Joint Project RITUN

Guidelines for improving the resilience of road tunnels

RITUN
RESILIENTE TUNNEL

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Resilient Road Tunnels (RITUN) - Guidelines for improving the resilience of road tunnels

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Publisher:
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Overall responsibility:
Dr. Jürgen Krieger
Federal Highway Research Institute (BASt)
Bruederstrasse 53,
51427 Bergisch Gladbach,
Phone: +49 (2204) 43-0,
e-mail: ref-b3@bast.de

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Foreword

The federal highways form the largest transport network for people and goods in Germany and are an essential foundation for our modern society and economic prosperity. Due to their connecting and shortening function, tunnels play a central role in this network in ensuring the efficiency of the road transport network. The damage or even complete loss of critical tunnels due to disruptive events can result in high restoration costs with long downtimes and thus in considerable economic damage. For this reason, the research project RITUN, funded by the German Federal Ministry of Education and Research (BMBF), investigated possibilities to improve the resilience of tunnels in order to contribute in a structured way to maintaining their availability and safety. The present guideline is an essential result of this project. It is based on a methodology for assessing the performance of tunnels in the event of an incident and identifying resilience measures to maintain and increase traffic flow after an incident. These results are based on risk analytical studies, traffic simulations and the cooperation of experts from research and practice. The results were tested in practice on a tunnel and an enclosure before publication.

We wish you every success in improving the resilience of your tunnels and would like to support you with this guide.

Summary

This guide contains all the information and tools necessary for practical application in order to systematically improve the resilience of road tunnels. This includes, on the one hand, increasing the resistance of tunnels to external influences and, on the other hand, accelerating the return to full availability after the occurrence of an event. The possibility of temporarily operating tunnels after an event while maintaining the required safety level is also taken into account, thus ensuring partial availability.

After a short introduction in the second chapter, the concept of resilience for road tunnels, the effects of resilience measures and their embedding in a systematic resilience management are presented.

A prerequisite for the identification of resilience measures is the knowledge of potential threats. For this purpose, all relevant threats have been assigned to points of impact on the basis of the all-hazards approach and damage scenarios have been derived from this. These were then transferred to a threat-damage matrix **(Annex 1)**.

Then the effects of the damage scenarios on tunnel operation and traffic are presented. In addition, minimum operating conditions were worked out which, by implementing compensation measures, allow a tunnel to continue operating safely after an incident. The compilation of the damage scenarios and their effects on tunnel operation and traffic were also transferred into a table **(Annex 2)**.

In the next step, the identified resilience measures are presented with a methodology for targeted selection **(Annex 3)**. In addition, so-called fact sheets with detailed information on the measures were developed **(Annex 4)**. For better understanding, an example of how to apply the guide was created, which can be downloaded from the project website (www.bast.de/ritun).

The guide concludes with concluding remarks on resilience, which take up aspects beyond the measures contained in this guide and encourage further engagement with the topic of resilience.

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Glossary

In the following, the terms required for a uniform understanding of this guide are defined.

Agility	Agility is a characteristic of management, flexible and that-beyond proactive, anticipatory and proactive action, to introduce necessary changes.
Threat	A threat is a potential hazard that could damage a harmful-effect and thereby enhance the functionality of the of road tunnels.
Disruptive Event	Disruptive events lead to shock effects (acute shocks) or creeping change processes (chronic s tresses), which describes the functionality of a system have a negative influence.
Danger	A threat becomes a potential danger if they point out a weakness (especially technical or organizational deficiencies) and thus condemn a damage.
Capacity	Capacity is the maximum possible traffic intensity that can be given boundary conditions can be achieved.
Functional Compensation	Through functional compensation, the loss of a certain functionality due to damage to a component can be fully or partially compensated for by existing redundancies or by other systems.
Safety-related Compensation	By means of safety-related compensation, the increase in risk due to damage to a component can be fully or partially compensated for by safety-related measures. Organizational and traffic measures can be used for this purpose.

Resilience Culture	Resilience culture describes the approach of observing and applying aspects of resilience with the promotion of awareness and trust in new forms of knowledge among the employees in an organizational unit such as the Road Administration.
Resilience	Resilience is the ability to prepare for disruptive events, to take them into account, to fend them off, to cope with their effects, to recover from them as quickly as possible and to adapt to them with increasing success [following (Thoma, 2014)].
Resilience management	Resilience management is a circular interplay of goal definition, identification of critical elements, risk analysis, resilience screening and action planning in combination with information transfer and periodic reviews.
Robustness	Robustness describes the ability of a system to withstand failures of individual system components without a loss of system functionality.
Damage Scenario	A damage scenario describes the changed situation at and in a tunnel after the occurrence of a disruptive event.
Safety relevance	Safety relevant are all damage scenarios that can cause relevant effects on the safety of persons.
Safety significance	Safety significant are all damage scenarios, which risk exceeding the tolerance range and lead to the achievement of the action range.

1 Introduction

Germany's social and economic stability is highly dependent on mobility and functioning commodity chains. The road transport infrastructure is the most interconnected of the transport infrastructures. Ageing, natural and man-made hazards threaten its security and availability. The growing complexity of the road infrastructure, its interdependencies with other critical infrastructures and the threats to be expected in the future from the use of new technologies, such as digitization, mean that questions of security and availability must be researched continuously and proactively and recommendations must be derived.

1.1 Background and Motivation

Special attention is paid to safety in tunnels because, unlike on the open road, road users are in a structure that restricts escape and rescue options. For this reason, incidents in tunnels have serious effects on user safety, the structure and the operational equipment compared to the open road. Restoration can lead to long traffic restrictions (tunnel closures) and as a consequence cause considerable extra travel time and environmental pollution by using alternative routes. Alternative routes via the subordinate network are often not dimensioned for the additional traffic volume, which leads to a reduced capacity as well as an increased number of accidents with material damage and accident victims. The additional loads, especially from freight traffic, can cause damage to the road substance of the alternative routes, which in turn leads to corresponding repair measures. These economic costs resulting from the indirect effects usually exceed the direct costs of the damage to tunnels and equipment many times over.

To illustrate this, the example of the truck fire in the Königshainer Berge tunnel in the course of the A4 Dresden - Görlitz, 14 km before the federal border with the Republic of Poland in May 2013 is given: The repair of the damage caused by the fire in the tunnel led to the closure of one tunnel tube for five months. Traffic was diverted from the freeway to bypass the tunnel. This resulted in considerable extra travel time and damage to the roads on the bypass.

Figure 1.1: Extinguishing work after the truck fire in the tunnel Königshainer Berge on 18.05.2013 (Source: Peter Eichler, kreisbrandmeister-goerlitz.de)

This example exemplifies a large number of events of the last few years and impressively illustrates the effects. The comparison of two fires in the Austrian tunnels Gleinalm (2018) and Arlberg (2019) with potentially similar sizes. Due to the considerable damage in the Gleinalm Tunnel, costs for construction measures of around €2 million were incurred, which were exceeded many times over due to the additional loss of toll revenue, the high load on the detour routes and extra travel time. The tunnel could be opened to traffic after it had been closed for about three months. The use of an automatic fire-fighting system in the Arlberg tunnel, on the other hand, prevented both user injury and damage to property and enabled the tunnel to be reopened after just a few hours.

It becomes obvious that solutions for improving the resilience of tunnels, i.e. for protection against hazards, to prevent and mitigate the effects of incidents and to accelerate the return to full performance, are of great importance for the entire road transport infrastructure. The RITUN guide has been developed to assist tunnel operators in achieving these goals.

1.2 Goal and Benefits

The aim of the RITUN project was to improve the resilience of road tunnels to disruptive events. In order to achieve this goal, a method was developed that allows an overall assessment of availability and resilience. In addition, suitable measures were developed to prevent and mitigate disruptive events and to achieve the necessary availability faster than before. For this purpose, minimum operating conditions were also investigated which have to be observed in order to continue operating tunnels temporarily - possibly with reduced performance.

This guide summarizes the results relevant to practice and presents them in the necessary depth for application. Further scientific results are included in the project reports and can be accessed on the project website www.bast.de/ritun.

1.3 Systematically to more resilience

At this point, the structure of the guide is explained in summary. As an introduction to the topic, the concept of resilience and the adaptation for tunnels are presented and the classification in the context of the so-called resilience management is discussed. The recognition of interdependencies with other critical infrastructures also plays an important role.

The methodology developed in RITUN consists of three core elements as shown in Figure 1.2.

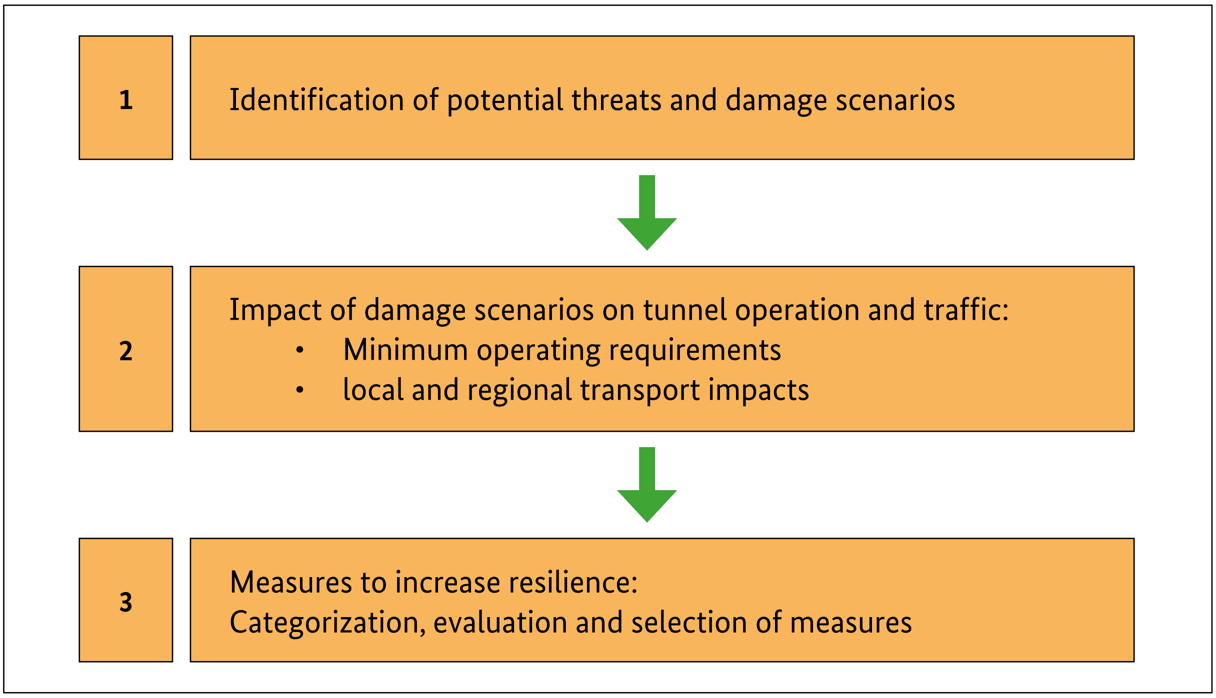


Figure 1.2: Structure and layout of the guide

STEP 1

In the first step, all currently relevant threats to the security and availability of road tunnels are presented and their points of impact are assigned. On this basis, potential damage scenarios are identified which occur due to a threat at the tunnel.

STEP 2

The effects of these damage scenarios will be investigated in more detail with regard to both tunnel operation and traffic. For this purpose, so-called minimum operating conditions were developed. These are decisive for whether and how a tunnel may continue to be operated in accordance with the required safety level as a result of an incident. Thus, availability can often be maintained to a large extent, possibly by using risk-reducing compensation measures. Subsequently, the traffic effects of the restricted operating scenarios are determined. This is done both on a local level in the immediate vicinity of the tunnel and on a regional level in the road network. Thus the influence on capacity and the resulting economic costs due to the traffic restrictions can be determined. With the help of this monetary evaluation, operators are provided with a decision-making aid for investments in improving resilience.

