefit analysis (CBA), as these require monetary bases of evaluation to be taken into account for all functionality components.

5.5 Conclusion

Depending on the state of planning, the costs and effects of resilience measures should be estimated as accurately as possible. This applies to investments, lower probabilities of damaging events and their impact on system functionality, extent of damage and system recovery time. Such estimates should enable the use of different evaluation methods with varying levels of detail (through to cost/benefit analysis). Where possible, uncertainties in estimates should be taken into account in the evaluation of resilience measures.

Where not all expected effects can be monetised, comparative value, utility value or cost effectiveness analyses can also be carried out. For a reliable evaluation of resilience measures, however, all three procedures should be used together.

The conclusion is also that the macroeconomic effects of measures in Germany are not factored into current projects and plans for projects. Corresponding procedures exist in particular in Austria and England (c.f. Appendix 2).

	Descriptive assessment	Multi-Criteria-Analysis (MCA): Comparative value analysis (CVA)	Multi-Criteria-Analysis (MCA): Cost/effectiveness analysis (CEA)/ Utility value analysis (UVA)	Cost/benefit analysis (CBA)
Is the method applicable in principle to all measures in the sphere of road infrastructure and modes of transport?	yes	yes	yes	yes
What preconditions (data, know-how, etc.) are required for use of the method?	No preconditions. Assessment is made on the basis of a qualitatively substantiated expert's appraisal Quantified and not quantified effects are taken into account	As descriptive assessment. In addition, scoring rules have to be drawn up. Quantified and not quantified effects are taken into account.	As for comparative value analysis (CVA) There must also be weightings for every indicator. Quantified and unquantified effects are taken into account	Effects have to be quantified e.g. with transport models. Monetary value approaches are not necessarily available. Quantification necessary.
How great is the level of complexity and the level of standardisation in the use of the method?	Formally low no standardisation	low no standardisation	Greater than for comparative value analysis due to weighting No standardisation	Highly complex High level of standardisation (see. BVWP, EWS)
How can the usefulness of the method in practice be evaluated?	Application seems simple, argument-based processes however also have the disadvantage that traceability is limited Support for decision-making is low: Decision-makers are hardly able to read the arguments for each indicator (this would take too long)	As for the descriptive assessment: application appears simple, however scoring rules are not normalised or standardised => may lead to low acceptance level Higher than descriptive specification as advantages and disadvantages can be recognised more quickly.	As for comparative value analysis Objective and indicator weighting not normalised or standardised => low level of acceptance Lower than comparative value analysis: Overall utility value less meaningful. No possibility of comparison as to whether the result is good or bad.	Time-consuming procedure to determine effects Heavy data requirement Very high: as investment in EUR is compared with benefits in the same dimension. The order of magnitude/relevance of individual indicators is proportionate to the social significance
How reliable, traceable and justifiable are the method-specific results? What uncertainties exist in their application?	Depending on the operator, results may differ as no clear model is used Major uncertainties	As for descriptive indicators In the case of quantification, there tends to be greater validity of results Lower uncertainty than descriptive specification	As for the comparative value analysis Traceability of the results however is made more difficult due to weighting of target and lack of standardisation	Tracing exists due to standardisation of procedures. Dependent on quality of the models and databases, but in principle better than the other procedures as greater consideration is given to quantification and deviations have to be formal. Uncertainties exist
Can macroeconomic effects be taken into account?	Only argumentative, (assertions) without evidence or models	As for descriptive arguments Otherwise as for all other indicators	As for descriptive arguments. Otherwise as for all other indicators	Modelling necessary Prerequisites currently not available in Germany

Figure 12: Comparison between the most important evaluation procedures

6 Case studies

This chapter uses case studies to indicate how the resilience concept can be translated into practical everyday routines in infrastructure management. Although the term resilience is used in many different academic disciplines nowadays, what appears to be an established and accepted concept in academic theory, has up to now rarely been consistently applied in everyday infrastructure management practice. The search for examples and case studies on practical implementation led to a clear picture: Although evaluations are frequently carried out on traffic measures, these are however less resilience measures they have mainly been drawn up for new construction and upgrade projects.

Relatively few studies have been found relating to resilience measures. For various reasons described below, the following five case studies nevertheless represent the current (international) state of application of the evaluation of resilience measures.

Case study 1, New Zealand:
"Measuring the Resilience of Transport Infrastructure" [3], New Zealand Transport Agency Research Report No. 546, 2014.

This concerns a research report drawn up by AECOM New Zealand Ltd and commissioned by the New Zealand (NZ) Transport Agency. The NZ Transport Agency is a New Zealand State enterprise reporting to the Ministry of Transport. The report contains a proposal for a concept for the evaluation of the resilience of the New Zealand transport system. It uses a method for providing a resilience score based on selected resilience indicators for individual structures, sections of track or the entire network. A very wide range of different types of damaging incidents can be taken into account which have an impact on the system under consideration (single and all-hazards approach). This evaluation concept assists decision-makers in selecting measures targeted to contribute to an increase in resilience that is as efficient as possible (increased resilience score).
This case study shows that resilience measures – departing from the technical and organisational road infrastructure system – are extended to the enterprise itself. For example, such questions are addressed as: How can risk and resilience awareness be increased among the staff members of an infrastructure operator?

In this case study, a specific concept is proposed for the measurement of the resilience of road infrastructure systems. In addition, approaches to implementation in the everyday processes of the infrastructure operators are indicated and demonstrated using examples. The resilience measurement concept seems plausible and implementation using what are known as "Dashboards"[5] practicable. In this way it becomes quickly apparent to the decision-maker where and to what extent measures contribute to an increase in resilience. With additional cost/benefit considerations (not described in the report), a cost-optimised set of measures could be identified in this way. The benefits of such standardised resilience measurement for the infrastructure operator resides primarily in the identification of measures that are as effective as possible to increase the resilience of individual structures or the entire infrastructure network within the perimeter of the decision-maker. The methods to determine the resilience score in the aforementioned case study are not complicated and can be implemented using most available IT programmes (e.g. Microsoft Excel) However, significant expense may be incurred in initially obtaining the relevant indicators and their continuous updating.

The fact that the question of resilience is discussed very comprehensively in this case study is also indicated in the appendix to the report by the note about the complexity of estimating the probabilities of the occurrence of damaging incidents and the associated uncertainties in the determination of risk. The authors in the case study recommend, in the estimation of probability of occurrence, the use of broader forms of distribution of the underlying probability distributions than has been customary. This means that more conservative assumptions have been made of intervals between the recurrence of damaging incidents (more frequent cases are assumed).

Case study 2, Switzerland:
"Evaluation of variants to improve winter safety on Kantonsstrasse Sils (the Sils Cantonal road)" [56], EBP report, 2014

To increase winter and summer safety on the main road between Silvaplana and Castasegna, the Canton of Graubünden in Switzerland commissioned the study of several variants. The civil engineering office for the Canton of Graubünden commissioned EBP Schweiz AG to evaluate three variants and the zero alternative using risk analyses. Essential indicators of the investigations were the periods of restricted use of the main road and therefore the loss of functionality of the road over

5 A dashboard contains a clear representation of the most important resilience indicators in this connection so that particularly low values can be identified and corresponding optional courses of action can be derived for the desired resilience of the system responsible.

time in the interests of the definition of resilience presented in Chapter 2.1.
The measures and variants which are in discussion in this case study are not necessarily to be understood to be resilience measures. However, taking into account the definition of resilience measures in Chapter 3.1 (measures exceeding the normative/compulsory specifications) in the context of the evaluation method outlined in the case study, undertaking more extensive risk considerations depending on the implementation variation (i.e. the initiation and implementation of this risk-based variant study itself) can itself also be understood to be a resilience measure.

