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IMPROVING ROAD TUNNEL RESILIENCE, CONSIDERING SAFETY AND AVAILABILITY

A PIARC BRIEFING NOTE
INCLUDING A COLLECTION OF CASE STUDIES

TECHNICAL COMMITTEE 4.4 *TUNNELS*

PIARC

STATEMENTS

The World Road Association (PIARC) is a nonprofit organisation established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

The study that is the subject of this report was defined in the PIARC Strategic Plan 2020-2023 and approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competences.

Any opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of their parent organisations or agencies.

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Front cover © J. Mitchell, Highways England, 2018: maintenance in the Saltash Tunnel, UK; the Saltash Tunnel is one of the case studies in this report

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EXECUTIVE SUMMARY

2022R04EN

IMPROVING ROAD TUNNEL RESILIENCE, CONSIDERING SAFETY AND AVAILABILITY

BRIEFING NOTE INCLUDING COLLECTION OF CASE STUDIES

This report presents a review of literature on the improvement of road tunnel resilience as well as a collection of case studies that illustrate how this topic is being dealt with in practice. The content of the report is addressed at several target groups involved in the planning, design, implementation, operation, maintenance and refurbishment of road tunnels, such as decision makers, tunnel owners and managers, tunnel operators, emergency response services, designers, tunnel safety experts, safety officers and risk analysis specialists. Much of the content of the report is relevant for both high-income as middle- and low-income countries, because resilience is a concept rather than a specified recipe; management approaches and improvement measures can (and should) be tailored to the local requirements, goals and circumstances.

Many definitions for "resilience" were found, but the Working Group decided on the following definition:

"The ability to prepare, plan for, resist, absorb, recover from, more successfully adapt to actual or potential negative effects of events or developments affecting the availability of a road tunnel in a timely and efficient way. In this context, an acceptable safety level is a mandatory constraint for the availability of the road tunnel".

This definition is in line with the current general definition of resilience by PIARC (TC 1.4, 2021) but adapted to road tunnels and their primary function. Since resilience in the road sector is addressed by several PIARC Committees as a cross-cutting issue on which work is ongoing, the definition may need to evolve in the future.

The literature review in this briefing note focusses on the following topics:

- General concepts and approaches for resilience management and improvement;
- Legislation, standards, strategies and policies;
- Criteria and requirements for resilience, availability and safety as a mandatory constraint;
- Various events and future developments to be resilient for, like weather conditions, climate change and other natural hazards like earthquakes and flooding, traffic incidents and traffic developments, calamities like fire, physical and cyber-security incidents, failure of technical or operational safety measures, including pandemics threatening the availability of the tunnel staff, maintenance and refurbishment works and technical and social developments like SMART mobility and the growing use of new energy carriers for vehicles;
- Possible measures to improve road tunnel resilience for these events;
- Organisational and managerial aspects of resilience improvement.

The collection of case studies in the briefing note covers the wide range of resilience topics and aspects mentioned above, thus providing valuable insight in current practices worldwide. Included are cases from Australia, Austria, Belgium, France, Germany, Italy, Japan, The Netherlands, South Africa, South Korea, Spain, Switzerland and The United Kingdom.

The report is completed with conclusions and recommendations for the target groups (see Chapter 5), an extensive reference list, a glossary and appendices.

This report is the second step in the development of a full technical report on road tunnel resilience. For this development, a “growing-document approach” is applied, which means that intermediate outputs are published. Each next publication contains added information to the previous one, ending with the full technical report. This approach makes it possible to dissiminate relevant information that is useful for the target groups during the course of this PIARC cycle (2020-2023) before the final report is ready. Moreover, this makes it possible to update information already published, on the basis of new developments and insights. This seems particularly relevant since resilience is a cross-cutting topic during this cycle, involving contributions from various other technical committees in PIARC. The first step in the development was the PIARC literature review report[1] on road tunnel resilience (2021LR01EN), published in 2021 [111]. The main part of present report mostly equals the content of [111] but with the addition of the collection of case studies. However, [111] has not become superfluous with the publication of the present report, because [111] contains an extensive appendix with summaries of the reviewed literature. This appendix is left out from the present report in order to limit the size of the document.

