# IMPROVING THE RESILIENCE OF ROAD TUNNELS UNDER THE PERSPECTIVE OF TUNNEL SAFETY

[1]Selcuk Nisancioglu, [2]Harald Kammerer

[1]Federal Highway Research Institute, Germany
[2]ILF Consulting Engineers Austria GmbH, Austria

## ABSTRACT

Aging infrastructure, increasing traffic, extreme events and climate change pose challenges to owners and operators of transport infrastructure. In particular, the non-availability of tunnels can lead to considerable economic losses and adverse consequences for the local and regional traffic situation. The BMBF-funded research project RITUN is therefore trying to develop ways of making tunnels more resilient. However, increasing the availability of road tunnels should only be achieved while complying with the minimum requirements of tunnel safety.

*Keywords: minimum operating requirements, road tunnels, safety, security, availability, qualitative and quantitative risk assessment, resilience*

## 1. INTRODUCTION

Resilience describes a system's ability to take into account, prepare for, repel, recover from and adapt ever more successfully to both familiar and emerging threats (acatech (Hrsg.), 2014). These threats are emergencies and disasters that affect the availability of road tunnel and are considered extraordinary in the way that their intensity goes beyond what is currently considered as a basis for assessment in the design of road tunnels. Existing guidelines and regulations focus on avoiding incidents and protecting the tunnel and tunnel users in the event of an incident. Recommendations on how to react appropriately in the event of an incident in order to reduce the extent of functional loss of the tunnel and accelerate the recovery process back to normal operation are often missing, however. Following this holistic understanding, the improvement of resilience can be achieved iteratively by identifying and implementing measures in the areas prevent, protect, react and recover.


**Figure 1**: Resilience cycle, in reference to (Bruneau, et al., 2003).

In Figure 1, the four resilience phases mentioned above are arranged in chronological order around the core phase "prepare". For example, resilience could be improved by reducing the loss of functionality or speeding up the recommissioning of the tunnel after an event, or by taking measures to prevent disruptive events, i.e. to reduce their probability of occurrences (Bruneau, et al., 2003).

On the basis of this approach, the research project developed a methodology for assessing the resilience of road tunnels. Special attention was paid to the formulation of so-called minimum operating requirements (MOR), which, by implementing compensation measures such as speed restrictions or block handling, allow a tunnel to continue operating temporarily after an incident, initially with reduced availability until full functionality is restored, while at the same time meeting tunnel safety requirements.

## 2. MINIMUM OPERATING REQUIREMENTS FOR THE TEMPORARY OPERATION OF ROAD TUNNELS

Tunnels are critical elements in terms of availability for individual mobility, supply to private households and the economy. The partial or total loss of performance leads to economic consequences, as the restoration usually causes long traffic restrictions and, as a consequence, additional travel time is caused by the use of low-performance alternative routes. For example in Germany road tunnels are designed and operated in accordance with international and national guidelines and regulations, e.g. (Directive 2004/54/EC, 2004), (FGSV, Road and Transport Research Association, 2006) and (BASt, Federal Highway Research Institut, 2019). Most of the required activities, e.g. risk assessment, aim to prevent incidents (‘prevent’) as well as protect the tunnel and its users in the case of an event (‘protect’). In contrast, few guidelines are concerned with how to react appropriately (‘respond’) in the case of an event and with how to recover full functionality or adapt in order to be better prepared for future disruptions (‘recover’). In the future, ageing infrastructure, increasing traffic, extreme events and climate change will present tunnel owners and operators with the challenge of implementing measures to maintain availability in the event of an incident. To this end, the first step is to define MOR, from which temporary measures for the operation of tunnels after an incident can then be derived to ensure the necessary operational safety.

In contrast to other European countries, there are no recommendations in Germany on MOR for road tunnels, which indicate which of the safety facilities can be temporarily dispensed with, and where tunnel operation is still justifiable from the perspective of personal safety. In France, the Centre d'Études des Tunnels (CETU) requires that minimum operating conditions shall be included in the emergency plans of tunnels along national roads and longer than 300m (CETU, Centre d'Études des Tunnels, 2006). They formulate limit values for the availability and performance of safety equipment and personnel. If these limits are not met, tunnels must be closed to traffic. The CETU distinguishes between non-compensable and compensable safety equipment. The failure of non-compensable equipment cannot be reduced by corrective measures (CETU, Centre d'Études des Tunnels, 2014). These facilities, such as power supply or ventilation, are usually designed redundantly in order to guarantee the required minimum availability or minimum power level. Identical requirements imposed by the Administration des ponts et chaussées in Luxembourg in same form for each electrical installation in the tunnel (RITUN Consortium, 2019).