Case study 3, USA:
"Seismic Options Analysis in Western Oregon" [57], EDR Group, 2014

For a magnitude 9.0 earthquake in the subduction zone in Western Oregon on the American Pacific coast, competent bodies worked out a scenario on infrastructural damages to be expected. In the context of this case study, this was the point of departure for analysis of economic losses caused by the disruptive deterioration of access and the interruption of supplies of goods. Analysis was made of the severity, the flows of goods and the sectors affected by the road closures, what direct economic losses resulted from this and what indirect and induced losses this would lead to. In another step, the extent to which it had been possible to reduce the damage by three separate extensive programmes of investment in earthquake safety to increase the resilience of the components of the infrastructure was investigated. This case study was selected because the tool used provided an example of a computer programme suitable for everyday use being able to assist decision-makers, which also involved an estimate of macroeconomic consequences of damaging incidents and impact on the road infrastructure and effects on the road traffic infrastructure.

The TREDPLAN case study is essentially based on a large database in which, in addition to the georeferenced inventory of the road infrastructure network, input variables such as population characteristics, economic and business models as well as trade and logistics flows are stored. By the intelligent combination of such basic data, the impact of external damaging events can be estimated on a system and its surrounding region.

TREDPLAN is a paid-for tool which is currently available for application in the USA. If the corresponding basic data was available, the tool could also be used in Europe and serve decision-makers as a useful aid in infrastructure management.

Case study 4, Europe:
"Security of Road Transport Networks (SeRoN)" [58], EU research project, 7th framework programme, 2012

In the "Security of Road Transport Networks (SeRoN)" research programme in the context of the 7th EU research framework programme, a method for the identification and quantification of the risks of critical road infrastructure elements was developed between 2009 and 2012 and applied as an example to case studies. On the basis of cost/effectiveness analyses, the relativity of possible additional measures is investigated. The evaluation of resilience is, therefore, based on an estimate of the resulting risks of the failure of a critical road element and the proportionality of possible additional risk-mitigating measures. The developed procedure gives a comprehensive and structured overview of possible protective measures for critical road infrastructure elements. Standardised guide costs were also indicated in the research project for many measures. No specific procedure for the selection of potentially suitable measures is defined further. This is left to the users of the method.

For the application of the procedure described above, an IT tool which can support infrastructure operators in the identification of critical network areas has been developed. The calculations within the (Excel) tool are of low-level complexity although the tool does include many worksheets so its application can be time-consuming. Because some of the input data has to be estimated by infrastructure operators and/or traffic experts, the effort in surveying the input variables is considerable and usually depends on access to traffic and logistics models. As soon as these basic inputs are present, the developed tool can, however. be a useful aid to decision-makers in infrastructure management. The tool application is clearly demonstrated using sample applications on particularly critical road routes (Öresund bridge and Brenner route). The case study aims to identify particularly critical sections of the road network. However, it does not contain any evaluation of measures in order to design such sections, structures or network areas in order to make them more resilient. Uncertainties in the estimation of the probabilities of occurrence or the extent of damage are only taken into account as fringe considerations.

Case study 5, Germany:
"Joint project SKRIBT [45] – protection of critical bridges and tunnels as part of roads", Federal Ministry for Education and Research (BMBF) & VDI Technologiezentrum GmBH & BASt, 2013

The SKRIBT project was initiated by the Federal Ministry for Education and Research (BMBF). It was the objective of the report to identify potential hazards for road bridges and tunnels (threat analysis), to carry out analyses of the structure and to develop protective measures. Various types of hazard can be taken into account (all-hazard approach). The term resilience is not used as such. The measures studied, however, reduce the probability of occurrence and the damage of a possible incident and therefore can also be treated as resilience measures in accordance with the definition in Chapter 3.1.
This case study demonstrates a state-of-the-art approach to unusual damaging events to road bridges and tunnels in Germany. The resilience concept is only implicitly addressed and implemented.

In this case, study-specific protective measures are recommended for bridges, tunnels and their users. This is on the basis of indicator-based identification of critical structures. This is essentially a procedure comparable to New Zealand case study 1, however the difference is that – by contrast with the resilience score – the approach in SKRIBT is based on criticality criteria rather than on considerations of resilience (see differentiation in Chapter 2.1). The cost of the measures associated with life cycle costs and effectiveness/cost analyses is also taken into account. The methods in the SKRIBT case study are described and presented very clearly. This creates an important basis for practical application. Once translated into the context of resilience consideration, the types and costs of measures listed can offer a very good basis for practical implementation of the resilience concept.

The identification of critical structures on the basis of the summary of different input and or indicator variables in the aforementioned case study is relatively complex. Determination of the input variables is time-consuming at the start of the procedure. Uncertainties in the estimates for the probabilities of occurrence and the extent of damage in the event of occurrence in this case study will not be entered into.

Fact sheets

These case studies, in the opinion of the authors, reflect the (international) state of application of resilience concepts. In addition to the summaries in the previous sections, they have been evaluated against the following questions:

1. What were the circumstances for the resilience considerations?
2. How was resilience evaluated/indexed?
3. How were resilience measures derived and how should they be assigned to the type classification in Figure 8?
4. How have resilience measures been evaluated? Where appropriate: What was the cost/benefit ratio? Have macroeconomic consequences been demonstrated?
5. How is practical implementation, applicability, practicability carried out or ensured?

The responses to these questions are summarised in the fact sheets in Appendix 1.

Findings

From analysis of the case studies and responses to the above questions, the following findings can be deduced on a primary level:

- The challenges of resilience management are currently primarily being discussed by academics instead of by infrastructure operators.
- The issue has come to the attention of the decision-makers, but its translation and implementation into practical everyday situations by infrastructure managers is still very piecemeal, very rarely completed and barely ever documented.
- From the case studies analysed, it is apparent that very different approaches to consideration of resilience and its determination are taken in different parts of the world.
- In the evaluation of resilience measures — a great many different assessment methods are used, when they are used at all. There is not one established standard method.

Detailed research on practical case studies has revealed that

- The trigger for the evaluated measures was not necessarily resilience.
- A very close relationship with and to some extent integration into risk analyses and evaluations exists.
- in the evaluation procedures applied, the effect of the measures under evaluation on the resilience of the transport system is treated only in a very marginal way.
- Macroeconomic effects are only very rarely integrated into the evaluations.

The case studies analysed however show that:

- Usable methods already exist for evaluating resilience measures.
- The actual major challenge for quantifiable and monetisable evaluations is knowledge of the probabilities of occurrence of disruption (or the development of suitable prediction models).
- For macroeconomic analyses in Germany, no principles and tools such as TREDPLAN in the USA are as yet available.

7 Conclusions and recommendations

7.1 Conclusions

Systemic consideration of resilience is currently a very broadly and intensively discussed subject in traffic infrastructure management internationally. There are numerous definitions of resilience. The essence of these discussions lies in an understanding which can be summarised as follows in [11]: Resilience is the capability of a system to avert actual or potentially damaging events, to prepare for them, to factor them in, to withstand them and to recover from them as quickly as possible. Damaging occurrences are disruptions or change processes caused by humans, technology or nature, which have disastrous consequences and are not taken into account in current standards and design codes. Resilience can only be increased by consistent interaction between technical, social and economic approaches to a solution. In particular the integrated thinking of the various possible solutions and their well-targeted combined use before, during and after a crisis are what differentiate resilient systems. Resilience is, moreover, not a static state but a characteristic of dynamic systems that are capable of development. The resilience of a system increases the better it is able to withstand harmful events. If resilience is low, even slight impacts or disruptions can cause significant system changes or the collapse of the functionality of the system.