STEP 3

On the basis of this preliminary work as well as operator interviews and expert workshops, potential measures to increase the resilience of road tunnels are presented in the final step. These are accompanied by a methodology that enables the evaluation of the effect of these measures on various aspects of resilience. This allows users to select, prioritize and implement measures in a targeted manner. The measures can be of technical or organizational nature and are assigned to the resiliency phases according to their time of effect.

APPENDIX AND APPLICATION EXAMPLES

In the appendix you will find an overview of the developed tools you need for a systematic improvement of resilience. You can download them as an editable file for individual processing and possible adjustments and extensions free of charge from the project website www.bast.de/ritun. Here you will also find application examples for the tools.

NOTES IN THE GUIDE

In addition, the guide provides further information and aids on the respective aspects of resilience, which you can use for a more in-depth study of the topic in question if necessary.

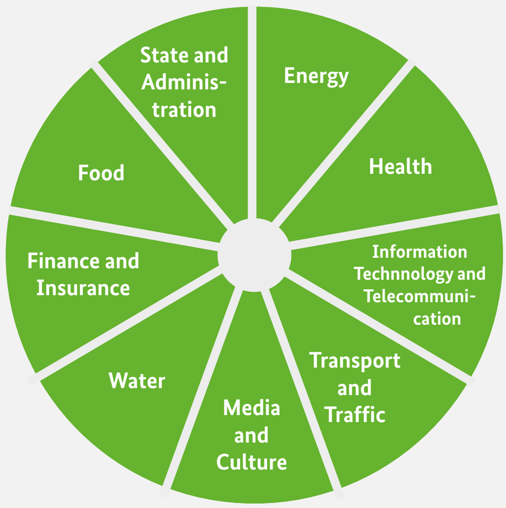
1.4 Scope and limits

Increasing the resilience of tunnels is a continuous process, which ideally should be embedded in a resilience management system and always be designed in the context of the interactions with other critical infrastructures. The basis of any management system is the initiation of the process by the so-called Top-Management, i.e. the highest level in the hierarchical organizational structure, which clearly identifies resources and assigns the necessary relevance to the topic. Depending on the hazard situation, the processes must be run through again.

This guideline is based on an action-oriented approach, which was developed under consideration of the currently valid German and European regulations (RABT, EABT). Improvements can only be achieved in those areas for which measures exist at the present time. Therefore, the implemented measures have to be evaluated and adjusted at regular intervals with regard to their effectiveness and efficiency. Ideally, new measures should also be developed and implemented in dialogue with other operators of critical infrastructures.

Critical Infrastructures

Critical infrastructures are organizational and physical structures and facilities of such vital importance to a nation's society and economy that their failure or degradation would result in sustained supply shortages, significant disruption of public safety and security, or other dramatic consequences



You can find further information at **https://www.kritis.bund.de/SubSites/Kritis/EN/Home/home_node.html**

Picture source: https://www.kritis.bund.de

2 Basics

2.1 Resilience

The term resilience has its origins in the Latin resilire (to bounce back, bounce off) and describes the physical ability of a body to bounce back to its original shape after a change of form. The term as well as the concept has become ubiquitous and is used in various disciplines, for example in the description of ecosystems, psychology and now also in engineering.

In this guide, resilience is understood as the ability of road tunnels to prepare for disruptive events, to take them into account, to fend them off, to cope with their effects, to recover from them as quickly as possible and to adapt to them with increasing success (following (Thoma, 2014)).

The concept can be represented graphically using the functionality progression over time (Figure 2.1). The smaller the area between the level of the original functionality and the functionality changed due to a disruptive event, the greater the resilience. This means that the system reacts more resiliently to disruptions and then returns to full performance more quickly. Resilience measures therefore aim to keep the loss of functionality due to events as low and as low as possible. This is achieved if measures reduce

- … the frequency of occurrence of disruptive events (1) and/or
- … reduce the loss of functionality ΔF (2) and/or
- … shorten the time until the original functionality Δt is returned (3).

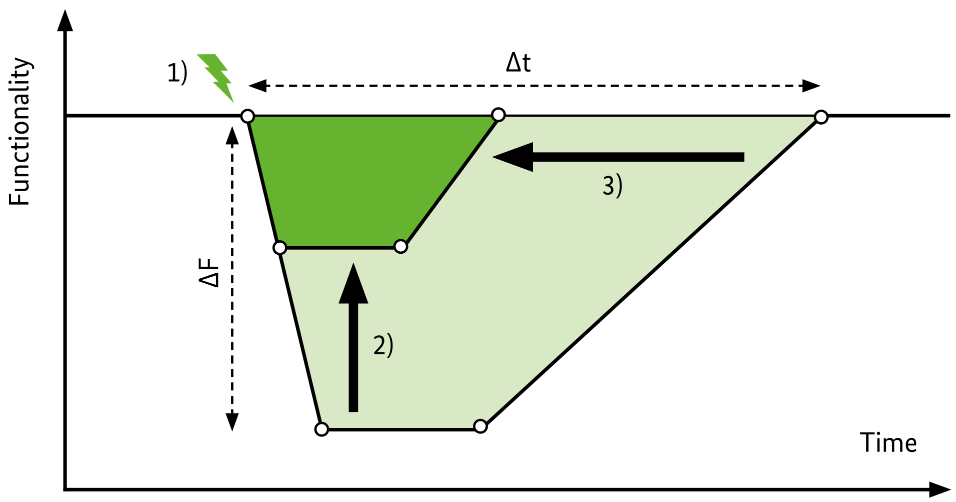


Figure 2.1: Effect of resilience measures on the course of the functionality curve, based on (Deublein et al. 2018)

The process for continuous improvement of resilience can be represented as a cycle (Figure 2.2) and consists of the phases

- … prevent,
- … protect,
- … react and
- … recover,

which run in chronological order, while the phase "prepare" as an integral element always precedes all other phases and also includes the aspect of learning from past events.

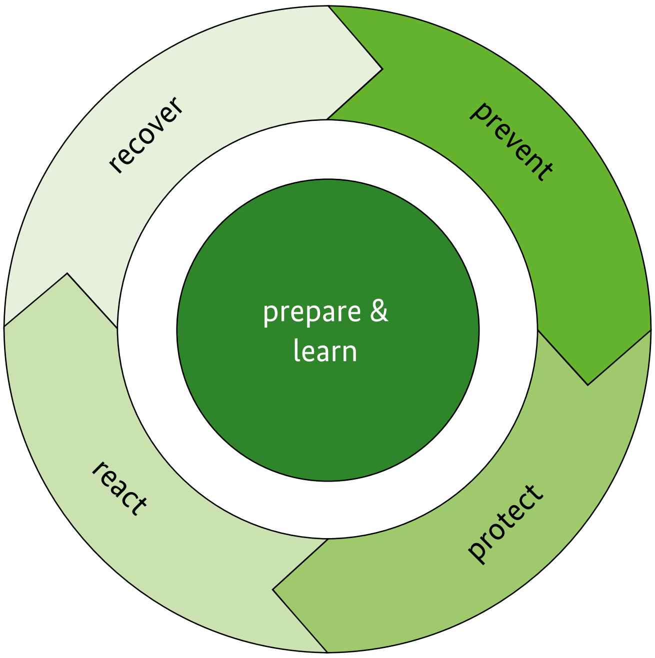


Figure 2.2: Resilience cycle, based on (Thoma, 2014)

2.2 The influence of measures on resilience

Resilience measures act in one or more phases of the resilience cycle and thus contribute to the resilience of the overall system. To illustrate their effect in the different phases, the following idealized figure 2.3 shows the respective influence of a measure on the course of the functionality curve.

a) Without measures: After a disruptive event has occurred, the functionality drops to its minimum value for the duration of the event and then returns to its original value in a recovery period.

b) Preventive measure: If the occurrence of a disruptive event can be prevented by measures of the "Prevent" phase, the functionality is completely preserved.

c) Protective or reactive measure: By measures of the phases "protect" and "react" the loss of functionality is reduced. Since this reduces the loss of functionality to be restored, the recovery time to full functionality is shortened.

d) Recovery measures: The restoration of full functionality is accelerated by measures of the "recover" phase, thus reducing the recovery time.

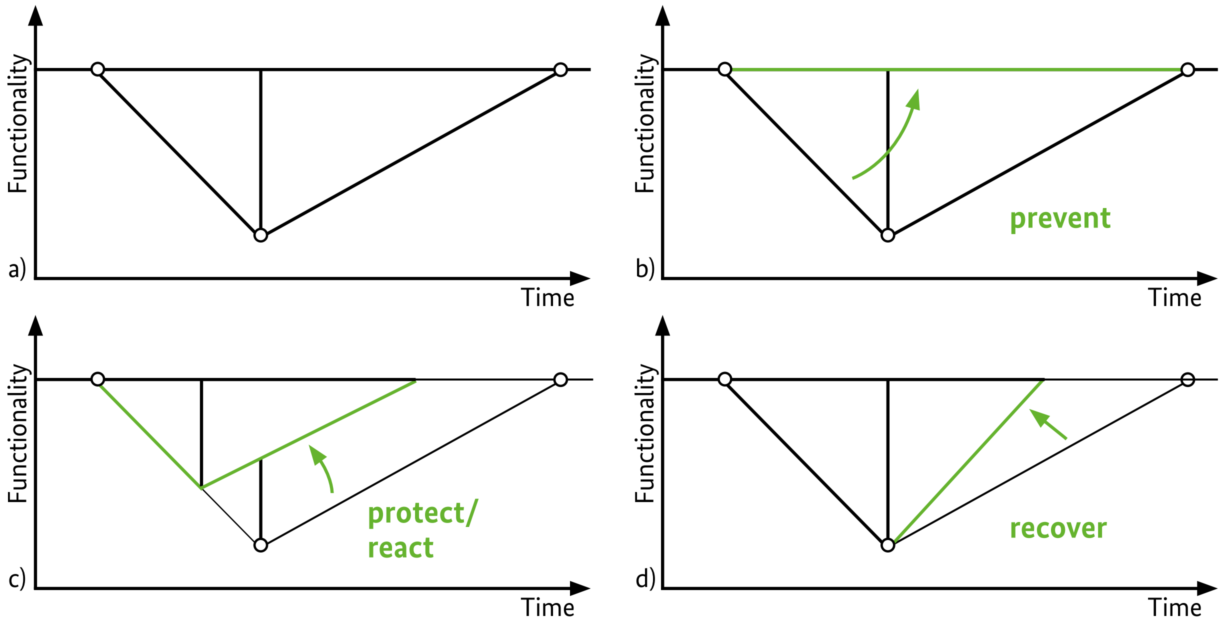


Figure 2.3: Idealized representation of the influence of resilience measures per phase
a) without measures, b) prevent, c) protect/react, d) recover

2.3 Functionality of road tunnels

The resilience of a system is defined, as already described, by its functionality. The requirements for road tunnels according to the German federal traffic route plan (BVWP) are fundamental for the definition of the functionality to be maintained or restored, which formulates targets for efficient, safe and environmentally friendly passenger and freight transport. Elements of the transport infrastructure therefore have several target values to be met (Table 2.1).