The Swiss Federal Roads Office (ASTRA) also defines permissible deviations from normal operation, i.e. failures of individual systems (parts) where traffic operation can be maintained without restrictions (ASTRA, Swiss Federal Roads Office, 2013). For each of the failures, the permissible duration of the deviation shall also be defined. If the damage cannot be repaired within the prescribed period, operation under minimum requirements results. In the case of failure combinations, operation under minimum requirements must also always be set up. The Austrian model specifies the elaboration of MOR by the tunnel operator in RVS 09.04.11 "Maintenance and Operation". Thus, an object-related assessment must be carried out for system malfunctions and events affecting the technical/traffic availability and replacement measures must be recommended (RVS 09.04.11, 2018). Overall, it can be stated that in the directives examined, regulations on MOR go beyond the level prescribed in Europe (Directive

2004/54/EC, 2004). The effects of damage on the safety level are described, compensation measures are recommended and acceptable permissible failure times and the duration of use of compensation measures are formulated. The compensation measures required in the guidelines primarily serve the purpose of personal safety, compliance with which is the prerequisite for determining MOR after disruptive events. None of the approaches prescribes a specific method for defining and evaluating compliance with MOR. In each case the approach has to be adopted and implemented for each individual tunnel by the respective tunnel operator. Therefore, it is likely that the evaluation is based on their extensive experience, i.e. expert judgement, and is informed by studies of equipment performance that were carried out during the design of the respective tunnel.

For the development of MOR, the RITUN project pursued a measure- and a risk-oriented approach: It is assumed that a tunnel equipped in accordance with RABT no longer provides the minimum safety level as a result of an event. On the basis of risk analyses, it can then be assessed whether the normatively required safety level can be achieved through compensation measures. The safety of the tunnel users  is the decisive risk factor here. As a reference value, the risk in a reference tunnel fully equipped in accordance with applicable regulations is used. This reference value corresponds to the first of two threshold values, which divide the risk scale into three areas (Figure 2).

The minimum safety level represents the minimum level of  safety to be guaranteed during normal operation and at the same time the upper limit of the generally accepted risk (acceptance range). The MOR corresponds to the second threshold value between a range of increased risk which can be tolerated for a limited period of time (tolerance range) and the range of unacceptable risk in which compensation for the risk is inevitably necessary to maintain availability (intervention range).

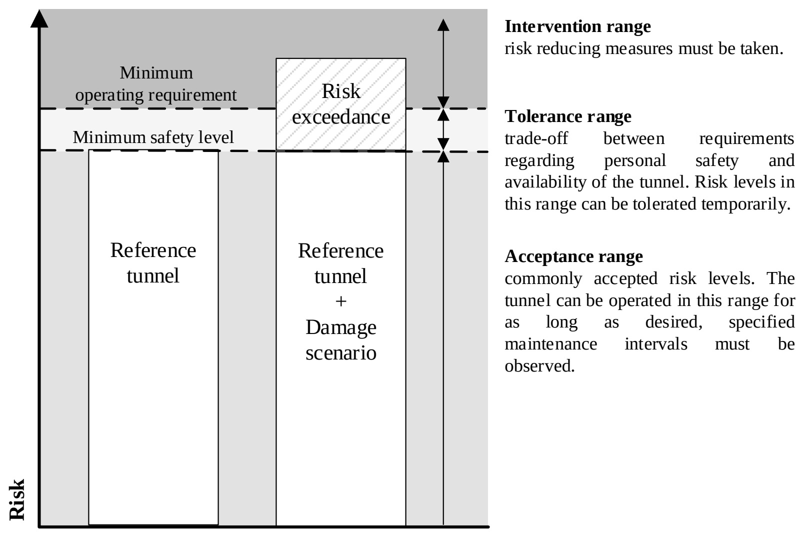


**Figure 2:** Thresholds of minimum safety level and minimum operating requirement dividing the risk axes into three ranges.