[1] The 2021 Literature review is available at this link: Detail of a publication | Virtual Library of PIARC | Improving Road Tunnel Resilience, Considering Safety and Availability - PIARC Literature Review.

CONTENTS

1. INTRODUCTION

1.1. PURPOSE

Road tunnels are usually part of an infrastructure that is vital for transport of people and goods, between countries, regions or different parts of a city, for social and economic benefits. The fact that the construction of tunnels is relatively expensive and time consuming underlines this importance. To be cost-effective, it is generally important to keep the tunnel available for traffic as much as possible, to process the through-pass capacity it was planned and designed for. Yet, compared to the open road, tunnels are relatively vulnerable when it comes to the risk of non-availability for traffic, because of the many required safety installations to enable safe passage. Maintenance of these installations usually causes hindrance for the traffic, and when one of these installations fails the tunnel might ultimately be temporary closed for safety reasons. Moreover, a traffic incident or fire in a tunnel often requires more time and effort to normalize the situation than on the open road, for example due to more difficult access for the emergency response services, and (when applicable) the required time to evacuate people from the tunnel and to repair damage to the structure and installations.

Basically, the operating conditions of a road tunnel are seldom constant and many events or hazards (including intended disruptions like terrorist or cyber attacks) can potentially threaten its availability (and thus its social and economic functions and benefits). Therefore, “resilience” is an important consideration in the planning, design, construction and operation and maintenance of the tunnel as a system.

The concept of resilience is routinely used in research in disciplines ranging from environmental research to materials science and engineering, psychology, sociology, and economics. The notion of resilience is commonly used to denote both strength and flexibility. A common definition for resilience was proposed by Bruneau et al. [1]:

“The ability of the system to reduce the chances of a shock, to absorb a shock if it occurs (abrupt reduction of performance) and to recover quickly after a shock (re-establish normal performance).”

This definition is part of a framework that was developed to quantify or measure the resilience of infrastructure in the event of an earthquake.

Applied to road tunnels, and in line with the key interests of tunnel owners / managers, tunnel authorities and road users, the Work Stream Tunnel Safety[2] described resilience as [2]:

“The ability to keep the tunnel available for traffic on an acceptable safety level, under various circumstances, notably disruptions of the normal situation”.

Note that an acceptable safety level is presented here as a constraint for the tunnel to be available for traffic. If the safety level is not acceptable anymore (as result of a certain event or incident), the tunnel should be closed. Of course, closure of the tunnel for safety reasons could be prevented by taking temporary alternative safety measures to assure an acceptable safety level, despite the non-availability of the normally active safety measures. Hence, the ability to take alternative measures

[2] International collaboration on tunnel safety, between the Netherlands, Flanders (Belgium), the United Kingdom and France.

when called for is an important contribution to the resilience of the tunnel system. The acceptability of the safety level of a tunnel depends on many factors including the (inter)national legislation, local laws, and policies and practices the tunnel manager is subject to.

The PIARC Road Dictionary[3] does not contain a definition for tunnel (system) resilience. However, based on recent PIARC reports like [4] and [5], it does define resilience to climate change:

"The Ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse effects of climate change".

Recently, a more general definition of resilience was developed by PIARC TC 1.4 [112]:

"The ability of a system, community or society exposed to a hazardous event, a trend or a disturbance, to resist, absorb, accommodate, adapt to, transform, learn and recover from the induced effects in a timely and efficient manner that maintain their essential function, identity and structure."

These PIARC definitions are in line with the general definition by Bruneau et al., but more explicitly add the dimension of successful adaption, hence the ability to change or improve by learning. This seems to be relevant for adaptation to long term developments and for improvement of the resilience performance where required. It more or less means the "closure" of the Deming-circle: Plan, Do, Check and Act (PDCA)[4]. We feel that the definition in the PIARC Road Dictionary reflects the Deming circle more clearly, while the TC 1.4 definition [112] better points out that the various resilience performances should be timely and efficient to maintain (and enhance) the essential function.

Thus, in consideration of the above mentioned examples, while focussing the primary function of a road tunnel, we propose the following definition for road tunnel resilience as a basis for this study:

"The ability to prepare, plan for, resist, absorb, recover from, more successfully adapt to actual or potential negative effects of events or developments affecting the availability of a road tunnel in a timely and efficient way. In this context, an acceptable safety level is a mandatory constraint for the availability of the road tunnel".