Table 2.1: Possible target values for defining functionality according to the German BVWP 2030

Category	Functionality (target value)	Indicator
Economic aspects	Travel/transport time	Vehicle hours
	Capacity	Capacity
	Operating costs	Carriage/transport costs
	Intra-local separation effect	Waiting time (inner city)
	Value creation effects	Added value/employment
Traffic Safety	Accident costs	Personal injury/property damage
Environment	Air pollutant/greenhouse gas emissions	Mileage
	Noise pollution	Mileage (urban)
	Impairment by the building	Qualitative indicators
	Landscape/local image	Qualitative indicators

The present guideline aims to ensure and improve the availability of tunnels by improving resilience and to reduce or avoid the traffic impact due to disruptive events by selecting appropriate measures. Therefore, the (remaining) capacity as well as the duration of a restricted operation or failure in case of an incident are used as decisive target values.

2.4 Resilience management

Ideally, the resilience measures developed in RITUN should be integrated into a systematic resilience management that strengthens the resilience of road tunnels against external influences. This is done by improving resilience through measures that proactively strengthen agility and reactively strengthen robustness (see (Wieland & Wallenburg, 2013)).

In this context, the RITUN resilience measures represent an essential part of the resilience management as shown in Figure 2.4 and cover the elements net screening (3), resilience assessment (4) and action planning (5).

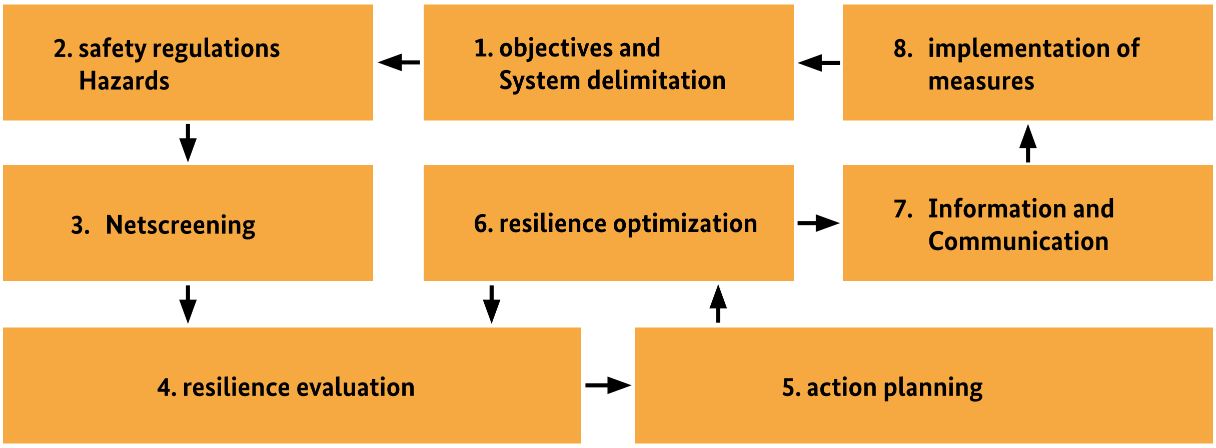


Figure 2.4: Elements of a resilience management (Deublein, Roth, Bruns, & Zulauf, 2018)

Netscreening is used to identify potentially critical tunnels with respect to resilience. Thus, by means of a rough check of the traffic network to be investigated using meaningful and simple parameters, the workload can be made acceptable. In the course of the **resilience assessment**, possible impacts and their potential effects on functionality are examined in order to obtain a first evaluation of individual road tunnels. These worksteps provide a sound basis for the targeted **planning of measures**.

In this context, it is also clear that resilience management is based on the risk management, embedding it in a management cycle and adding elements such as networking with stakeholders and learning from events.

Interdependencies with Critical Infrastructures

To identify interdependencies with critical infrastructures, the instruments of the RESILENS project (Realising European ReSILiencE for CritIcaL INfraStructure) are available. Here, a guideline for overall resilience management was developed in cooperation with BASt, which can also be used by road infrastructure operators. This guideline is supplemented by a resilience management matrix and an audit toolkit, which enable you to evaluate your tunnel on different spatial scales (urban, regional, national and cross-border) and thus to become aware of dependencies and responsibilities to other critical infrastructures and to derive measures. The link to the evaluation will be made available on the project website www.bast.de/ritun. Here you can carry out the evaluation online.

3 Threats and Damage Scenarios

In the following chapter, the threats to road tunnels identified by the all-hazards approach are categorized. If a threat meets a vulnerability (especially technical or organizational deficiencies), a potential threat of damage is created. The identification of relevant damage scenarios as a result of these threats was carried out in consultation with experts in tunnel planning, tunnel safety and tunnel operation.

3.1 Threats

A distinction is made between potential man-made threats and threats of natural origin. Threats that cannot be assigned to one of these categories are assigned to the category "other".

Threat identification

The identified threats in the Threat Damage Matrix in **Annex 1** are numbered and refer to fact sheets from the AllTraIn project. These fact-sheets contain further information on individual threats. They can be downloaded free of charge from the project website.
http://www.alltrain-project.eu/results/

AllTraIn also offers the possibility of identifying relevant threats online and in English. You can find the AllTraIn tool at:
http://www.alltrain-project.eu/tool/

The operating instructions for the tool are provided by the AllTraIn guide, which you can also download from **http://www.alltrain-project.eu/results/**.

3.1.1 All hazards approach

A threat is a potential danger that can have a damaging effect and thus reduce the functionality of road tunnels. In identifying the hazards, the all-hazards approach is followed in accordance with the National Strategy for Critical Infrastructure Protection KRITIS (German Federal Ministry of the Interior, 2009). In doing so, all threats potentially relevant for tunnels are considered equally. These include threats of natural origin and those posed by humans. Threats that do not belong to any of these categories are listed separately as “other”. The extent to which a tunnel is potentially endangered by a threat depends on exposure criteria, triggering conditions and existing weak points. Relevant threats are therefore defined as potential events that may affect the safety and/or availability of traffic in tunnels.

3.1.2 Points of Impact

In RITUN, threats are assigned to ploints of impact in order to identify and select measures in a targeted manner. A distinction is made between the following points of impact:

- … Tunnel structure
- … Tunnel equipment
- … Network element (in which the tunnel is located, defined by road access and exit)
- … Centralized systems (e.g. tunnel control center, operating building, energy supply)

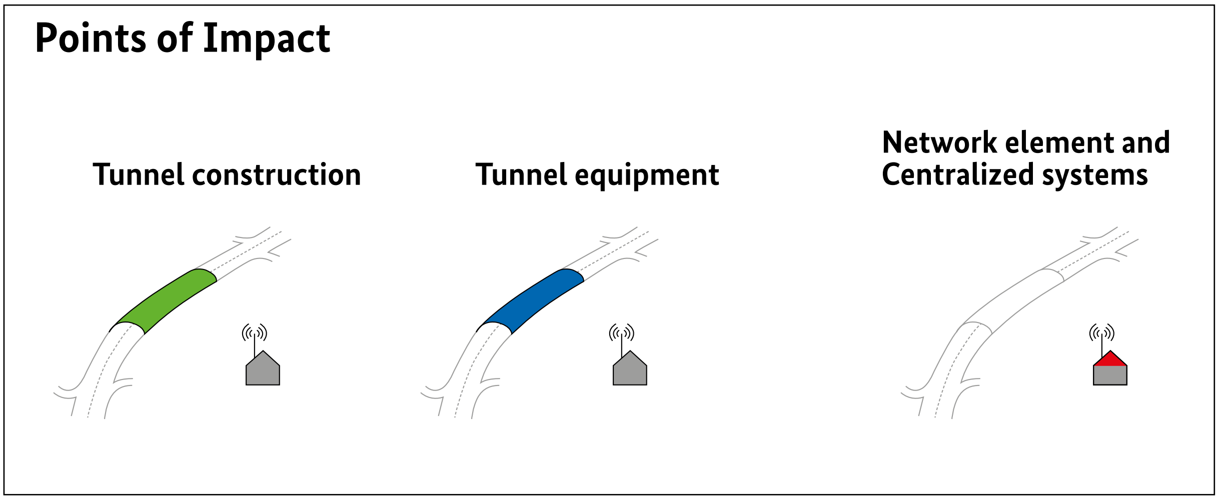


Figure 3.1: Points of Impact

3.1.3 Information on intentional man-made threats

At this point, we will briefly discuss the specifics of man-made intended threats. These include physical, cyber- and cyber-physical attacks, i.e. targeted actions by persons or groups of persons from direct near or from cyberspace. Both the probability of occurrence of targeted attacks and the extent of damage are difficult to estimate, since the threat situation is constantly changing.

Physical attacks, such as blocking entrances, exits or escape routes, and causing a fire or explosion, are easy to carry out due to the easy access and decentralized nature of the tunnel infrastructure.

A successful cyber attack on a tunnel control center could lead to the situation that all monitored tunnels have to be controlled locally via the operating buildings. This could quickly lead to personnel bottlenecks. In the past, little emphasis was placed on security when developing the systems, which is why many of them are comparatively easy to attack. As details about the operating systems, protocols and devices used become generally accessible, further weak points are discovered and exploits are provided. This makes attacks against networked components increasingly easier.

Cyber-physical attacks are cyber-attacks in the first step, but in the further course they aim to damage physical systems. The most prominent case is certainly the malware Stuxnet, which destroyed the centrifuges of the uranium enrichment plants in Iran. A similar scenario is conceivable for safety components of tunnels.

Cyber-Security of tunnels and tunnel control centers

Within the framework of the Cyber-Safe project, a guideline and evaluation software were developed based on the BSI basic protection catalogs and on the results of penetration tests. These can be downloaded free of charge from the website **www.bast.de/ritun**. The evaluation software presents all measures that are available to improve the cyber security of tunnels and tunnel control centers. However, since the improvement of cyber security is a continuous process, it is recommended to obtain information and the latest updates findings from the German Federal Office for Information Security (BSI) at **www.bsi.bund.de** at regular intervals.

3.2 Damage scenarios

Threats can trigger a wide range of damage scenarios, the extent of which depends on the location and severity of the event. Individual damages can be caused by different threats. At the same time, one threat can lead to different damage scenarios. For better understanding, this relationship is shown schematically in Figure 3.2.

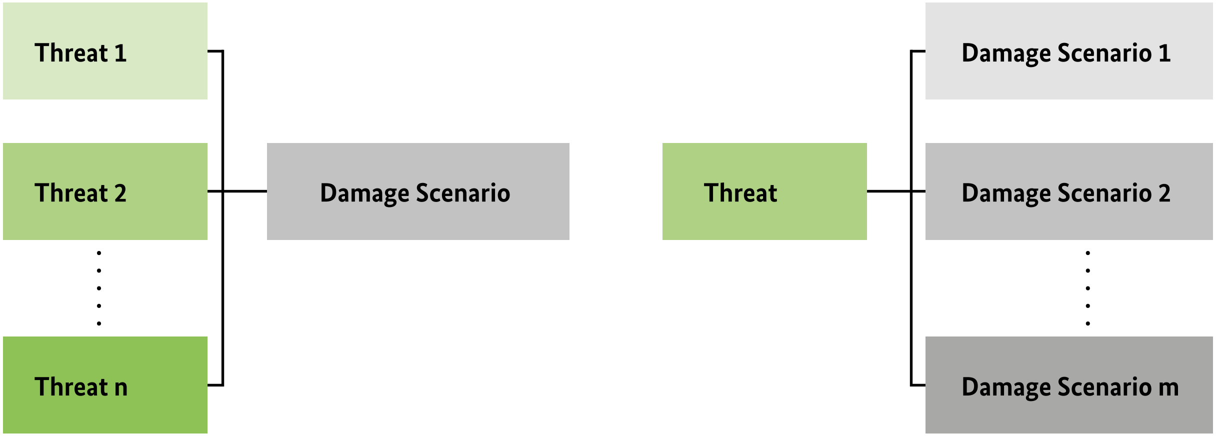


Figure 3.2: Schematic relationship between threats and damage scenarios

This guide focuses on disruptive events. These are extraordinary events that exceed the requirements of applicable regulations and can therefore not be (fully) absorbed by the safety measures available in tunnels equipped in German RABT-compliant design and can thus lead to particularly serious damage scenarios. There is no basis for an evaluation of the relationships between threats and damage scenarios in the necessary number, since the predominant Part of the threats is characterized by a low frequency of occurrence. Therefore, it is often not possible to draw a reliable and transferable damage picture which can be assigned to a specific threat. The damage scenarios were therefore examined and evaluated independently of their causal threat. This has the advantage that the developed evaluation methodology is suitable for assessing the effects of new types of threats that have not been considered at the current state of the art, and that this approach meets the need to deal with the unexpected or unknown in terms of resilience.