## 3. METHOD FOR ASSESSING THE RISK AFTER AN EVENT

Safety is described as the absence of unacceptable adverse consequences (DIN EN 50126-1, 2018). Therefore, if any individual damage scenario has no negative impact on the safety of tunnel users that scenario shall be classified as not relevant. It follows that the tunnel can be operated without restrictions and any damages can be repaired during the next scheduled maintenance. Relevant damage scenarios lead to an increase in risk and, in theory, to the minimum safety level being exceeded (Figure 2). For some scenarios, risk increases significantly, i.e. it exceeds the range of tolerable risk. The risk increase is triggered either by increased probability or increased severity of events that threaten users and personnel inside a tunnel. A damage scenario's significance is evaluated, exclusively for safety relevant damage scenarios, using qualitative and quantitative methods.

### 3.1. Threats under the All Hazard Approach

A threat is a potential hazard that can cause damage and thereby compromise the safety and/or availability of tunnels. Based on the All-Hazard Approach (AllTraIn, 2015), therefore, in a first step all natural and man-made threats relevant to road tunnels were identified. They were then categorised according to the point of impact (structure, equipment, road section and/or centralised tunnel systems). Many of the identified threats are characterised by a low probability of occurrence, which means that the statistical basis for a systematic evaluation of the relationships between the various threats, the point of impact and the extent of the resulting damage is lacking. For this reason, the possible effects of threats are qualitatively mapped and evaluated using a hazard damage matrix. This makes it clear that individual threats can trigger several damage scenarios and that different threats can also lead to the same damage scenarios. For further investigations the damage scenarios were decoupled from the concrete threats resp. causes in terms of their risk-increasing effect.

### 3.2. Damage Scenarios

The identification of relevant damage scenarios in light of possible threats was carried out in consultation with experts of tunnel planning, safety and operation. In an approach similar to the one adopted in the Austrian guidelines, a total of 99 individual damage scenarios were identified considering components of tunnel structure and equipment. Damage scenarios are grouped according to their point of impact into structural, obstructive and equipment damage scenarios. The structural scenarios describe damage to the tunnel structure itself caused by static, dynamic or thermal loads. Obstructions of the tunnel width without occurrence of damages, e.g. due to rockfall, snow drift or flooding, are attributed to the obstructive damage scenarios and result in restricted or interrupted traffic flow. Equipment damage scenarios combine both the physical damage and technical malfunction of tunnel equipment. In each category different components of functional systems can be affected by different levels of partial or complete malfunction (failure modes). The damage may have a direct impact on tunnel operation and lead to a reduction in the level of safety. In order to compensate for this, and thus maintain availability after an incident, it is necessary to adapt traffic in the tunnel to the changed risk. If this is not possible, the tunnel must be completely closed to traffic for safety reasons.

## 4. POTENTIAL RISK MITIGATION MEASURES AFTER AN INCIDENT

The compensation measures for risk reduction after an incident are divided into functional compensation and additional compensation measures. The development of compensatory measures is based on a single damage scenario. The simultaneity of several damage scenarios and thus the unavailability for functional compensation of suitable operational equipment as well as their consequences for the selection of appropriate safety-related compensation measures are not considered in the course of MOR. The possibilities of using compensation measures were discussed and determined in a technical workshop with experts.

### 4.1. Functional compensation

The reduction or loss of functionality of the component affected by damage scenario is fully or partially compensated by any remaining redundancies of the component itself or by other systems. Consequently, at best, the original safety level can be achieved. Where full functional compensation, or at least functional compensation within the tolerance range, is achievable, the tunnel may continue to operate under normal traffic conditions until unscheduled maintenance.

If this is not or only partially feasible and the risk remains within the scope of action, (additional) safety compensation measures shall be taken to reduce the risk to a tolerable level. For example, a failure of the manual fire alarm systems (manual call points), which are rarely used anyway, can be fully functionally compensated by the automatic (linear heat detection system). Conversely, however, this is not possible, in which case additional safety-related compensation measures are required.

If damage or malfunctions are also present in other components and therefore not or not fully functional, these cannot be used for functional compensation.