Discussions about resilience focus on a view that should be as unified as possible that, on the one hand, takes into account not only individual objects in the road infrastructure sector, but the entire system and, moreover, also far-reaching indirect and non-material aspects in the consideration of the possible consequences. Accordingly, systemic and holistic concepts are the prime focus in this context:

- Resilience is not a system state which is reached once and then fixed, rather it is a system characteristic that has to be continually “trained” and improved or maintained.
- Neither robustness nor resilience can serve as a sole paradigm for protective concepts in road infrastructure management. Modern protection concepts should be based on a balanced strategy that will withstand scrutiny from multiple perspectives. Individual components must be robust and networks resilient.
- Considering the resilience of an entire system is particularly important and is also a significant challenge. In particular in view of the portfolio of parts of the infrastructure, infrastructure is more than just a series of physical systems. Functionality in the sense of a system/compound structure plays an important part. In the context of road infrastructure, ensuring supplies and services to society is also a factor. Such functionality must be available even when one or more links in the infrastructure chain have failed or broken down.

Provision for dynamic system functionality over time under the effect of damaging incidents may be referred to as the resilience of a system. The subject of resilience is discussed primarily in academic publications and theoretical reports.

7.2 Recommendations

The following recommendations are derived from the methods described in Chapter 5.4, on the methods for the evaluation of resilience measures and the findings from the case studies in Chapter 6:

- Integration into existing procedures: To ensure a high level of acceptance, widespread use and consistent consideration of the resilience concept, various new evaluation methods should not be used, but the resilience aspect integrated where possible into existing procedures or such procedures should be “upgraded” as appropriate (see Chapter 6, case study 2).
- Regardless of how resilience measures can be evaluated, it should be verified that resilience is listed as a separate benefit component in the target system, e.g. is itemised in the evaluation of new builds and upgrades. For this, an appropriate procedure for the

measurement of the potential effect of the measures must be developed. If determination of quantitative impact and monetisation proves to be too time-consuming, this can take place using a pragmatic scoring system such as is employed for instance in New Zealand (Chapter 6, case study 1, [3]).

- An innovative approach to resilience management that should take place in the first instance could pragmatically take the form of a two-step process:

1) In the first step, network screening is carried out on a broad (network) level (with low-level detail) to identify the weak points in the system. The following questions should be investigated in the process: Do all system elements conform to the current standards and rules (compliance)? What elements in the system are to be assessed as particularly critical (criticality)? Where is there increased need for resilience due to a potential risk situation? In implementation, an indicator system as described in case study 1 from New Zealand is recommended.

2) In a second step – with a knowledge of the critical elements in the system – specific, in-depth, more complex resilience analyses should be carried out at structure level. The decisive question here is: Where and to what extent is it worthwhile investing in increasing resilience? What system elements and damaging events are to be taken into account in the analyses? What are the most important functionality components (to be evaluated)? The question of practicability and utility is also important. What level of detail is worthwhile and appropriate for the evaluation of the intended resilience measures?

- The evaluation procedures described can be used for resilience management to be established in the future. Depending on the extent of the resilience measure, the extent of the determination of the effectiveness is increasingly complex depending on the extent of the determination of the impact and therefore increasingly expensive. Due to the relatively high expense of monetising the individual components of system functionality, it is recommended only to resort to the evaluation method of cost/benefit analysis for extensive (expensive) resilience measures.
  The evaluation of smaller (less cost-intensive) resilience measures is possible as an alternative also using other methods (individually or preferably in combination).

- Last but not least, a unified understanding of the terminology and the use of consistent terminology is recommended: all those involved in the context of infrastructure management should use the same terms with the same understanding in discussion of resilience measures. This report forms a foundation for this to happen.

8 Prospects

The long-term objective of the BASt is the development and implementation of consistent and integrated resilience management. Integrated resilience management means that all phases of the resilience cycle (prepare, prevent, protect, respond, recover) and all groups of measures (technical, planning/organisational) and levels (structure, network) are included in the resilience consideration.

The first step in this direction has been taken using the above investigations towards a consistent basis for the understanding of the term resilience and possible resilience measures. On the other hand, an overview of possible methods for the evaluation of resilience measures has been created.

Now, on the basis of these findings, further development and application of the methodical procedures in the context of integrated resilience management must be initiated so that they can be used in future as a practical aid for decision-makers in road-infrastructure management.

The following aspects are considered to be of importance in any such further development:

- An approach that is relatively quick to implement, pragmatic and supposed to be rapidly accepted lies in the implementation of the resilience consideration in existing evaluation concepts of road-infrastructure management (e.g. resilience as a target system in the BVWP).
- A decisive step towards a holistic, conceptual and systematic assessment of the availability or functionality of road infrastructure in the event of adverse impacts lies in the further development and in the demonstration of the practical feasibility of the methods for identification of measures set out in this research project. A future objective is to ensure, by systematic identification of economically proportionate measures, the overcoming of adverse impacts on the infrastructure system. This means, with

appropriate use of resources, to ensure restoration of functionality as quickly as possible and the operation of infrastructure after a disruptive incident. The development of such approaches to identify particularly suitable resilience measures across all resilience phases is an important research requirement and has already been initiated for the “respond” and “recover” phases by BASt.

- Development of a suitable indicator system to assess the resilience of a road traffic network. In order to make any statements concerning the resilience of a system or to be able to compare different systems, a coherent method is needed to evaluate the resilience of road infrastructure. Closely connected with existing concepts for the assessment of criticality (see case study 4, SeRon), these can be supplemented or broadened in the direction of a resilience evaluation. The objective consists in an indicator-based derivation of a resilience score at structure or network level which can serve as a benchmark both for dedicated resilience management but also in comparison with other cities, regions, structures etc.
- Development of a method for the identification of (cost-)optimised measures to increase resilience of the structure or the network. This corresponds, for example to a combination of the New Zealand approach to scoring (see case study 1) and a computer-aided tool still to be developed which, on the basis of cost-effectiveness analyses, detects the most efficient levers (measures) to increase resilience in the system.
- Determination of the necessary minimum resilience required of systems. This is associated with the question: If resilience can be evaluated, what resilience value is it desirable to achieve? What is the target value and can such a target resilience be specified at all?
- Investigations on the real-time resilience dashboard e.g. dependent on water-level in the event of persistent rainfall. Combination with early warning system and real-time risk modelling.
- Verification of the opportunities for linking various data sources in order to map mobility flows and to be able to resort to real-time predictions of mobility behaviour in the event of disruptive events, to take action and take control.
- Estimates of the consequences of potential events e.g. by flood prediction models, provide important input values as the basis of the resilience evaluations. The new development of such models or the implementation of existing models in the overall context of resilience management represents an important future task. Associated with this is the guarantee of information availability by appropriately linking relevant databases (transport, population, natural hazards, accident risk maps, mobility flows etc.).
- Accidents involving property damage themselves often lead to significant losses of capacity in the road network. By the development of accident prediction models, for individual road sections, accident probabilities can be estimated and mapped (in future or in real time) according to traffic and infrastructure parameters. Such accident prediction models already exist for the Swiss and Austrian motorway network [59] [60]. Geo-referenced transposition onto network maps can give a direct overview of network sections expected to be susceptible to accidents.
- Creation of interfaces for all those involved. Resilience management cannot be expanded and developed exclusively by the infrastructure operators responsible. All stakeholders (representatives of the emergency services, those in positions of responsibility in the communities affected, public transport representatives, communication service providers, research bodies, etc.) must all be persuaded to support a common objective.