According to the definition of the points of impact, threats can lead to structural, operational and blocking damage scenarios.

Structural scenarios describe structural damage to the tunnel structure, caused by static, dynamic or thermal loads due to the threats. **Operational scenarios** result from the loss of function of the safety technology of the tunnel equipment and in centralized systems. Blockades of the tunnel, without the occurrence of immediate damage, are assigned to the **blocking scenarios** and lead to a restriction or interruption of the traffic flow and affect the network element in which the tunnel is located.

All safety relevant systems can be assigned to these categories. Finally, concrete components of these systems are named which can potentially be damaged or affected.

All relevant damage scenarios that can be caused by threats were identified and summarized in a threat and damage matrix (Annex 1). It is possible that entire tunnel sections are no longer supplied with power, or that the system performance prescribed by German RABT can no longer be fully achieved. The length of the affected tunnel section can vary from a few meters (e.g. failure of a luminaire) to several 100 meters (e.g. in case of failure of an emergency exit). The relevant dimensions of a damage scenario were determined in the course of a qualitative assessment methodology, or were determined in the course of the quantitative investigation.

3.3 Summary

Basically, it can be said that in the identification of potential threats and the damage that can occur, a large number of parameters interact in a complex interplay. It is therefore not possible to make general statements about threats and damage scenarios. Each tunnel must be evaluated individually depending on its characteristics, environmental influences and its function in the network. To achieve this, a threat-damage matrix (Annex 1) has been developed which assigns threats to different points of impact so that you can see which threats are relevant for which components and thus identify the relevant threats for the tunnel to be individually evaluated.

4 Effects of Damage Scenarios on Tunnel Operation and Traffic

4.1 Minimum Operating Requirements

In order to assess the effects of damage scenarios on tunnel operation and to be able to optimize it in the future, minimum operating requirements were developed. This defines whether and under which conditions a road tunnel may continue to be operated after the occurrence of a damage scenario. With the help of possible risk-reducing compensatory measures, the availability of road tunnels can partially maintained while maintaining the required safety level. The early running through of certain scenarios and the preliminary establishment of minimum operating conditions helps to react during the phase. Thus, this approach was examined as a very important resilience measure in terms of Business Continuity Management (BCM) for the recovery phase.

Business Continuity Management (BCM)

Processes are becoming more susceptible to disruptions as a result of increasing aging, overload, climate change and IT-supported operations. Outsourcing by integrating subcontractors also poses new challenges for secure operations. Business Continuity Management (BCM) refers to all organizational, technical and personnel measures that serve to continue core processes after a loss scenario has occurred. Furthermore, BCM supports the successive continuation of business processes in the event of longer lasting failures or disruptions. The requirements for a BCM system are defined in ISO 22301. The German Federal Office for Information Security (BSI) is also working on a standard (BSI Standard 200-4, working status April 19, 2019), which will be relevant to BCM in terms of the IT security of tunnels and tunnel control centers.

In order to be able to estimate the impact of an event on the operation and availability of a tunnel, it is necessary to define a safety criterion that defines the boundary state between tolerable and critical risk. This was done by the Development of minimum operating conditions under which a tunnel may be (temporarily) operated in response to a disruptive event.

After a damage scenario has occurred, it must be examined whether tunnel operation can be continued or which additional compensatory measures are necessary to ensure an adequate safety level. This question arises mainly in the case of operational damages. In the case of structural damage that does not endanger the stability of the structure, as well as in the case of obstructive damage scenarios, the respective traffic operation scenario results directly from the requirements for the repair of the damage (repair) or obstruction. The risk resulting from the operational damage scenarios was determined and evaluated using qualitative and quantitative risk analysis methods. This was done in RITUN using the Austrian tunnel risk model "TuRisMo" according to RVS 09.03.11. Thus, damage scenarios as well as the safety-related compensation measures were quantitatively evaluated. This correlation is shown in Figure 4.1.

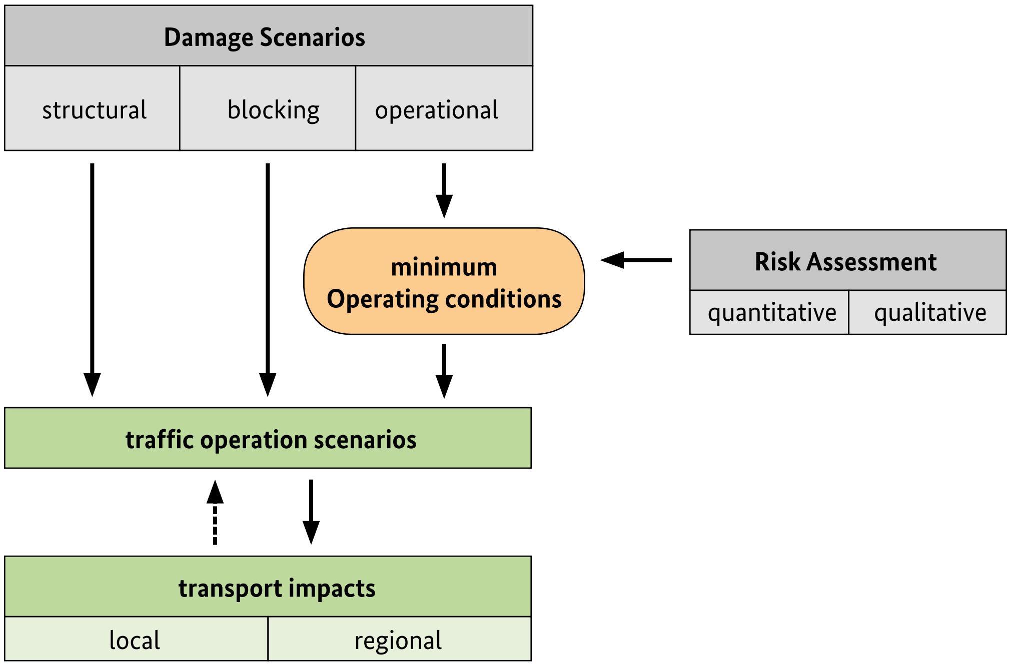


Figure 4.1: Relationship between damage scenarios and tunnel operation over minimum operating conditions

Minimum operating conditions for the temporary operation of road tunnels

The investigations for the qualitative and quantitative evaluation of the damage scenarios and compensation measures will not be explained further here due to the large scope of the project. The detailed derivation can be found in chapter 4 of the AP3 report. It can be downloaded free of charge from the website **www.bast.de/ritun**. Only results that are relevant for understanding the guide are presented here.

4.1.1 Applicability in the sense of applicable regulations

In a tunnel equipped in accordance with German RABT, compliance with the prescribed minimum safety level is generally no longer ensured as a result of a damage scenario. On the basis of risk analyses it can be assessed in a comprehensible way whether the prescribed risk criteria are met, possibly with the aid of compensation measures, so that the normatively required safety level can still be maintained. In the German RABT it is explicitly pointed out that deviations from the specifications made in the guidelines for the specific tunnel are permitted if the described safety level is not undercut.

The safety of the tunnel users is the decisive risk factor here. As a reference value, the risk in a model tunnel fully equipped in accordance with applicable regulations is used. This reference value corresponds to the first of two thresholds that divide the risk scale into three areas (see Figure 4.2).

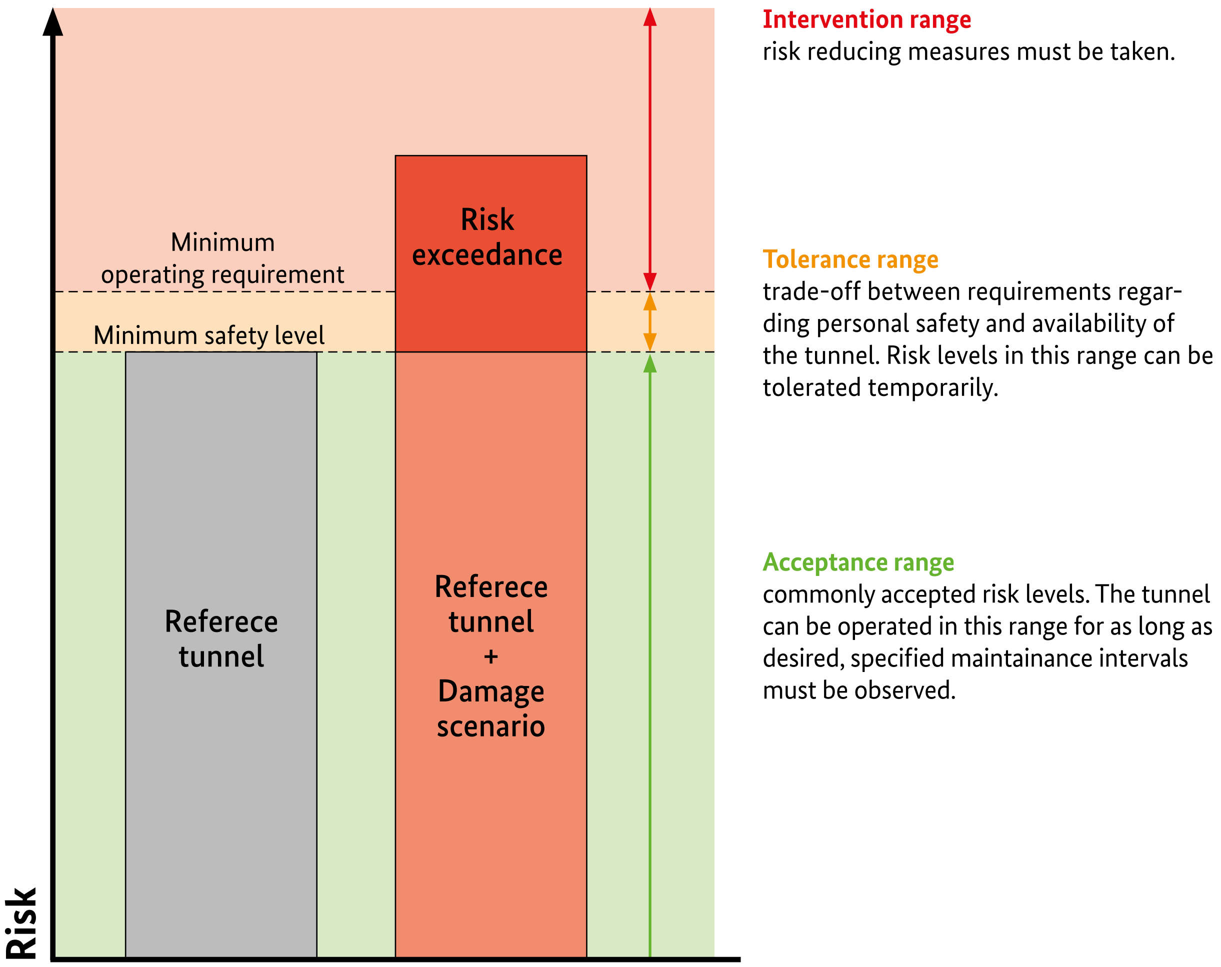


Figure 4.2: Thresholds for acceptable and unacceptable risks in the safety assessment of road tunnels

The minimum safety level represents the minimum safety to be guaranteed in normal operation and at the same time the upper limit of the acceptance range according to generally applicable guidelines and regulations (e.g. RABT). The tolerance range is a range in which the risk due to a loss scenario may lie for a limited duration. The duration as well as the range can be determined by decision makers according to the situation, depending on requirements for personal safety on the one hand, and the availability of the Tunnels on the other side. The action area is an area of unreasonable risk where compensation for the increase in risk due to a loss scenario is necessarily required to ensure the minimum operating condition.