Since resilience in the road sector is addressed by several PIARC Committees as a cross-cutting issue on which work is ongoing, this definition may need to evolve in the future.

The definition applies to the availability of the tunnel, that is, the functionality of the road going through the tunnel tube. However, the required resilience to keep a tunnel available for traffic under safe conditions actually applies to the whole tunnel ***system***.

A "tunnel system" is defined as the system that consists of:

- The road, in and nearby the tunnel, possibly including an alternative route for the occasions that the tunnel is closed for traffic or certain vehicles;
- The tunnel structure;
- The tunnel technical installations (TTI), including the control systems;
- The control centre from which the tunnel is operated (when applicable);

[3] See: https://www.piarc.org/en/activities/Road-Dictionary-Terminology-Road-Transport

[4] See figure 14 in section 3.2.1 for an adaptation of the Deming circle to resilience (the resilience circle)

- The organization (staff) and the business and tunnel processes of the tunnel manager, for instance regarding incident response;
- In addition, the following elements can be part of the tunnel system:
  - the traffic management measures for the road network, as far as they have an influence on the traffic situation in the tunnel; these measures, possibly integrated with the tunnel measures as mentioned above, may include (dynamic) signage, a lane control system, a traffic management centre, procedures and personnel;
  - Interactions with other objects/systems (e.g. when the tunnel is part of an interconnected underground infrastructure, or when the road network outside the road tunnel is operated by another organization).

All these elements work together as a system to assure the safe availability for the tunnel users, at a certain designated service level (based on requirements set by the tunnel manager). Hence, the integrated performance of all these elements define the resilience of the tunnel system. Notably the organization of the tunnel manager is a very important "active" element in the resilience performance and the improvement thereof.

In line with the above mentioned considerations, PIARC's Strategic Plan 2020-2023 mentions road tunnel resilience as a new focus topic to be studied, to identify and recommend "measures to increase the availability of the tunnel for users and measures to increase the robustness (construction and operation) of the tunnel".

The present report is the result of a literature review and a collection of case studies, as a second step towards a full technical report on the matter[5]. Its **purpose** is to describe the concept of resilience for road tunnels and to give an overview of the relevant aspects, as well as some general recommendations on the possibilities to improve resilience, based on the examined literature and cases, as well as the knowledge and experiences of the Working Group members. In addition, the report will allow target groups to collect further information on the topics that are relevant to them.

The next step will be to further expand this report to a full technical report, scheduled for 2023, by adding, among other things, some more information on the effectiveness and cost-effectiveness of various measures to enhance resilience.

1.2. SCOPE

Resilience is a broad concept that involves many aspects or topics. The Working Group developed mind maps to get a picture of the scope, see figures 1 and 2 in the following pages.

The literature review and collection of case studies were actually aimed at this full scope, in line with the purpose mentioned in section 1.1. This means that the content of this report aims to present a general overview, without going into detail too much.

There were no limitations to the geographical scope of the study. The study focused on world-wide knowledge and experiences.

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[5] The first step was the publication of a literature review report in 2021 [111]. The main part of this briefing note mostly equals the content of the literature review report ,but with the addition of the collection of case studies.

Lastly, although the focus of the study is on tunnels, we are mindful of the fact that tunnels are part of a road network, therefore not stand-alone objects. Thus, the relations between a tunnel and the network as a whole were taken into account when required; see section 2.7 for a further explanation.

1.3. Target groups

This report addresses several target groups that are involved in the planning, design, implementation, operation, maintenance and refurbishment of road tunnels, such as decision makers, tunnel owners and managers, tunnel operators, emergency response services, designers, tunnel safety experts, safety officers and risk analysis specialists.

Much of the content of the report is relevant for both high-income as middle- and low-income countries, because resilience is a concept rather than a specified recipe; management approaches and improvement measures can (and should) be tailored to the local requirements, goals and circumstances.

1.4. Working method

1.4.1. Literature review

The mind maps in figures 1 and 2 were used as a basis for the collection and review of literature sources by the Working Group members. Given the broad scope, and to assure a certain focus and to avoid a certain overlap in the work as much as possible, it was decided to appoint task groups to each topic as presented in the mind maps (0, 1, 2a, 2b, 2c, 2d, 2e, 2f and 3). Moreover, the definition for road tunnel resilience, as presented in section 1.1, served as guidance for the focus of the reviews. Since literature sources can address more than one topic, task groups exchanged sources where applicable. Therefore, a source was sometimes reviewed by several task groups, but each time with a specific focus.