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- Federal Roads Agency ASTRA, Experten-gruppe Ausstellbuchten, Analyse und Evalua-tion von Massnahmen zu Ausstellbuchten in Nationalstrassentunneln", Ernst Basler + Part-ner, Ingenieurbüro Schüler , 2012 (Group of experts, service bays, analysis and evaluation of measures in service bays in national road tunnels, not public; investigations subsequent to the bus accident on 13 March 2012 in a nation-al road tunnel on the A9 motorway at Sierre)

A1: Fact sheets on case studies

Fact sheet 1	Measuring the resilience of transport infrastructure
NZ TRANSPORT AGENCY WAKA KOTAHI	Hughes, J. F. and Healy K. (2014). Measuring the resilience of transport infrastructure. NZ transport Agency research report 546. 82pp. (https://www.nzta.govt.nz/)

Summary

The report has been drawn up by AECOM New Zealand Ltd and was commissioned by the *New Zealand (NZ) Transport Agency*. The *NZ Transport Agency* is a New Zealand state-owned company reporting to the Ministry of Transport. The objective of the studies for the drawing up of the report was to develop a concept for the evaluation of resilience of the New Zealand transport system. Various types of disaster can be taken into account (single and all-hazards approach).

Reason for the report

The trigger for the drawing up of the report was the general responsibility for a functioning safe transport system. The *National Infrastructure Plan 2011* also obliges the transport authority to develop indicators to assess the resilience of the system in the area for which it is responsible.

How has resilience been evaluated/indexed?

Resilience is assessed using resilience indicators. By means of a list of associated measures, the extent to which these are implemented is evaluated on a scale of 1 to 4. The weighting of different categories is possible. Output is a resilience value between 1 (low resilience) and 4 (very high resilience). Using this resilience value (score), various structures and networks can be compared with one another.

How were measures derived and which measures were they?

For various dimensions (technical and organisational), principles (robustness, redundancy, etc.) and categories (structural, procedural, etc.) indicators have been developed that can be combined with corresponding measures. Such fine classification enables measures to be introduced on the basis of the resilience values determined, exactly where resilience appears necessary on the basis of a low resilience value.

The resilience measures discussed in the case study can be assigned to the type classification of measures as follows:

Resilience measures	**Structure**		**Network/region**	
Phase	Technical	Planning/ organisational	Technical	Planning/ organisational
prepare	• Maintenance work • Structure monitoring • Early warning systems	• Integration of resilient design in guidelines • Backups and regular updating of important information • Suitable insurance of structures • Restoration plans • Plans for necessary replacement material	• Traffic monitoring	• Develop internal company risk and resilience awareness • Knowledge and information transfer • Partnerships with other sectors • Risk analyses taking into account cascade effects • Check projects for resilience • Define usage plans and materials • Traffic management plans for different scenarios • Replacement route planning with prioritisation • Concept for the prioritisation of resource distribution • Emergency training involving the public • Backups and regular updating of important network-wide information

				• Preventive clarification of access entitlement to private ground in case of an incident • Securing financing, cooperative working groups, cost distribution agreements • Plans for the designation of alternative routes
prevent	*no details*			
protect				
respond	*no details*	• User information • Prepare overlapping channels of communication	• Create redundant transport routes with sufficient capacity and minimum travel time difference • Make alternative transport arrangements with sufficient capacities available	• User information on problems and alternative routes • Use overlapping communication channels
recover	• Ensure availability of spare materials	*no details*		

How have measures been evaluated? What was the cost/benefit ratio? Have macroeconomic consequences been demonstrated?

In this case study, no evaluation of measures has taken place. To implement the methods described in the above report, a case study is being carried out by the NZ Transport Agency, among other things: “Improving network safety and resilience”. Here, the focus in particular lies on a 5km long road (State Highway 73) between Canterbury and the west coast that is particularly narrow, and regularly blocked by falling rocks and heavy snowfall. Completion of this 2 million dollar project is planned for 2019.

Are implementation, applicability, practicability, etc. evaluated?

This is purely a resilience evaluation tool with an easy-to-understand scoring system. Using this resilience evaluation, the decision-makers can identify the state of resilience of their system and what levers they should pull in order to increase the resilience of their system. Prioritisation or selection of measures could take place using the integration of an additional cost/benefit ratio (is not being made to date).

There is no risk estimate (extent of damage using probability of occurrence). The schema was not used in the context of the report on an actual case study.

Fact sheet 2	Evaluation of variants to improve winter safety on the Sils cantonal road (Switzerland)

Summary

The Canton of Graubünden developed several variants to increase winter and summer safety on the main road between Silvaplana and Castasegna. The Civil Engineering Agency for the Canton of Graubünden commissioned EBP to evaluate three variants and the zero alternative

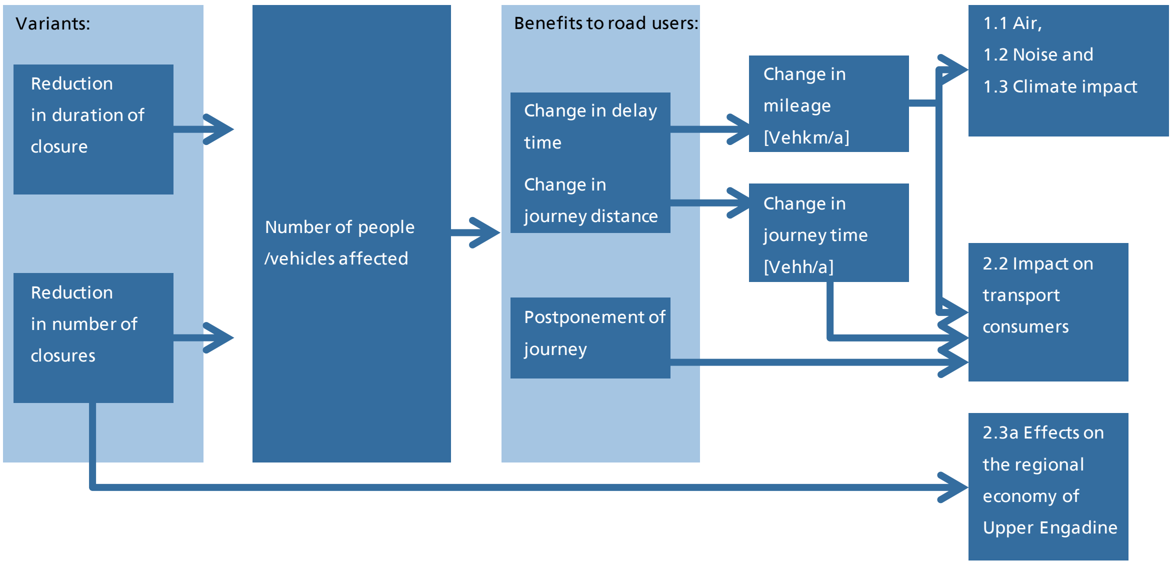
Reason for the report

The main H3b Silvaplana – Castasegna road is at risk from natural events over a section of around 3.5 kilometres between Sils Föglias and Sils Plaun da Lej. Mainly these are avalanches, but there are also landslides, debris flows and falling rocks and blocks. As protective measures only exist in certain places, the cantonal road has to be closed off when there is a hazard (in particular when there is a risk of avalanche). Disruption to this important Cantonal traffic route cuts Bergell off from the rest of the district. Then work and tourism traffic between Upper Engadine and North Italy are affected. This gives rise to direct and indirect economic losses.