4.1.2 Methodology for evaluating damage scenarios

In order to improve the availability after an event while meeting minimum requirements for personal safety, the framework for the evaluation of damage scenarios shown in Figure 4.3 was developed. First, the potential of the damage scenario to increase the risk is evaluated. It is assumed that no other systems are able to compensate for the failure of equipment components. Compensation by means of alternative, available systems or by risk-reducing measures is considered in the next steps. It can then be decided whether the damage is to be compensated in the course of a scheduled or unscheduled repair.

to be corrected.

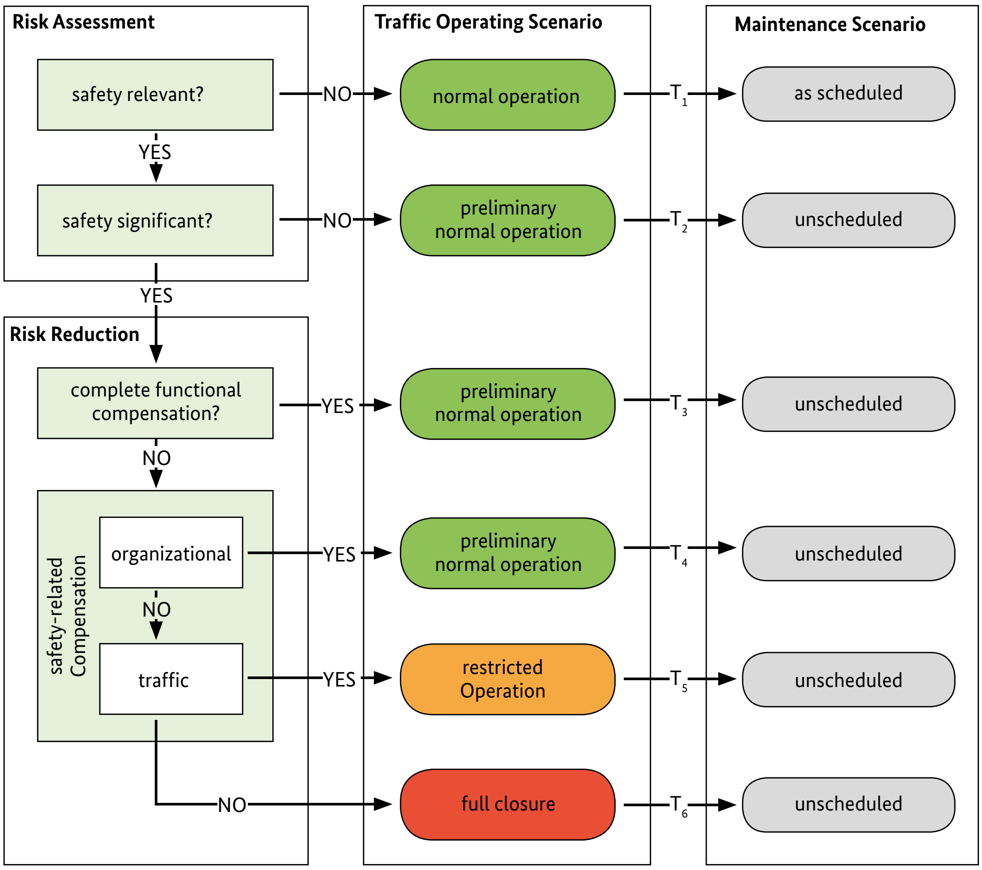


Figure 4.3: Framework for evaluating the effects of damage scenarios on operation and maintenance

Explanations about the framework:

Risk assessment is performed by evaluating safety relevance and safety significance. Safety-relevant are all damage scenarios that can cause relevant effects on the safety of persons through their occurrence. Safety-relevant are all damage scenarios that show a risk exceeding the tolerance range and lead to the achievement of the action area.

A risk reduction of the risks increased by a damage scenario can be achieved by functional and safety compensation. Through functional compensation, the damage of a component can be fully or partially compensated for by existing redundancies or by other systems. If a sufficient reduction of the risk cannot be achieved by functional compensation, additional safety measures must be taken. Organizational and traffic-related measures can be used or combined.

Organizational measures for safety-related compensation have no influence on the flow of traffic, so it is possible to switch over to temporary normal operation. If, however, traffic measures are necessary, these will result in a restricted traffic operation scenario. Despite a sufficient safety level, possibly even below the reference level, the repair of the damage has high priority due to the sometimes considerable effects on the traffic flow and should be carried out as soon as possible.

Technical measures such as video detection, thermal scanners or automatic fire fighting systems, which are not part of the equipment required by the German RABT, can also help to reduce the probability of occurrence and extent of damage caused by accidents and fires. Since these would usually have to be retrofitted, they represent technical measures of friction, which will be described in more detail later in chapter 5.

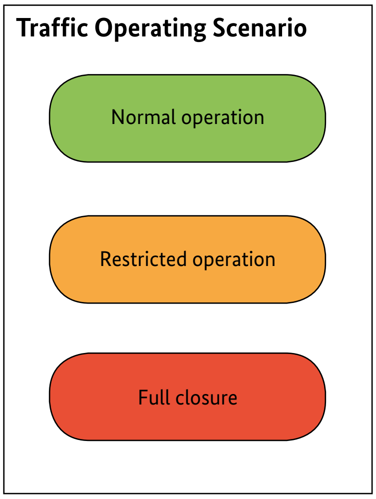


Figure 4.4: Categorization of the traffic operating scenarios

A restriction of **traffic operation** in terms of user safety is usually implemented if the required safety level cannot be achieved with functional compensation or organizational measures. Here, three basic traffic operation scenarios are distinguished, from normal operation to restricted operation scenarios, e.g. speed reduction or lane closures, up to complete closure of the tunnel (see Figure 4.4).

Normal operation can be maintained if no traffic measures are required to reduce the risk to a tolerable or acceptable level, thus not compromising user safety.

Preliminary normal operation can be used if there is no safety-relevant hazard and the damage does not need to be repaired immediately. In the case of a security-significant damage scenario, preliminary normal operation can only be achieved by compensating for the increased risk. This must be continuously monitored until the damage is repaired. If the conditions of the preliminary normal operation change, the safety level must be re-examined and, if necessary, the traffic operation scenario must be adjusted.

Speed reductions or route restrictions for certain types of vehicles are mainly suitable for safety compensation through traffic restrictions. These measures therefore result in restricted operation.

A full closure is required if an increase in risk cannot be counteracted or can only be counteracted inadequately by functional or safety compensation.

The **maintenance scenario** is finally considered in the framework and distinguishes between scheduled and unscheduled maintenance scenarios. The planned maintenance scenario describes a measure required in the RABT for the preservation of the tunnel structure and operation.

Unscheduled maintenance is always required when a safety-relevant damage scenario exists. Since unscheduled maintenance is usually accompanied by traffic restrictions, it is often not understood by the users. It is therefore in the interest of the tunnel operator to keep the duration and the occurrence of unscheduled maintenance scenarios as low as possible. If necessary, measures to reduce the user risk into the tolerance range are sufficient in practice to bridge the time until the next scheduled maintenance.

4.2 Traffic effects

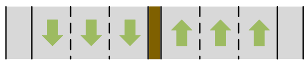
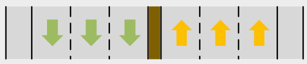
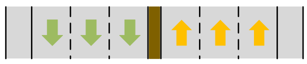
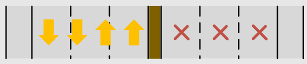
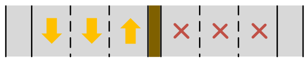
The effects of the damage scenarios on traffic are analyzed on two levels. First, the influence of restricted operating scenarios on capacity at local level, i.e. in the immediate vicinity of the tunnel, is determined. On the basis of these results, effects in the surrounding road network can also be examined at regional level.

4.2.1 Traffic impacts at local level

With the help of microscopic traffic simulations, the capacity is determined as a proportion of normal operation depending on the traffic operating scenarios in order to quantify the remaining availability of a road tunnel. For this purpose, the capacity of a road tunnel in normal operation is given as 100%. Restricted operation scenarios partly result in a reduction of the traffic capacity, the remaining capacity is indicated with the corresponding percentage.

Exemplary results of some traffic operation scenarios for directional tunnels with three lanes and side lane are shown in table 4.1. Detailed information and all results of the microscopic traffic modelling are available in the corresponding report for AP4 at www.bast.de/ritun.

Table 4.1: Capacity of three-lane directional tunnels depending on the operating scenario

traffic operating scenario		Capacity (%)	
Designation	Schematic sketch	↓	↑
Normal operation		100	100
Speed reduction 60 km/h		100	100
Speed reduction 40 km/h		100	90
Blocking of a lane, speed reduction		100	65
Blocking of two lanes, speed reduction		100	25
Blocking of one tube, two-way operation in 2nd tube 2:2		65	65
Blocking of one tube, two-way operation in 2nd tube 2:1		65	25
Full closure		0	0

Legend for Table 4.1: ↑ Normal operation, ↑ Restricted operation, × Lanes blocked

The compilation of the damage scenarios and their effects on tunnel operation and traffic can be found, due to its size, as a table as **Annex 2** in the annex of the guide. It is available as an editable file on the project website (www.bast.de/ritun).

4.2.2 Traffic effects at the network level

In RITUN, the regional traffic effects and the resulting overall economic costs of availability restrictions were examined using the Pfaffenstein tunnel and the Bayreuth enclosure in Bavaria as examples, based on the traffic planning software PTV Visum 18, a subnetwork from the PTV Validate 7.2 and subsequently developed a control and evaluation module based on Microsoft Excel for use.

> At this point in the guide, only the results of the study on traffic impacts at the network level are presented. The procedure used to determine the effects and economic costs at the Pfaffenstein tunnel and the Bayreuth enclosure can be requested free of charge from BASt or downloaded directly from **www.bast.de/ritun**. An operating manual is also available there. The procedure can also be used to select alternative routes in the event of an incident from the point of view of economic costs. A prerequisite for this is the use of the PTV Validate software.

For the two tunnels analyzed, the effects of unavailability or limited availability were quantified for different scenarios, which differ in terms of traffic restrictions and duration. The effects were first mapped in a subnetwork of the traffic model Validate. The model results were used to calculate the macroeconomic costs of changes in

- … travel and transport times,
- … operating costs,
- … air pollutant and climate gas emissions
- … and accidents

using the methodology of the Federal Transport Infrastructure Plan 2030. According to this, the unavailability or limited availability of the Pfaffenstein tunnel can result in macroeconomic costs of up to approx. 760,000 €/day, depending on the selected scenario. For the Bayreuth enclosure, the overall economic costs are even higher at up to approx. 920,000 €/day.

4.3 Summary

In order to assess the effects of damage scenarios on tunnel operation and to avoid tunnel closure by means of risk-reducing compensation measures while maintaining the required safety level, minimum operating requirements were developed. It is recommended to investigate these minimum operating requirements for damage events in advance in order to be able to maintain reduced availability in case of an incident. The investigations on the effects of the reduced availability at the network level clearly show that the resulting economic costs are high and thus justify the investments in resilience measures.

5 Measures to Increase Resilience

The following chapter presents suitable resilience measures and the methodology for evaluating their effectiveness, on the basis of which they can be selected. The identified measures are assigned thereby according to the time of their effect development to the different resilience phases. These can be assigned besides the temporal process of the functionality, in order to be able to represent the resilience-increasing influences of the measures comprehensibly (Figure 5.1).