A relevant literature source in a language other than English was reviewed by a Working Group member with sufficient understanding of that language (e.g. a native speaker). The main results of the literature review are presented in chapter 3 and the list of reviewed literature sources is assembled in chapter 6. The detailed results (review per literature source) are available in the appendices of the literature review report [111]. Although far from complete, the Working Group feels that the review very well reflects the essence of the concept of resilience, adapted to road tunnels.

1.4.2. Collection of case studies

Based on the results of (and the recommendations derived from) the literature review, the Working Group members collected practical examples of how the broad concept of resilience is applied with road tunnels in their country (or in a country in which they are professionally active). Again, task groups were appointed to organize the work, this time per country. Thus, a task group consisted of the working group members from the relevant country. For the description of the case studies, a standard format was used as a guideline, see Appendix A. The quality control of the documented case studies was also organized per task group (or between task groups when a task group consisted of only one Working Group member). The main results are addressed in chapter 4, while the case studies themselves are assembled in the appendices B to S.

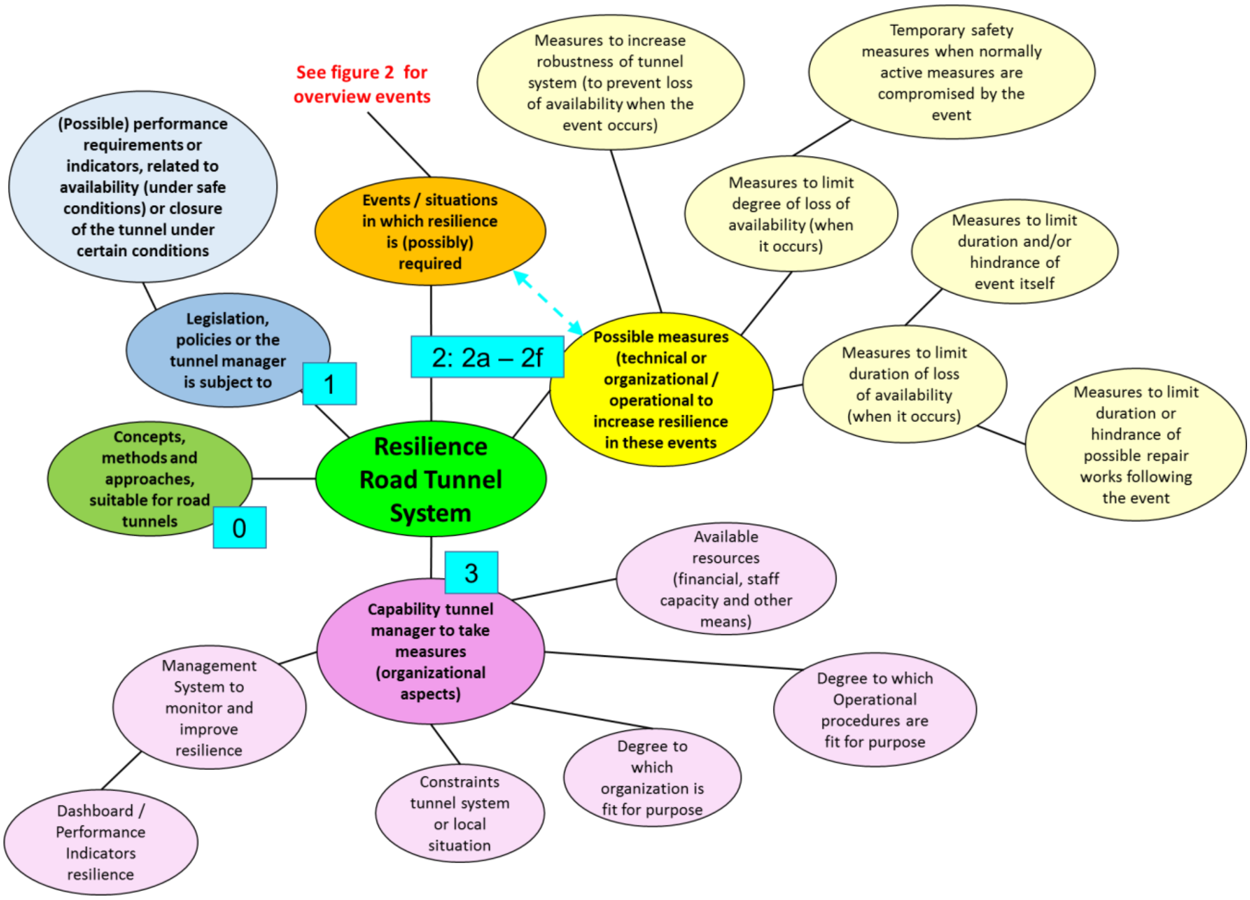

Figure 1. Overview topics related to road tunnel resilience, as a basis for the literature review

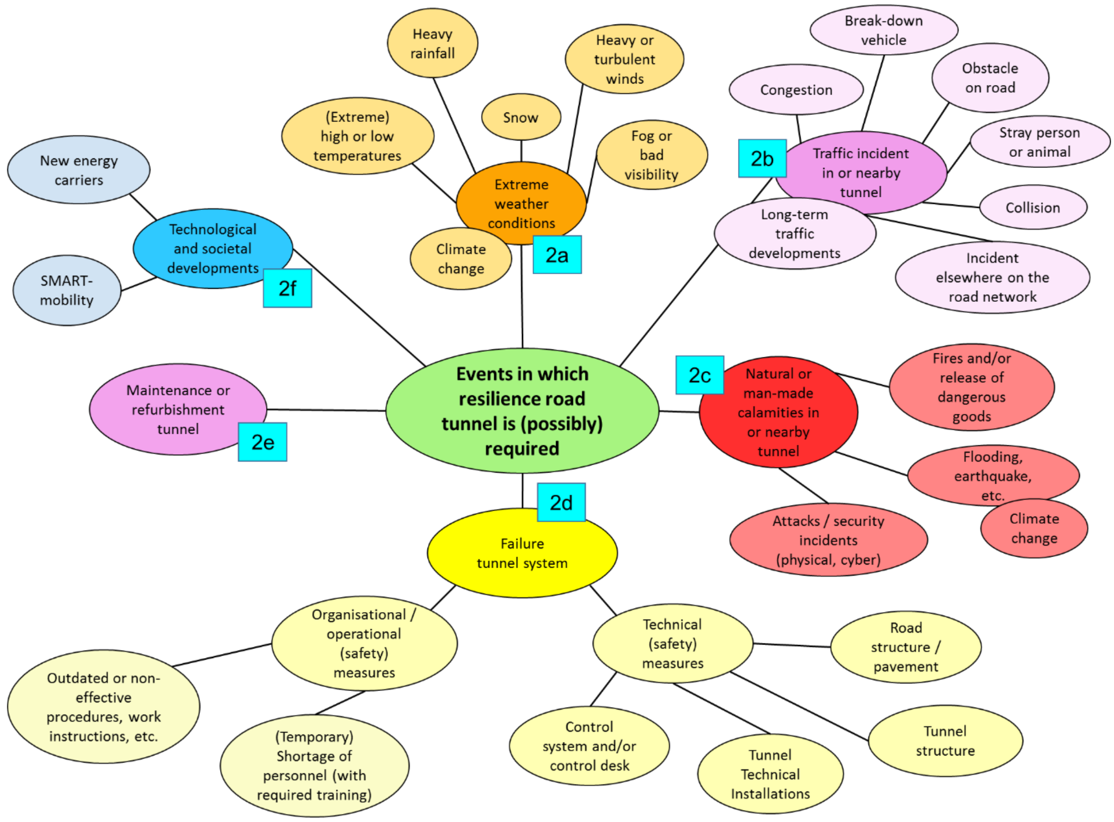

Figure 2. Overview of events or situations in which road tunnel resilience is (possibly) required

1.5. CONTENT

To explain the concept of resilience somewhat more, as applied to road tunnels according to our definition, some characteristics and examples are presented in **Chapter 2**. The purpose of these examples is to help the reader to assess the meaning and value of findings of the literature review somewhat better. In general, literature presents many approaches and frameworks for resilience, so the content of Chapter 2 is not to be interpreted as "the best view" but as an introduction to get a feeling for the concept. On the other hand, it can be noted that the approaches found in literature are mostly elaborations of – or variations on - the theme presented in Chapter 2.