How has resilience been evaluated/indexed?

The closing of the road is a measure to avoid damage in the event of an incident. The development variants may be regarded as resilience measures as, in the event of an incident with avalanches etc. they ensure that there is no road closure. The impact is therefore eliminated or mitigated.

An essential element of the evaluation were closure periods. The shorter the closure period, the higher the benefit. The effect of the variants on some indicators in the cost/benefit analysis depends on the extent to which the closure periods are reduced. The association between reducing the closure periods and the indicators is mapped in the following chart.



By reducing the number of closures and the duration of closure, road users benefit. Therefore, it should be determined how many people or vehicles benefit from a reduction in closure periods. The benefits to road users by comparison with the zero alternative may consist in a shorter delay until the road is opened, less regular diversions via a longer route or a smaller number of journeys that are eliminated altogether or which are postponed by (several) days. Taking into account the number of people or vehicles affected in each case, travel and vehicle hours differ each year. In the cantonal variant, it is also taken into account that in the event of closures and diversions via Sils, mileage increases and delays occur due to single-lane traffic. The changes are taken into account in the calculation of the indicators of air, noise, impact on the climate and effects on transport customers. In the indicator of the impact on transport consumers, it is also taken into account how many road users have to postpone their journey for one or more days. Determination of the impact on the regional economy is directly based on the reduction in the number of closures without explicit reference to demand for transport.

How were measures derived and which measures were they?

The various measures were worked out prior to evaluation by the administrative authority.

Resilience measures / Phase	Structure		Network/Region	
	Technical	Planning/ organisational	Technical	Planning/ organisational
prepare	*no details*	• Monitoring of avalanche risk	*no details*	
prevent	• Avalanche towers	• Controlled avalanche triggering and short-time road closures		
protect	• Construction of a tunnel and/or gallery	*no details*		
respond	*no details*			
recover			*no details*	• Indication of an alternative route

How were measures evaluated? What was the cost/benefit ratio? Have macroeconomic consequences been demonstrated?

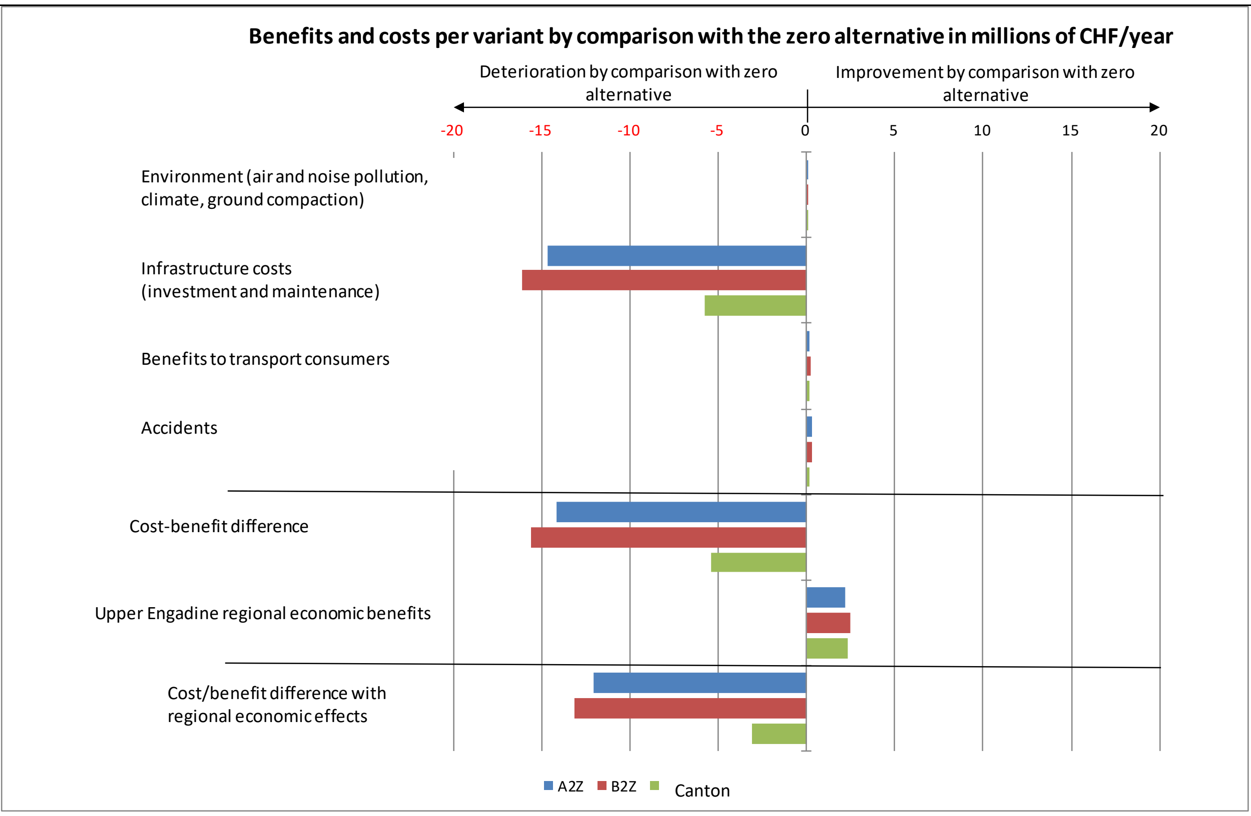
For the evaluation of the resilience measures the procedures of descriptive specification and cost/benefit analysis are used to compare different variants as a complementary process. The table below summarises the target and indicator system used for cost/benefit analysis and the descriptive specification, and is differentiated into three sectors: environment, economy and society.

Sector	**Indicator**	**Cost/benefit analysis**	**Descriptive**
1. Environment	1.1. Air and noise pollution	X	-
	1.2. Climate-relevant impact	X	-
	1.3 Ground compaction	X	-
	1.4 Landscape and location profile	-	X
	1.5 Water bodies	-	X
	1.6 Material management, tunnel excavation	-	X
2. Economy	2.1 Infrastructure costs: Investment, operation and maintenance costs, infrastructure	X	-
	2.2 Effects on transport consumers	X	-
	2.3a Effects on the regional economy:		
	• Upper Engadine	X	-
	• Bergell	-	X
	2.3b Image Engadine	-	X
	2.4 Realisation time	-	X
	2.5 Construction risk	-	X
3. Society	3.1 Effects on pedestrians, Sils	-	X
	3.2 Accidents due to natural hazards	X	-
	3.3 Accessibility of Sils	-	X

The results of the cost/benefit analysis for the main evaluation are mapped in the following chart. Here, the cost/benefit difference is shown as the sum of target contributions, namely the environment, infrastructure costs, benefits, road users and accidents. The cost/benefit difference thereby calculated corresponds to national specifications for the evaluation of traffic infrastructure measures.

The cost/benefit difference in accordance with the procedures of the Federal Government (Switzerland), does not take into account regional economic impacts as these can often represent a redistribution between regions.[6] The regional economic impact on the Upper Engadine area however is also calculated and shown here.