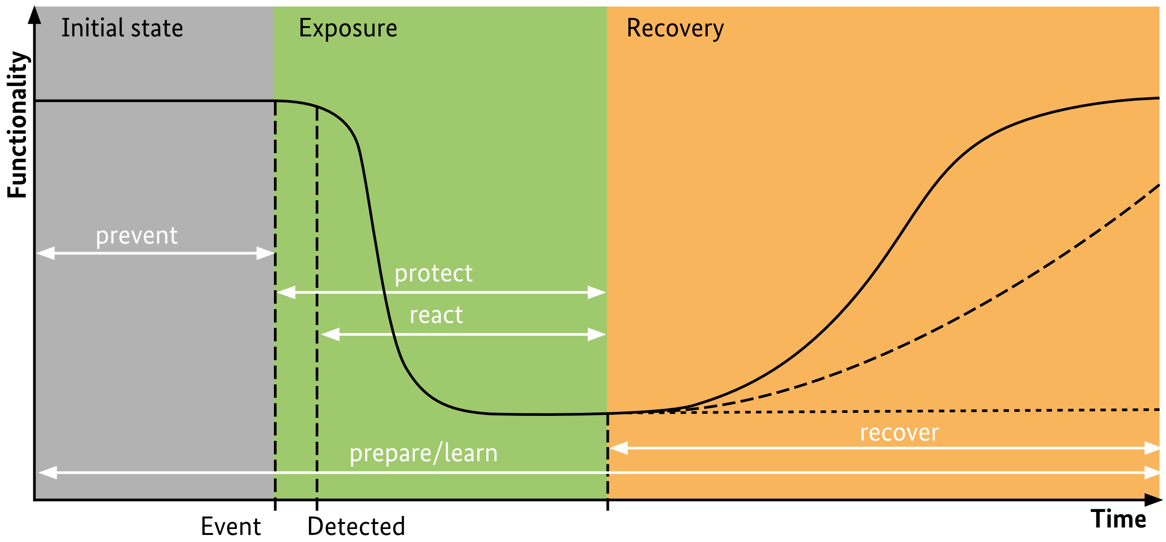


Figure 5.1: Temporal assignment of the resilience phases to the functionality curve

Resilience measures are described as follows, depending on their time of effect:

Preventive measures act before an event to reduce the probability of disruptive events occurring.

Protective measures are passive measures that are effective after the occurrence of a disruptive event until it is overcome in order to prevent or mitigate certain damage scenarios.

Reactive measures are active measures that are initiated after the detection of a disruptive event and remain in effect until it is overcome in order to prevent or mitigate certain damage scenarios.

Recovery measures take effect after a disruptive event has been mastered to enable the fastest possible return to the original functionality.

Preparatory measures and learning are continuously pursued measures that Develop effectiveness across all phases and harden known and new weaknesses.

5.1 Categorization of resilience measures

In the first step, the measures are divided into **Preventive** and **Mitigative Measures**, which are effective before and after the occurrence of the damage scenario, as shown in Figure 5.2.

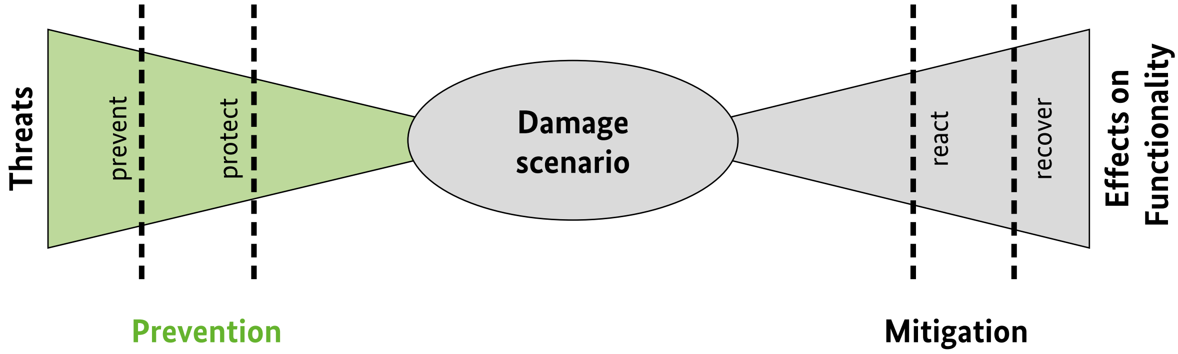


Figure 5.2: Classification according to prevention and mitigation of damage scenarios

The following categories are chosen for the exact assignment of the measures:

Prevention P

- P1 Monitor and maintain the technical condition of the tunnel ("prevent")
- P2 Prevent disruptive events ("prevent")
- P3 Prevent or mitigate damage caused by disruptive events ("protect")

Mitigation M

- M1 Reduction of loss of functionality due to damage scenarios ("react")
- M2 Rapid restoration of functionality ("recover")

Leadership & Culture F (without further subcategories)

- … F Preparatory measures such as establishing a resilience culture
- … F Awareness-raising measures (learning)

In addition, the measures are differentiated between their types of impact at

- … organizational (O) and
- … technical (T) level.

This results in the indexation for the categorization of individual measures as follows

- … Category (P, M, F)
- … Subcategory (1..n)
- … Effect type (T, O) and corresponding sequential number

Based on this structure, the identified measures are summarized in the following overview tables.

Table 5.1: Overview of resilience measures of the category "Prevention P"

Prevention P	**Subcategory**	**P1 Monitor and maintain the technical condition**
	Type of effect	Organizational
	P1 – O1	Optimized maintenance intervals
	P1 – O2	Introduction of a plant health system
	P1 – O3	Maintenance and service management system (beyond the recommendations of RABT)
	Type of effect	Technical
	P1 – T1	Installation of additional sensors to monitor the technical condition
	Subcategory	**P2 Prevent disruptive events**
	Type of effect	Organizational
	P2 – O1	Access regulation for inventory documents
	P2 – O2	Restriction for transport of dangerous goods
	P2 – O3	Hazard Analysis
	P2 – O4	Exposure analysis
	P2 – O5	Agree availability values with service providers, e.g. electricity, data connection, water
	Type of effect	Technical
	P2 – T1	Water level monitoring
	P2 – T2	Thermoscanner
	P2 – T3	Avalanche barrier
	P2 –T4	Rockfall protection
	P2 – T5	Preventive avalanche blasting
	P2 – T6	Snow Fence
	P2 – T7	Higher clearance gauge
	P2 –T8	Gas Detectors
	P2 – T9	Test environment for software updates
	P2 – T10	Avoiding large longitudinal inclinations
	Subcategory	**P3 Prevent or mitigate damage due to disruptive events**
	Type of effect	Organizational
	P3 – O1	Vulnerability Analysis
	P3 – O2	Physical access management
	P3 – O3	Protection against infection

Continuation of Table 5.1

Prevention P	Type of effect	Technical
	P3 – T1	Windbreak panels
	P3 – T2	Wind speed warning system
	P3 – T3	Ram protection
	P3 – T4	Dimensioning / design for seismic load
	P3 – T5	Protective measures against water ingress in the tunnel
	P3 – T6	Automatic fire fighting system
	P3 – T7	Flood protection elements
	P3 – T8	Structural explosion protection
	P3 – T9	Structural fire protection
	P3 – T10	Protection of safety equipment in the tunnel against physical access
	P3 – T11	Softstop Barrier

Table 5.2: Overview of the resilience measures of the category "Mitigation M"

Mitigation M	**Subcategory**	**M1 Reduction of loss of functionality due to damage scenarios**
	Type of effect	Organizational
	M1 – O1	Training of the emergency services
	M1 – O2	TLZ operators training, training of personnel for emergency operation from the master craftsman's shop
	M1 – O3	Video surveillance of tunnels with a length < 400 m
	M1 – O4	Recognize (potential) attacks
	M1 – O5	Communicate restrictions to affected persons
	Type of effect	Technical
	M1 – T1	Access control of security equipment
	M1 – T2	Increase of the extinguishing water supply
	M1 – T3	Stationary or mobile emergency power generator
	M1 – T4	Back-up Control Center / Redundant TLZ
	M1 – T5	Video detection
	M1 – T6	Acoustic tunnel monitoring (AKUT)
	M1 – T7	Dangerous goods detection
	M1 – T8	ITCC Integration (International Tunnel Control Center)
	M1 – T9	Securing access to information technology components
	M1 – T10	Separate service tube for maintenance work

Continuation of Table 5.2

	Subcategory	M2 Rapid restoration of (partial) functionality
Mitigation M	Type of effect	Organizational
	M2 – O1	Accelerated approval and awarding processes
	M2 – O2	Accelerated building permit
	M2 – O3	Definition / checking of detour routes
	M2 – O4	Multimodal alternatives
	M2 – O5	Side lane release
	M2 – O6	Definition of minimum operating conditions
	M2 – O7	Storage of spare parts
	M2 – O8	Use of modular systems for several tunnels
	M2 – O9	Framework agreements maintenance
	M2 – O10	In-house electrotechnically trained personnel
	M2 – O11	Operation in temporary oncoming traffic
	M2 – O12	Agreement of fixed rates with service providers
	Type of effect	Technical
	M2 – T1	Cross sections with (passable) side strip
	M2 – T2	Equipment of RV tunnels for temporary GV operation

Table 5.3: Categorization of the resilience measures of the category "Leadership & Culture F"

	Type of effect	Content
Führung & Kultur F	F – O1	Define responsibilities
	F – O2	Establishing a resilience culture
	F – O3	Campaigns for user information
	F – O4	Best Practice Exchange
	F – O5	Security awareness raising
	F – O6	Provision of a "resilience budget"
	F – O7	Processing of past events ("Learning")
	F – O8	Current documentation
	F – O9	Integration of resilience in Alarm and Emergency Plans
	F – O10	Extended event database
	F – O11	Support from colleagues in other departments
	F – O12	Cost sharing with other affected parties / beneficiaries of protective measures
	F – O13	Exchange of data with other authorities (legal conditions, technical solution)
	F – O14	Ergonomic design of the Tunnel Control Center user interfaces

5.2 Evaluation of resilience measures

In order to simplify the selection of resilience measures, taking into account all parameters, a methodology was developed on the basis of which the measures have already been evaluated by experts. A three-step "traffic light format" is used in some cases to make the characteristics easy to visualize. All measures with their associated Evaluations can be found as an editable file on the project website (www.bast.de/ritun) and as an overview graphic in **Annex 3**. The underlying evaluation parameters are explained below.

5.2.1 Evaluation parameter: Availability

The availability parameter indicates how (preventive and/or mitigative) and to what extent the measure works. In particular, influences on traffic effects, such as a reduction in capacity or the duration of limited operation, were investigated.

#	Measure	Availability	
		Prevention	Mitigation
P1	Monitoring and maintenance of the technical condition		
P1 – O1	Optimized maintenance intervals	🟢	🟠
P1 – O2	Introduction of a plant health system	🟢	🟠
P1 – O3	Maintenance and service management system (beyond the recommendations of German RABT)	🟢	🟠
P1 – T1	Installation of additional sensors to monitor the technical condition	🟢	🟠

Table 5.3: Evaluation of measures regarding their influence on availability through prevention or mitigation

5.2.2 Evaluation parameter: Synergy effects

Possible synergy effects that may result from the implementation of the measures were also assessed, as these can significantly influence the cost efficiency of measures if resilience-enhancing effects are achieved in several areas at the same time.