The findings of the literature study are assembled in **Chapter 3**, with a separate section for each topic. Focus in this chapter is on similarities and differences found in the literature sources, topics or items that are not yet covered by literature, as well as recommendations and measures to improve resilience that are applicable to – or specifically meant for - road tunnels.

Chapter 4 contains the main findings from the collected case studies, on how the resilience concept is applied in practice on road tunnels. The case studies themselves are presented in the appendices B to S. The collection illustrates that the concept of resilience covers a broad variety of aspects and topics to be taken into account.

Last, in **Chapter 5**, the main conclusions and recommendations are summarized, with additions based on the knowledge and experience of the Working Group, where relevant.

The report is completed with a Bibliography, a Glossary and the already mentioned appendices.

Note:

This report is the second step in the development of a full technical report on road tunnel resilience. For this development, a "growing-document approach" is applied, which means that intermediate outputs are published. Each next publication contains added information to the previous one, ending with the full technical report. This approach makes it possible to dissiminate relevant information that is useful for the target groups during the course of this PIARC cycle (2020-2023) before the final report is ready. Moreover, this makes it possible to update information already published, on the basis of new developments and insights. This seems particularly relevant since resilience is a cross-cutting topic during this cycle, involving contributions from various other technical committees in PIARC. The first step in the development was the PIARC literature review report[6] on road tunnel resilience (2021LR01EN), published in 2021 [111]. The main part of present report is largely the same as in [111], except that chapter 4 on the case studies was added (the case studies themselves were added in the appendices). Compared to [111], some clarifications, improvements and additions were implemented in chapters 1, 2, 3 and 5, for instance an added clarification that a high availability of the tunnel does not necessarily imply a high resilience, see section 2.6. Further, the Bibliography and Glossary were expanded. However, [111] has not become superfluous with the publication of the present report, because [111] contains an extensive appendix with summaries of the reviewed literature sources (on which the content of chapter 3 is based). This appendix is left out from the present report in order to limit the size of the document.

[6] The 2021 Literature review is available at this link: Detail of a publication | Virtual Library of PIARC | Improving Road Tunnel Resilience, Considering Safety and Availability - PIARC Literature Review.

2. ROAD TUNNEL RESILIENCE

2.1. CHARACTERISTICS

In section 1.1, road tunnel resilience was defined as:

*“The ability to prepare, plan for, **resist**, **absorb**, **recover from**, more successfully **adapt** to actual or potential negative effects of events or developments affecting the availability of a road tunnel in a timely and efficient way. In this context, an acceptable safety level is a mandatory constraint for the availability of the road tunnel”.*

The bold keywords in the definition represent the main characteristics of a resilient system.

Bruneau et al. [1] stated that a resilient system shows:

- Reduced failure probabilities;
- Reduced consequences from failures, in terms of lives lost, damage, and negative economic and social consequences;
- Reduced time to recovery (restoration of a specific system or set of systems to their ‘‘normal’’ level of performance).

These characteristics match the ability to absorb and recover from an event (prevention and mitigation). A distinction is being made between the <u>degree</u> of disruption / failure and the <u>duration</u> of the disruption / failure.

Rose [3] called the ability to limit the degree of a disruption “static resilience” and the ability to limit the duration of the disruption “dynamic resilience”. Note that the degree of disruption is firstly limited by the preventive resilience. Secondly, when the negative effects of an event cannot be fully prevented, further limitation of the degree of disruption can be achieved by mitigating measures (mitigation resilience). By definition, when a disruption occurs, the duration can only be limited by mitigating measures (again, mitigation resilience).

Not mentioned as a characteristic by Bruneau et al. [1], but addressed in other literature sources like [68] as well as in our definition of road tunnel resilience, is the ability to more successfully adapt to circumstances, the “adaptive resilience”. This would mean:

- Improving performance over time (in terms of more efficiency or a higher performance level) when the same type of event repeats, and/or:
- Maintaining or improving performance (in terms of more efficiency or a higher performance level) when developments occur that lead to significant changes in the characteristics of a certain type of event(s), or to a new type of event(s) that one did not have to deal with in the past.