[6]) In this way, lost income in Upper Engadine for instance can lead to additional income in other regions such as Flims, Arosa or Davos.



A negative cost/benefit difference not including impact on the regional economy results from an economic perspective for all three variants. The infrastructure costs barely bring any benefits. From an economic perspective, therefore, none of the variants are to be recommended.

If the regional economic benefit for the Upper Engadine area is also taken into account, the result improves. Nevertheless, variants A2Z and B2Z continue to show clearly negative cost/benefit differences amounting to 10.8 or 11.5 million Swiss Francs per year. Due to the lower infrastructure costs, the Canton variant achieves a comparatively slight negative cost/benefit difference of 1.6 million Francs per year taking into account regional economic effects. It should be noted here, however, that in the view of the experts, the values assumed for regional economic benefit are very high.

The extent to which the variants bring improvements for the regional economy in Upper Engadine and in Bergell is to be investigated here. Due to reduced closure times, by contrast with the zero alternative, there is additional income from tourism and in the building industry. Moreover, staffing expenditure is reduced. Improved accessibility due to reduced closure time also has an influence on the image of the region. The damage cost rate for a day's closure is determined using economic information. This is approx. 3 million CHF per day. The macroeconomic effects used in the cost/benefit analysis were taken into account with a change in the closure days in the variants.

Are implementation, applicability, practicability etc. evaluated?

Procedures and processes can be implemented and are applicable and practicable. The entire evaluation takes approx. 500 working hours including data research, preparation, meetings and presentations.

Fact sheet 3	Seismic Options Analysis in Western Oregon (USA)

Portland Business Alliance / Oregon Business Council / Port of Portland (2014): Economic Impacts of Congestion in Oregon (Chapter 8: Seismic Options Analysis). Processed by: EDR Group, Boston (EBP partner company)

Summary

For a 9.0 magnitude earthquake in the subduction zone in Western Oregon on the American Pacific coast, competent bodies worked out a scenario on infrastructural damage to be expected. This was the starting point for the analyses of economic losses caused by the disruptive deterioration of accessibility and the interruption of flows of goods. Which flows of goods and which sectors were affected by the road closures were analysed how severely, what direct losses this gave rise to, and what indirect and induced losses this would lead to. In a further step, the extent to which the damage could be reduced by three different extensive programmes of investment in earthquake resistance to increase the resilience of the infrastructure was investigated.

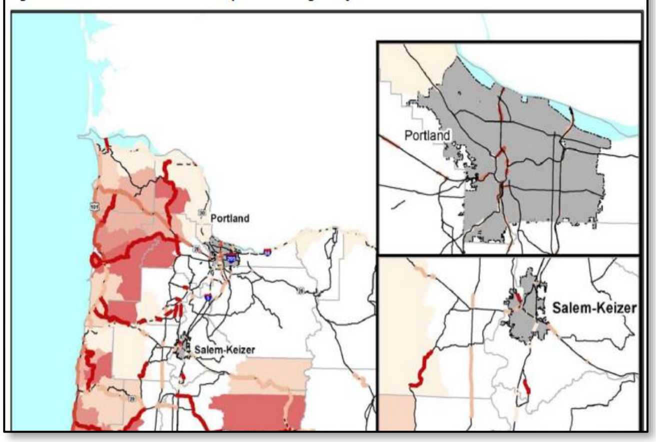
Reason for the report

Preliminary reports provided the necessary scenarios for infrastructural damage and investment programmes. In the context of this analysis, it was intended to show how investment programmes affect the earthquake safety of major road networks or how a lack of them affects the economy of Oregon in the event of a major seismic event.

How has resilience been evaluated/indexed?

The basic scenario, in which Western Oregon is affected by an earthquake without prior investment in the resilience of the road network, is compared with three different investment scenarios. The IT tool TREDPLAN used in this case study enables the analysis and evaluation of the effects on specific flows of goods. With the help of a transport model, efficiency loss in the transport system is determined, which is also the input variable for the tool. The numerical results take the form of the change in macroeconomic variables such as employment or national product or gross domestic product (GDP).

Figure 8-2. Isolated Zones and Repair Phasing: Major Seismic Event Scenario

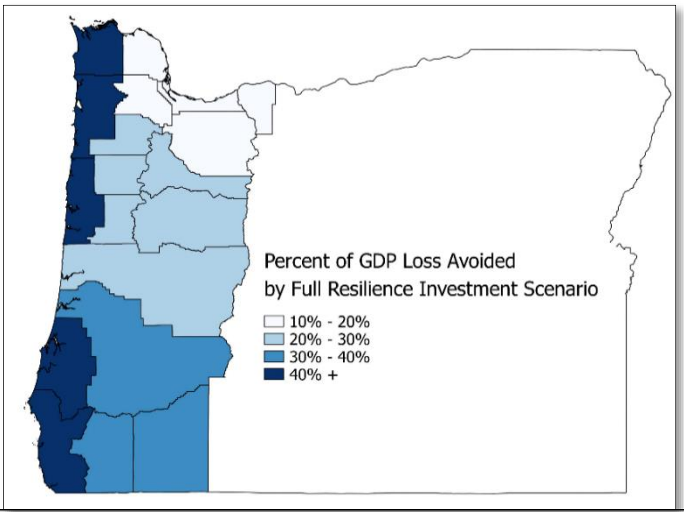


How were measures derived and which measures were they?

The measures (investment programmes to increase the resilience of the road network) were predefined in this project. However, assessment of the consequences of an external event and thereby efficient planning of measures were assisted by using TREDPLAN. The origins and destinations between which goods, that are of particular significance to the regional economy, are transported were determined, for instance. The resilience of the modes of transport that serve those routes and which are particularly important for the economic activity of the region can be intensified with appropriate measures.

<table>
<tr><td rowspan="2">Resilience measures

Phase</td><th colspan="2">Object</th><th colspan="2">Network/Region</th></tr>
<tr><td>Technical</td><td>Planning/ organisational</td><td>Technical</td><td>Planning/ organisational</td></tr>
<tr><td>prepare</td><td colspan="4" rowspan="5">TREDPLAN is used in the case of infrastructure situations that are particularly critical in order to estimate the effects of certain measures on the overall system to be analysed. The use of such a tool goes beyond the criteria in planning standards and, therefore, can be seen as a planning/organisational measure at network or regional level.</td></tr>
<tr><td>prevent</td></tr>
<tr><td>protect</td></tr>
<tr><td>respond</td></tr>
<tr><td>recover</td></tr>
</table>

How were measures evaluated? What was the cost/benefit ratio? Have macroeconomic consequences been demonstrated?
The extent of the macroeconomic damage caused by the seismic event was determined, along with the proportion of them that could be prevented by resilience measures. The measures are evaluated in the context of resilience analysis with regard to macroeconomic indicators such as employment or national product or gross domestic product (GDP). 
Are implementation, applicability, practicability etc. evaluated?
The analyses carried out require input/output models. The tools used in this case TREDPLAN (https://www.tredis.com/products/tredplan) and TREDIS (http://www.tredis.com/products/product-overview) are not available for Europe.

Fact sheet 4	Security of Road Transport Networks (SeRoN)

Summary

In the research project "Security of Road Transport Networks (SeRoN)" in the context of the 7th EU research framework programme, between 2009 and 2012 a method was developed for the identification and quantification of the risks of critical road infrastructure elements and was applied taking case studies as an example.

Reason for the report

Research project in the context of the 7th EU framework programme

How has resilience been evaluated/indexed?