Synergy effects			
Security	Cross-object	Across all tunnels	Threat-spanning
🟢	Y	Y	Y
🟠	N	N	Y
🔴	N	Y	Y

Table 5.4: Evaluation of measures regarding synergy effects

The following are evaluated:

... Synergy effects for safety

As a basic requirement, the influence on tunnel safety is assessed. Aspects to be considered are, for example, the effects of the measures on the frequency of events endangering persons and the general conditions for self rescue and rescue by emergency personnel. If a resilience measure leads to a reduction of safety (red traffic light), additional safety measures have to be implemented.

... Cross-object synergy effects

In addition to the effect in the tunnel itself (object level), measures can also achieve effects on the surrounding road network (network level). These are particularly present in the measures of the category "Guided tour & culture F".

... Synergy effects across tunnels

Many of the measures show their effect not only in one but in several tunnels. This can be achieved, for example, by measures at the tunnel control center.

... Synergy effects across threats

In addition, it is shown whether a measure unfolds its effect specifically for a threat, or whether it unfolds across threats.

5.2.3 Evaluation parameter: Feasibility

Measures were evaluated with regard to their feasibility in existing and new tunnels. In new construction, the purely technical or organizational implementation in itself only poses a problem in very few cases. Possible difficulties result from additional costs or geometrical circumstances, for example, from limited space, traffic requirements of the average daily traffic or from constrained points of the route.

In the case of the implementation of resilience measures in existing tunnels, factors such as the time required for implementation, traffic restrictions in the course of the implementation in the tunnel or the need to adapt existing structures are considered. Last but not least, acceptance by the relevant stakeholders also plays a decisive role in the implementation of measures.

#	Measure	Existing			New		
		Realiza-bility	Costs	recom-mended	Realiza-bility	Costs	recom-mended
P1	Monitoring and maintenance of the technical condition						
P1 – O1	Optimized maintenance intervals	🟢	🟠		🟢	🟠	
P1 – O2	Introduction of a plant health system	🟠	🟠		🟢	🟠	
P1 – O3	Maintenance and Maintenance management system (beyond the recommendations of the German RABT)	🟢	🟠		🟢	🟠	
P1 – T1	Installation of additional sensors to monitor the technical condition	🟢	🟠		🟢	🟠	

Table 5.5: Evaluation of feasibility differentiated by existing and new tunnels

5.2.4 Evaluation parameter: Costs

This parameter takes into account the magnitude of the costs of implementing the measures regardless of their effect. The costs of measures result from:

- … the investment costs
- … the operating and maintenance costs over the life cycle
- … the (macroeconomic) costs of the temporary traffic disruption

The costs can then be compared with the:

1. Expected damages and losses if no measures are taken.
2. Reduced damage and losses that can be expected after implementation of measures.

Organizational measures are usually the easiest to implement and adapt. They often have a tunnel- and threat-spanning effect. Substantial costs are incurred for staff training, the procurement of new work equipment and reorganization. With technical and structural measures, a distinction must be made between existing and new tunnels. Retrofits such as the installation of additional sensors, a high-pressure spray mist system or a ram protection system often cannot be implemented without disrupting traffic. In addition, there are further costs due to maintenance and repair as well as the associated traffic disruptions.

5.3 Selection of measures

For the decision whether a measure is classified as "recommended", the interaction of the presented evaluation parameters must be evaluated.

Availability		Interaction				Existing			New		
Preven-tion	Mitigation	Security - safety	Object-over-lapping	Tunnel-over-reaching	threat-over-lapping	Realizabi-lity	Costs	recom-mended	Realizabi-lity	Costs	recom-mended
🟢🟠🔴	🟢🟠🔴	🟢🟠🔴	Y/N	Y/N	Y/N	🟢🟠🔴	🟢🟠🔴	Y/N	🟢🟠🔴	🟢🟠🔴	Y/N

Table 5.6: Overview of the evaluation parameters of resilience measures

Annex 3 contains all resilience measures that have already been implemented on the basis of the methodology. The selection with regard to the implementation of a certain measure is to be made object-specifically. Although the methodology is used to prioritize the measures, other measures may also be suitable for specific objects in order to increase resilience. Therefore, the tables for the evaluation of the measures are made available to you as editable file, so that you can make your own object-specific evaluation. You can download them from the project website at www.bast.de/ritun.

In order to support you in the selection of measures, so-called fact sheets were developed for each individual measure, which you can access on the project website. These contain information regarding the measures on:

… the associated resilience phase

… the points of impact

… the implementation (building, event, traffic, natural hazard management, management level)

… the use case (existing, new tunnel)

… the time horizon (short-term, medium-term, long-term, irrelevant)

… Interactions with:

- Personal safety
- Object-overlapping
- Tunnel-overreaching
- Threat-overlapping

… those responsible for implementation

Annex 4 shows an example of the fact sheet for the resilience measure "Equipping of directional tunnels for temporary two-way traffic" (M2-T2). All fact sheets can be downloaded from the project website.

The goal of increasing availability must always be achieved while ensuring that sufficient traffic safety is maintained. The implementation of resilience measures often has positive effects on traffic safety. However, the opposite can also be the case. Examples are the operation in two-way traffic in a directional traffic tunnel or the release of the side lanes in a tunnel. Without additional risk-reducing measures and appropriate equipment, the original safety level often cannot be maintained.

Resilience Paradox

When selecting and implementing resilience measures, it must be taken into account that, in addition to improving availability, some of the resilience measures can also create new dependencies or open up new areas of attack. Therefore these should be identified and hardened before implementation.

Examples:

- … Additional sensor technology (increasing confusion and growing number of signals that the operator has to check or consider when making decisions) (e.g. P1-T1, P2-T2)
- … Increasing automation to support the operating staff (everyday work is (too) simplified, staff may not be trained to handle difficult situations) (e.g. P1-O2, P1-O3)
- … Increasing networking (sharing sensitive information or creating new dependencies) (e.g. F-O13)

5.4 Summary

For the selection of suitable resilience measures, a simple methodology was deliberately used. The measures were grouped into Preventive and Mitigative Measures depending on their effectiveness. These are supplemented by measures in the category "Leadership and Culture", which are intended to enable the establishment of a resilience culture throughout the organization. For the selection of resilience measures, parameters were formulated that qualitatively assess the effects on availability, synergy effects, feasibility and costs incurred. In addition, fact sheets were developed that contain detailed information on the individual resilience measures.

6 Concluding Remarks on the Resilience of Road Tunnels

Improving the resilience of road tunnels requires the ability to identify and evaluate threats and situations, to make decisions and learn from experience. Sufficient reserves and redundancies are necessary to avoid chronic overload of certain resources. Core tasks must be defined and sufficient resources such as well-trained personnel or spare parts as well as the necessary information must be available for these tasks in order to reliably maintain core processes with a minimum of safety in case of disruptive events and to initiate and implement the necessary measures for coping with them in parallel. This is not only about the resources and reserves of one's own organization (also across locations), but also those of service providers, suppliers and emergency organizations, as well as avoiding excessive concentrations of resources and functions in one place.

Appropriate up-to-date documentation, standardized tools, clearly defined tasks and responsibilities and joint exercises for such cases are a prerequisite for successful implementation. Prices contractually agreed in advance with service providers help to avoid incurring costs during the management of crises. In addition, possibilities should be explored to be able to start recovery work quickly. These include framework contracts that also cover crisis situations, simplified procurement and award procedures and the possibility of paying down payments and advances. Possibilities of warehousing as well as the procurement of spare parts even in case of supply bottlenecks must also be considered.

Since the complex dependencies are difficult to grasp, a comprehensive risk assessment and, if necessary, the ability to maintain a minimum level of operation with one's own resources are becoming increasingly important. Corresponding risk analyses must therefore include threats to the operational organization and to central facilities such as tunnel control centers, e.g. the accessibility of control rooms, highway maintenance facilities, storage areas, etc. or the effects of epidemics, for example.

Cooperation with other organizations with which mutual dependencies exist, such as utilities (electricity, water and data connections) and tunnel users (e.g. emergency services) must also be coordinated in advance.

The basis for target-oriented decisions is current and accurate data on the availability of resources, the actual state of the systems, alternative routes and their utilisation, expected duration for restoring full functionality and the like.For this purpose, it may be necessary to go beyond the requirements of the RABT / EABT to collect data in tunnels and along the lines, exchange it with other agencies and make it available to users. Modern technologies can help both in an increasingly dynamic everyday working life and in dealing with disruptive events. Today, it is possible to give on-site staff (in the tunnel) access to central systems and have them supported by remote experts. The prerequisite for this is a good data connection and appropriate cyber security measures.

Beyond the technical and organizational measures presented in the guidelines, the establishment of an organization-wide resilience culture is of crucial importance. All employees must be allowed to address weak points and to develop and implement suggestions for improvement. Employees often know from their daily work which processes and instruments work well or less well. Particularly after coping with disruptive events, a critical assessment should be made. "Lessons Learned" workshops can record what went well in coping with the events and what needs to be improved. This knowledge must be recorded and made available to all who need it. And in such a way that the knowledge is available then and there, where it is needed to complete the tasks.

Organizational Resilience

The international standard ISO 22316:2017 Security and resilience – Organizational resilience – Principles and attributes defines the principles of organizational resilience as well as the attributes and activities that help an organization to increase its resilience. Of central importance for the resilience of an organization are:

... An appropriate culture

... Sufficient resources

... The ability to cooperate with other organizations and stakeholders

... The ability to learn

... Up-to-date and reliable information and communication

RITUN RESILIENTE TUNNEL

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8 Appendix

All Annexes are only printed as examples to briefly describe their use. The Annexes are available on the project homepage at www.bast.de/ritun. Annexes 2 and 3 are provided in editable form in order to be able to consider object-specific boundary conditions during application.

Annex 1: Threat-Damage Matrix

The threat-damage matrix assigns threats to different tunnel components where damage can occur. How to use the matrix:

- If you look at the matrix within a column from top to bottom, you can identify potentially simultaneous damage scenarios as a result of a specific threat.
- If you look at the matrix in the row from left to right, you can see which threats are relevant to individual systems, so that you can identify threats to the tunnel being evaluated.

Annex 1: Threat-Damage Matrix

- green: Tunnel structure incl. pre-portal area
- grey: Tunnel equipment incl. pre-portal area
- yellow: Central facilities
- orange: Network element