### 4.2. Additional compensation measures

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 combined. In contrast to functional compensation, safety-related measures can have a positive effect on other safety-critical functions than the compromised one and thus contribute to a reduction of the risk. These measures or combinations of measures can be used either as a supplement to an incomplete compensation or independently in the case of an impossible functional compensation. The measures that can be taken include

- Speed limit: On the one hand, a speed limit leads to a reduction in the frequency of accidents and the extent of mechanical damage.
- Consistent control of the average speed: Section control results in a reduction of speed below the actual maximum speed limit and compliance with the average speed over a section of road, as well as harmonization of driving behavior. On the one hand, this reduces the frequency of accidents; on the other hand, it reduces the mechanical damage effects.
- Truck driving bans: Events with large fire loads (30 MW up to 100 MW) can be avoided by a ban on truck traffic.
- Driving ban for dangerous goods transports: In order to reduce the extent of the damage by avoiding extraordinarily high fire loads (100MW and more) without closing the tunnel to all truck traffic, a driving ban on hazardous goods transports can be applied.
- Driving ban for cars: In view of strategically particularly important traffic routes for industry and the corresponding possible pressure to maintain availability for truck traffic, there is theoretically the possibility of a driving ban on cars. Due to the resulting significant reduction in the number of people in the tunnel in case of fire, the extent of damage is reduced. In addition, a lower accident rate can be achieved, on the one hand because of the greatly reduced number of vehicles and the resulting reduced interactions in the traffic flow, and on the other hand because only trained professional drivers drive through the tunnel with the truck drivers.
- Fire brigade stand-by: Under the measure, it is assumed that there is a permanently operational fire brigade in the immediate vicinity of the tunnel ("portal fire brigade") which can intervene quickly in the event of a fire in the tunnel (journey time < 5 minutes). In case of fire, the extent of damage caused by fire is reduced by efficient fire fighting and external rescue. In addition, positive effects with regard to the rescue of persons in the event of fire as well as mechanical accidents can be qualitatively taken into account.
- Ongoing control runs: The route service can continuously get an idea of the current situation on site by means of control runs; this is of high relevance especially in case of a non-functional video surveillance. In this way, an event can be detected and assessed more quickly, so that it can be reacted to accordingly.

### 4.3. Traffic Operating Scenarios

A restriction of traffic operation after an incident for the purpose of tunnel user safety is usually implemented if the required safety level cannot be achieved with compensation measures. Following the risk assessment of a damage that has occurred, three traffic-related operating scenarios can be distinguished: Normal operation, restricted operation and full closure.

Normal operation can be maintained if no traffic measures are required to reduce the risk to a tolerable or more acceptable level. This is the case, for example, if a damage scenario has been classified as not relevant for the safety of persons. In the case of a safety-relevant damage scenario, temporary normal operation can only be achieved by compensating for the increase in risk. This is to be checked continuously until the damage is repaired. If the conditions of the temporary normal operation change, the safety level shall be re-examined and, if necessary, the traffic operation scenario shall be adjusted.

For safety compensation through traffic restrictions, speed reductions or route restrictions for some types of vehicles (e.g. transport of dangerous goods) are mainly suitable. It should be considered that the operating phases "situation assessment and temporary operation" and "maintenance" place different demands on the traffic operating scenario. For example, the requirements for tunnel user safety following an extraordinary event are decisive. During the repair of the damage, additional requirements for the execution of the repair work must be taken into account when selecting appropriate traffic operation.

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

## 5. SUMMARY AND OUTLOOK

The results of the RITUN research project are intended to help owners and operators to improve the resilience of road tunnels. For this purpose, so-called minimum operating requirements were investigated, which are an essential prerequisite for maintaining availability after an incident. Furthermore, possible compensatory measures were identified which could reduce the resulting risk after an incident. Discussions with various tunnel operators showed that in particular the development of measures to maintain or increase a defined traffic flow immediately after an incident, but also during the repair work until road tunnels are fully reopened, is a useful approach. In this context, different operating modes for maintaining availability were also examined. Basically, it can be stated that a large number of parameters interact in a complex interplay and influence the safety of tunnels after an event. Therefore, no general statements can be made regarding the effectiveness of the presented compensation measures. However, the investigations carried out provide information about the influence of the compensation measures on the risk. Therefore, they have to be evaluated individually, considering the specific conditions of individual tunnels on the basis of a quantitative risk analysis.

As a result of the RITUN project, a manual was developed which shows possible measures that can be implemented to quickly achieve partial availability after an incident until the original tunnel operation is resumed. To this end, target-oriented resilience measures were identified and evaluated and summarized in the form of a checklist. The manual can support owners and operators in considering not only safety aspects for tunnel users and structures, but also availability aspects, when planning, equipping and operating tunnels. To verify the applicability of the results, they were tested in a real tunnel in Southern Germany.

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