The procedure for evaluation of the resilience of road sections takes place on the basis of four procedural steps:

1. Identification of potential critical elements in a defined road network:

The method focuses on tunnels and bridges as potentially the most critical elements in road networks. Criticality is evaluated according to different structure-specific characteristics (e.g. length, frequency of traffic, proportion of heavy traffic, expected repair time).

2. Evaluation and prioritisation of the relevancy of the identified elements

Prioritisation is worked out from the point of view of network-wide consequences in the event of a failure of the identified elements.

3. Risk estimation for the most critical elements

For the most critical elements, the risks are estimated on the basis of a defined catalogue of hazards and assessment criteria. For the risk assessment, in addition to the frequency of occurrence of trigger events, the direct consequences (e.g. fatalities and casualties, damage to property) as well as the indirect consequences (e.g. regional economic effects due to travel delays and environmental pollution due to diversions) are taken into account in monetised form.

4. Analysis and evaluation of risk mitigation measures

Based on cost/effectiveness analyses, the proportionality of possible additional measures is investigated.

The evaluation of resilience is therefore based on an estimate of the resulting risks of the breakdown of a critical road element and the proportionality of possible additional risk-mitigating measures.

The procedure developed was applied as an example for several bridges and tunnels in the European road network. The analyses focused on the applications and validation of the procedure and not on a specific search for resilience measures for the appropriate structures.

How were measures derived and which measures were they?

The procedure developed gives a comprehensive breakdown of possible protective measures for critical road infrastructure elements. Standardised guide costs were also indicated in the research project for many measures. A specific procedure for the selection of potentially suitable measures is not defined further. This is left to the users of the method.

The resilience measures discussed in the case study can be classified as follows into type categories of measures:

Resilience measures Phase	Structure		Network/Region	
	Technical	Planning/ organisational	Technical	Planning/ organisational
prepare	• Monitoring of the structure • Traffic monitoring and control • Rapid, real time detection and communication	• On-site inspections • Advance regulation of processes and requirements • Training of the monitoring and operating staff • Development of emergency and hazard prevention plans • Emergency practices	• Traffic monitoring and control	• Advance regulation of processes and requirements • Training of the monitoring and operating staff • Development of emergency and hazard prevention plans • Emergency practices
prevent	• Physical barriers • IT security • Limiting of damaging effects	• Access control	*no details*	
protect	• Protective clothing • Reinforcement of structural elements • Design and layout	*no details*		
respond	• Site characteristics • Escape and evacuation conditions	• Suitable road user information and instructions	• Redundant design	• Suitable road user information and instruction
recover	• Temporary exchange • Rapid repair	• Reconstruction and restoration plans • Accelerated planning and development of planning permissions • Effective damage assessment	*no details*	• Indication of alternative routes • Network control measures • Crisis plans • Effective damage assessment

How were measures evaluated? What was the cost/benefit ratio? Have macroeconomic consequences been demonstrated?

The assessment of risk mitigation measures (or measures to increase resilience) is based on cost/effectiveness analysis). The network-wide (monetised) estimate is compared here with the costs (for investment and operation) of possible additional measures in the event of consequences of possible non-availability of the critical road infrastructure elements with a view towards deciding upon any such measure.

Are implementation, applicability, practicability etc. evaluated?

The procedure developed in the research project focuses on network-wide effects in a failure-critical road infrastructure element. For those of direct and indirect effects, to some extent very complex model calculations have been used in the research project for the determination of the consequences. For example, comprehensive analyses of the traffic delays have been determined using extensive transport models. For a broad application – e.g. for the entire Federal trunk road network – the developed procedure and the associated methods and model are too expensive in some cases. Accordingly, the procedure is primarily suitable for specific individual case studies.

Fact sheet 5	SKRIBT joint project – protection of critical bridges and tunnels along road routes

The Federal Ministry for Education and Research (BMBF) & VDI Technologiezentrum GmbH (2013): Joint project SKRIBT – Protection of critical bridges and tunnels along road routes. Final report: protection of critical bridges and tunnels (http://www.skribt.org/).

Summary

The SKRIBT project was initiated by the BMBF. It was the objective of the report to identify potential hazards for road bridges and tunnels (threat analysis), to carry out structure analyses and to develop protective measures. Various types of hazard can be taken into account.

Reason for the report

The report was drawn up in the context of the SKRIBT project, as part of the "Research for civil security" programme.

How has resilience been evaluated/indexed?

The term resilience is not used as such. The measures however reduce the probability of occurrence and the damage caused by a possible incident and, therefore, can be considered to be resilience measures. A threat and structure analysis was carried out. Critical structural works were identified, taking into account users, construction and traffic.

How were measures derived and which measures were they?

The effects of an incident were compared with the resistance capability of a structure and measures derived from this comparison to increase resistance capability. Classification into technical structural, operating and organisational measures followed, allocated to various competent parties (structure owner, structure operator, emergency services). Preventive and mitigating measures for structure and user protection. The measures were assigned to one or more event categories.

Resilience measures	**Structure**		**Network/Region**	
Phase	Technical	Planning/ organisational	Technical	Planning/ organisational
prepare	• Hazardous goods identification (T) • ITCC integration (T) • Faster incident detection (T) • Wind-speed warning system (B) • Water level measurement (B)	• TLZ Operator training (T), alarm- and hazard prevention plans (T), exercises by operating and emergency services (T), advance information to tunnel users (T), situation training tunnel users (T), emergency practices on bridges (B)	*no details*	
prevent	• Physical barriers/access prevention (B) • Prevention of parking under bridges (B) • Wind screens (B) • Extension of freeboard (B) • Limiting of hazardous goods (T) • Gas detection (T) • Detection of overheating vehicles (T)	• Keeping inventory documents locked away (B)		
protect	• High-performance concrete used as the structural concrete (B,T), facing formwork made from micro-reinforced high-performance concrete (B,T), fire protection concrete (T), damper concrete (T), double-skin construction (T), reinforcement and screed (B), shear walls instead of pillars (B), impact protection (B), bearing protection (B) • Dimensioning for explosion	*no details*		

	stresses (T) • Design of statically undefined systems (B) • Design for higher impact stresses (B) • Fire resistant cladding (T), automatic fire fighting system (T), extended blazing fire phase (T), smoke extraction (T) • Shorter emergency escape intervals (T) • Special bridge emergency call (B)			
respond	• Automatic blocking devices (B), Softstop barrier (T)	• Tunnel communication	• Global redundancy	*no details*
recover	*no details*			

How were measures evaluated? What was the cost/benefit ratio? Have macroeconomic consequences been demonstrated?

Effectiveness/costs analysis taking into account social acceptance and operating and economic aspects. Cost/benefit difference and cost/benefit ratio were assessed for the four example structures. Macroeconomic aspects were assessed.

Are evaluation, applicability, practicability etc. evaluated?

Using four example structures, applicability was verified. According to the report, a procedure was made available which, despite a high level of complexity, demonstrates high practicability.

A2: Examples of assessments of macroeconomic consequences of transport measures

There are various statistical and/or macroeconomic models for testing the macroeconomic consequences of (resilience) measures. These can be distinguished by the transport input variables (infrastructure or accessibility) and macroeconomic output variables (capital productivity, value creation, employment, property prices):

- Analyses of infrastructure and capital productivity
- Regional economic models: Analyses of accessibility and value creation

Appropriate procedures and approaches, as used also for the evaluation of resilience measures, have been summarised below. These studies document the state of research [49] relevant to practical situations. [49] also lists more recent developments such as system dynamics models e.g. the ASTRA model and integrated evaluation models such as HIGHTOOL or TRIMODE. ASTRA however serves to simulate the spread of new technologies. The integrated evaluation models too only link existing partial models together which, in turn, link back to existing and regional economic models, which will also be described later on.