		Threat	Storm	Heavy rain	Extreme snowfall	Storm surge	Lightning strike	Earthquake	Ground deformation, displacement	Ground subsidence	sinkhole	Snow avalanche	Debris flow	Landslides	Deep slope movement	Rockfall	Rockfall	Landslide	River, lake floods	Flash flood	Urban flooding	Ground flood	Glacial flood / water outburst	Explosion	Brand	Blockade	Vehicle dimensions too large / ramming	Release of hazardous substances	Sabotage / Vandalism	Theft	Cyber attack	overturned trees	Wildfire	Power failure
			Natural hazards																					man-made								Other		
			meteoro-logical					geo-physical				gravitational							hydrological															
Cate-gory	System	Component # All Train	01	02	03	06	08	14	15	16	18	23	24	25	26	27	28	29	30	31	32	33	34	41	42	43	44, 47	46	48	49	50	35	36	40
structural	Building	Single tunnel tube						green	green	green	green	green	green	green	green			green						green	green									
structural	Building	All tunnel tubes						green	green	green	green	green	green	green	green			green						green	green									
structural	Compo-nent	Inner shell						green	green	green	green		green	green	green									green	green									
structural	Compo-nent	False ceiling						green	green	green	green													green	green		green							
structural	Compo-nent	Lining				green		green	green	green	green								green	green	green			green	green		green							
structural	Roadway	Roadway						green	green	green	green		green	green	green									green	green			green						
obstruc-ting	Roadway	Roadway		orange	orange	orange						orange	orange	orange	orange	orange	orange	orange	orange	orange	orange		orange			orange		orange				orange	orange	
operatio-nal	Drainage	Roadway drainage		grey		grey							grey	grey					grey	grey	grey	grey	grey	grey	grey			grey	grey					
operatio-nal	Energy supply	Medium voltage		yellow		yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow		yellow	yellow	yellow				yellow		yellow			yellow
operatio-nal	Energy supply	Low voltage		grey		grey		grey	grey	grey	grey													grey	grey				grey		grey			
operatio-nal	Energy supply	UPS system				yellow																		yellow	yellow				yellow		yellow			
operatio-nal	Lighting	Interior section lighting																						grey	grey		grey		grey	grey	grey			
operatio-nal	Lighting	Driveway lighting																						grey	grey		grey		grey	grey	grey			
operatio-nal	Lighting	Lighting of the escape routes																						grey	grey				grey	grey	grey			
operatio-nal	Venti-lation	Longitudinal ventila-tion Jet fans	grey																					grey	grey		grey		grey		grey			
operatio-nal	Venti-lation	Cross ventilation Ventilation flaps	grey																					grey	grey		grey		grey		grey			
operatio-nal	Venti-lation	Cross ventilation Jet fans	grey																					grey	grey		grey		grey		grey			
operatio-nal	Venti-lation	Ventilation of the escape routes																						grey	grey				grey		grey			
operatio-nal	Commu-nication facilities	Emergency call device																	grey	grey	grey		grey	grey	grey		grey		grey		grey			
operatio-nal	Commu-nication facilities	Opening contacts of the emergency call device																	grey	grey	grey		grey	grey	grey				grey		grey			
operatio-nal	Commu-nication facilities	Video surveillance																						grey	grey		grey		grey	grey	grey			
operatio-nal	Commu-nication facilities	Tunnel radio									grey	grey	grey	grey	grey	grey								grey	grey				grey		grey			
operatio-nal	Commu-nication facilities	Traffic radio/radio									grey	grey	grey	grey	grey	grey								grey	grey				grey		grey			
operatio-nal	Commu-nication facilities	Loudspeaker																						grey	grey		grey		grey	grey	grey			
operatio-nal	Fire alarm systems	Manual call point																	grey	grey	grey		grey	grey	grey				grey		grey			
operatio-nal	Fire alarm systems	linear heat detection system																						grey	grey		grey		grey		grey			
operatio-nal	Fire alarm systems	Hand-held fire extinguisher tapping contacts																	grey	grey	grey		grey	grey	grey				grey		grey			
operatio-nal	Fire-fighting equip-ment	Portable fire extinguisher																	grey	grey	grey		grey	grey	grey		grey		grey	grey				
operatio-nal	Fire-fighting equip-ment	Extinguishing water supply						grey	grey	grey	grey			grey	grey		grey	grey	grey	grey	grey		grey	grey	grey		grey		grey					
operatio-nal	Emer-gency exits, escape and rescue routes	Emergency exit																						grey	grey	grey	grey		grey					
operatio-nal	Emer-gency exits, escape and rescue routes	Emergency exit door opening contacts																	grey	grey	grey			grey	grey				grey		grey			
operatio-nal	Emer-gency exits, escape and rescue routes	Illuminated frame emergency exit																						grey	grey				grey		grey			
operatio-nal	Emer-gency exits, escape and rescue routes	Orientation lighting																	grey	grey	grey			grey	grey		grey		grey	grey	grey			
operatio-nal	Emer-gency exits, escape and rescue routes	Escape route marking																	grey	grey	grey			grey	grey		grey		grey	grey				

Damage scenario

Annex 2: Damage scenarios and their effects on tunnel operation and traffic

The effects of all damage scenarios on tunnel operation and traffic are presented in table form. The structure of this Annex is based on the methodology for evaluating damage scenarios as explained in Chapter 4.1.2.

Appendix 2: Damage scenarios and their effects on tunnel operation and traffic

Schadensszenario					Assessment methodology	Safety relevance	Safety significance	functional compensation	Share	safety-related compensation		traffic Operating scenario	Notes
#	Category	System	Component	Error mode						organisational measures	transport measures		
1	structural	Building	Single tunnel tube	Loss of stability								Full closure	in the affected tube
2	structural	Building	All tunnel tubes	Loss of stability								Full closure	in all tubes
3	structural	Component	Inner shell	Load bearing capacity impaired								Full closure	in the affected tubes
4	structural	Component	Inner shell	Load-bearing capacity not affected, single lane affected								Normal operation	Normal operation until the repair work is carried out, traffic operation scenario during the repair work results from the space requirements of the construction work
5	structural	Component	Inner shell	Load-bearing capacity not impaired, entire cross-section								Normal operation	Normal operation until the repair work is carried out, traffic operation scenario during the repair work results from the space requirements of the construction work
6	structural	Component	False ceiling	Load bearing capacity impaired								Full closure	in the affected tubes
7	structural	Component	False ceiling	Load-bearing capacity not affected, single lane affected								Normal operation	Normal operation until the repair work is carried out, traffic operation scenario during the repair work results from the space requirements of the construction work

Annex 3: Evaluation of resilience measures

Using the methodology for evaluating resilience measures in Chapter 5.2, all identified measures are evaluated in table form at a general level. Both, object-specifically necessary changes can be made, and additional measures can be added.

Evaluation of the resilience measure of the category "Prevention P

#	Measure	Availability		Synergy effects				Existing			New Tunnel		
		Preven-tion	Mitiga-tion	Safety-security	cross-object	across tunnels	cross-threat	Feasi-bility	Costs	recom-mended	Feasi-bility	Costs	recom-mended
P1	Monitor and maintain the technical condition												
P1 – O1	Optimised maintenance intervals	🟢	🟠	🟠	N	Y	Y	🟢	🟠		🟢	🟠	
P1 – O2	Introduction of a plant health system	🟢	🟠	🟠	N	Y	Y	🟠	🟠		🟢	🟠	
P1 – O3	Maintenance and service management system (beyond the recommendations of the RABT)	🟢	🟠	🟠	N	Y	Y	🟢	🟠		🟢	🟠	
P1 – T1	Installation of additional sensors to monitor the technical condition	🟢	🟠	🟠				🟢	🟠		🟢	🟠	
P2	Preventing disruptive events												
P2 – O1	Access regulation for inventory documents	🟠	🟠	🟠	N	Y	Y	🟢	🟢		🟢	🟢	
P2 – O2	Restriction for transports of dangerous goods	🟢	🟠	🟢	N	N	N	🟢	🟢		🟢	🟢	
P2 – O3	Hazard analysis	🟢	🟠	🟠	N	N		🟢	🟢		🟢	🟢	
P2 – O4	Exposure analysis	🟢	🟠	🟠	N	N		🟢	🟢		🟢	🟢	
P2 – O5	Agree availability values with service providers, e.g. electricity, data connection, water	🟢	🟠	🟠	N	Y	Y	🟢	🟠		🟢	🟠	
P2 – T1	Level monitoring	🟠	🟠	🟠	N	N	N	🟢	🟠		🟢	🟠	
P2 – T2	Thermal scanner	🟢	🟠	🟢	N	N	N	🟢	🟠			🟠	
P2 – T3	Avalanche control	🟢	🟠	🟠	N	N	N	🟢	🟠		🟢	🟠	
P2 – T4	Rockfall protection	🟢	🟠	🟠	N	N	N	🟢	🟠		🟢	🟠	
P2 – T5	Preventive avalanche blasting	🟠	🟠	🟠	N	N	N	🟠	🟠		🟠	🟠	
P2 – T6	Snow fence	🟠	🟠	🟠	N	N	N	🟢	🟢		🟢	🟢	
P2 – T7	higher clearance	🟢	🟠	🟠	N	N	N	🔴	🔴		🟠	🔴	
P2 – T8	Gas detectors	🟠	🟠	🟢	N	N	N	🟢	🟠		🟢	🟠	
P2 – T9	Test environment for software updates	🟢	🟠	🟠	N	Y	Y	🟢	🟠		🟢	🟠	
P2 –T10	Avoid large longitudinal slopes	🟢	🟠	🟢	N	N	N	🔴	🔴		🟠	🟠	
P3	Preventing or mitigating damaging events due to disruptive events												
P3 – O1	Vulnerability analysis	🟢	🟠	🟠	N	N	Y	🟢	🟢		🟢	🟢	
P3 – O2	physical access management	🟢	🟠	🟠	N	N	Y	🟢	🟠		🟢	🟠	
P3 – O3	Infection control	🟢	🟠	🟠	N	Y	Y	🟢	🟠		🟢	🟠	
P3 – T1	Windbreak panels	🟠	🟠	🟠	N	N	N	🟢	🟢		🟢	🟢	
P3 – T2	Wind speed warning system	🟠	🟠	🟠	N	N	N	🟢	🟠		🟢	🟠	

Annex 4: Fact Sheets on Resilience Measures

The fact sheets contain information on the parameters of the evaluation methodology and further information for the selection of appropriate measures. At this point, the fact sheet for "Equipping of directional tunnels for temporary two-way traffic" is shown as an example. All fact sheets can be downloaded from the project website.

Equipping of directional tunnels for temporary two-way traffic

Brief description

If a tube of a twin-tube tunnel with directional traffic guidance has to be closed, temporary operation in two-way traffic is an effective measure for partially maintaining functionality. The prerequisite for this is the appropriate safety equipment of the tunnel with the following additional requirements and components:

- Ventilation dimensioning for two-way traffic
- Adaptable entrance lighting at both portals
- Guidance system for changing lanes
- (Variable) traffic signs for both directions of travel
- Possibly (structural) centre separation

Impact type

☒ technical ☐ organisational

Resilience phase

☐ prevent ☐ protect ☐ respond ☒ recover ☐ prepare

Points of impact

☒ Tunnelstructure incl. portals ☐ Centralized systems ☒ Network element ☒ Regional surroundings

Implementation

☒ Building management ☐ Event management ☒ Traffic management ☐ Natural hazards management ☐ Management level

Application

☒ New tunnel ☒ Existing tunnel

Time horizon

☐ short term ☒ medium-term ☐ long-term ☐ Not relevant (for new tunnel)

Availability effects

Operation in temporary two-way traffic enables the partial maintenance of traffic flow in both directions. This means that partial availability can be restored quickly.

Synergy effects

- Safety
  Operation in two-way traffic generally entails additional risks compared to directional traffic, which is why risk-reducing measures must be taken in any case.
- Across tunnels
  No
- Across threats
  Yes

Feasibility

Person responsible: Tunnel manager
Additional safety-related equipment elements are usually required. Particular attention must be paid to the adequate dimensioning of the ventilation.

PROJECT CONSORTIUM

This document was prepared by the consortium of the RITUN joint project.

Project partners:

Federal Highway Research Institute (BASt)
Department of Tunnel and Foundation Engineering, Tunnel Operation, Civil Safety
Brüderstrasse 53, 51427 Bergisch Gladbach

ILF Consulting Engineers GmbH
Werner-Eckert-Straße 7
81829 Munich

Associated Partner:

Bavarian State Building Administration
Central Office for Engineering Structures and Geo Risks
Schwere-Reiter-Strasse 41
80797 Munich

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The document is also available at www.bast.de/ritun. Orders for the printed version should be sent to the following address:

Federal Highway Research Institute
B3 - Department of Tunnel and Foundation Engineering, Tunnel Operation, Civil Security
Brüderstraße 53
51427 Bergisch Gladbach, Germany

+49 (0) 02204 6300 ref-b3@bast.de

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Project team (in alphabetical order)
Dipl.-Ing. Michael Barth
Dipl.-Ing. Ulrich Bergerhausen
M.Sc. Amelie Hoffmann
Dipl.-Ing. Harald Kammerer
Dipl.-Ing. Bernhard Klampfer
Dipl.-Ing. Bernhard Kohl
Dr.-Ing. Selcuk Nisancioglu