Analyses on infrastructure and capital productivity

The following studies demonstrate the extent to which an investment increases macroeconomic capital stock and how high the capital productivity of such an investment is. It is not taken into account what sort of projects these are, whether they are useful from a traffic planner's perspective or how they affect travel times.

In principle, such capital productivities could also be determined and used for investments in resilience measures. If such capital productivities exist, these could be simply applied.

Swiss Economic Institute at ETH Zurich, (Konjunkturforschungsstelle) – KOF (2005)

In an analysis of literature, KOF studied several foreign and domestic empirical studies in which connections were described between infrastructure investments and economic growth using statistical models. In most studies, growth-increasing effects of investments in public infrastructure were demonstrated empirically.

For the profitability calculation of infrastructure investments in Switzerland, the KOF assumes a production elasticity of between 0.02 and 0.06. The profitability of the Swiss traffic infrastructure capital of 6% to 12% calculated from this is considered by the authors to be a somewhat conservative estimate. The estimated lower limit of profitability of around 6% is however higher than the current actual interest rate and many forms of investment.

Rhineland-Westphalian Institute for Business Development, RWI (2010)

The study "Traffic infrastructure – growth aspects in the context of a formative financial policy" by the RWI investigates the economic effects of investments made into traffic infrastructure in Germany, without taking into account changes in accessibility. Using three models (vector-autoregressive model, panel analysis and structural model), regression coefficients and elasticities are calculated between investments in traffic infrastructure and several economic indicators (GDP, employment, investment volume, prices, etc.), and checked for statistical significance.

Using the vector-autoregressive model, the authors determine a positive growth effect from traffic infrastructure investments after one year. Over the course of time, thereafter, this did not continue. In addition, it is demonstrated that investments in road transport develop more intensive growth effects than those in rail transport. With the panel analysis, a positive link was determined between traffic investment and GDP, in which the elasticity indicators derived were rather low values (0.03 – 0.08). In places with less well-developed traffic infrastructure (east Germany compared to west Germany), such investments seem to achieve more value-creation-relevant effects. Like the vector-autoregressive model, the structure model also shows effects one year after investment, diminishing significantly as time goes on.

Regional economic models: Analyses of accessibility and value creation

The approaches taken here attempt at directly improving the transport network and their effect on value creation (BIP) primarily by means of statistical regression analysis. An accessibility indicator is always calculated with this. Accessibility, however, is determined in different ways in the studies investigated, e.g.:

1. *BAK Basel (2011):* BAK Basel – a dedicated accessibility indicator primarily based on the determination of travel times. Instead of travel times, airline distances can also be used, in which the centrality of the geographical location is then determined.

To determine the relationships between value creation (GDP) and accessibility, conventional econometric structural models are used which, in addition to multimodal accessibility indicators (MIV + ÖV) contain several control variables on the level of the MS regions. By means of such a model, an annual GDP rise of 1.1 to 3.2 billion CHF was derived for the Gotthard base tunnel which corresponds to an amortisation period of the transport infrastructure of 4 to 11 years.

2. *Department for Transport, DfT and Graham, United Kingdom (2005-2009):* Improved access leads to concentration of economic activities according to the United Kingdom Department for Transport (DfT) and thereby to positive externalities, known as agglomeration effects. According to Graham (2006), the efficiency of a transport system has an indirect effect on the productivity of workforces. For this, he coins the term *effective density*, which reflects the number of workers in a sector at a particular place plus those in other locations, inversely weighted by a distance factor. The effective density may be determined in four ways. In a further investigation Graham et al. (2009), in addition to revised elasticity indicators, demonstrate sector-specific distance degradation factors for more accurate determination of effective density. The values are reproduced in the table below. Their use is recommended by the DfT to calculate agglomeration effects in cost/benefit analyses and is documented for several projects to develop the railway infrastructure in the United Kingdom (e.g. Crossrail)

	elasticity of productivity with relation to effective density	Distance degradation factor
Branch		
Manufacturing	0.021	1.097
Construction	0.034	1.562
Consumer Services	0.024	1.818
Business Services	0.083	1.746
All industries	0.043	1.655

Figure 13: Indicators of sector-specific elasticity of productivity with relation to effective density and distance degradation according to Graham et al. (2009)

3. *Ernst Basler + Partner, EBP (2005):* In this study, cluster analyses are used to set out production functions for three types of region (cities and environs, border and peripheral regions, Alpine districts) and four sectors (agriculture, industry, services excluding tourism, tourism) in Austria which also include the *accessibility* factor. This is measured by means of a potential base derived from the number of inhabitants that can be reached by a political district (population accessibility potential). The model was used on two case studies. Measure-specific changes in gross value creation of 459 million EUR/a or 340 million EUR/a correspond to an increase in national gross value creation of 0.22% or 0.16%. The benefit is then calculated in accordance with conventional cost/benefit analyses. The benefit in the cost/benefit analysis is around 265 million EUR/ or 151 million EUR/a, lower than according to the value creation analysis. Any double counting has then already been eliminated. The study also demonstrates how changes to gross value added could be integrated into cost/benefit analyses in future.

Institut für Höhere Studien (Institute of Higher Studies), IHS (2006)

The IHS has prepared the accessibility-dependent regional model (EAR), which creates a link between accessibility and socio-economic key indicators such as gross value creation, number of companies, number of jobs etc. The accessibility of a region is therefore defined using the following formula:

$$EI_i = \sum (a_{ij}) * w_{ij}$$

The meaning of the variables is as follows:

EI_i: Accessibility of the region i,
a_{ij}: Travel time between the region i and a region j
w_{ij}: Individual weighting factor depending on the accessibility indicator
The factor w_{ij} in the above formula can be adapted to the calculation of the following accessibility indicators:

- Long-distance accessibility
- Short-distance accessibility
- Frequency-weighted long-distance accessibility
- Frequency-weighted short-distance accessibility
- Distance from a regional centre

The IHS determines elasticities of gross regional product depending on frequency-weighted long-distance accessibility of 0.02 and the distance from the regional centre of 0.01. Based on this, the IHS calculates the probable value creation effects of four Austrian railway projects on the geographical aggregation level of the federal regions. They are reported in figure 14.

increase in gross value in Austrian regions [Mio EUR/10a]			
	Semmering-Basistunnel (old project)	Bypass Selzthal	Mariazellerbahn
Burgenland	0	0	0
Kärnten	43.99	0	0
Niederösterreich	78.51	0	8.14
Oberösterreich	0	0	0
Salzburg	0	2	0
Steiermark	80.42	9	0
Tirol	0	2.23	0
Vorarlberg	0	1.09	0
Wien	83.11	0	0
Summe	**286.03**	**14.32**	**8.14**

Figure 14: Increase in gross value creation in the Austrian regions based on three rail projects

The IWW et al. [61] model includes the following potential factors: infrastructure, highly-skilled human resources, location factors and environmental quality. These potential factors are combined with an exogenous parameter using a Cobb-Douglas function and estimated as a cross-section. The results for calculations with new infrastructure indicate potentials for economic development. These only occur if the transport infrastructure represents a bottleneck in regional development. The calculated potentials are only of relevance to economic analysis if this is the case..