So, to summarize, a resilient road tunnel system, compliant with our definition, would ideally show one or more of the following characteristics:

- Preventive resilience (static): the ability to fully resist/absorb or limit the negative effects of a certain event, so that loss of availability is either prevented or limited, while maintaining an acceptable safety level as a mandatory constraint; Bruneau et al. [1] call this “robustness”;

- Mitigation resilience (static and dynamic): the ability to recover from the negative effects of a certain event, either by limiting the degree or the duration of loss of availability, while maintaining an acceptable safety level as a mandatory constraint;
- Adaptive resilience: the ability to improve (the efficiency of) the availability performance of the tunnel under the same recurring circumstances or to maintain or improve (the efficiency of) the availability performance under changing circumstances (adaptation to long-term developments), while maintaining an acceptable safety level as a mandatory constraint. Note that what is considered an acceptable safety level may change over time as well; thus, adaptive resilience may also be required to adapt to changing or increasing (legal) safety requirements. Also note that changes in order to adapt can be either positive or negative; for instance, possibilities to decrease energy consumption would make measures more efficient and more sustainable; and a new road in the network could possibly decrease the traffic volume in the tunnel, allowing for lower availability requirements, hence less strict measures. As a last example, the development of SMART mobility could mean that some safety equipment in the tunnel could be phased out.

Basically, since the circumstances and boundary conditions under which the tunnel is operated will constantly change, improving resilience will normally be a continuous process. Goals and measures to enhance this may engage on one or more of the above-mentioned characteristics. See **Chapter 3** for possibilities found in literature.

In the next sections these characteristics will be illustrated with some examples.

2.2. PREVENTIVE RESILIENCE (STATIC)

An example of preventive resilience is shown in figure 3. This figure shows a graph of the availability of a tunnel for traffic as a function of time.

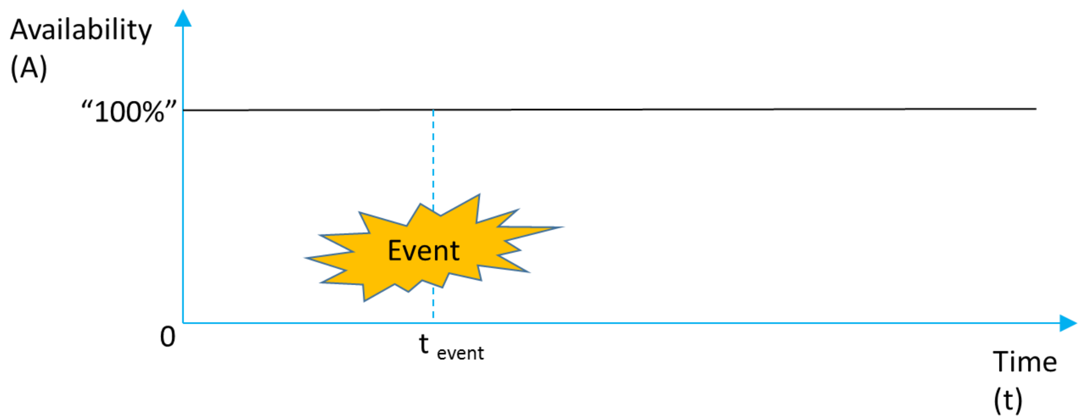

Figure 3. Example of full absorption of negative effects of an event

At a certain moment, an event takes place that can potentially affect the availability of the tunnel. However, the tunnel system can fully absorb the negative effects of the event, so loss of availability is prevented.

Such an event could be a heavy rain shower, that can be handled by the drainage and pumping system of the tunnel, thus avoiding a puddle that would lead to the closure of one or more lanes or even the entire tunnel tube, because road safety would be compromised to an unacceptable level.

2.3. MITIGATION RESILIENCE (STATIC AND DYNAMIC)

An example illustrating mitigation resilience is shown in figure 4. In this case, the negative effects of a certain event cannot be fully absorbed, causing the availability of the tunnel to be disrupted to a certain degree, for a certain period of time. The full availability is restored by the recovery actions by the tunnel system (symbolized by the "repair" icon in the graph).

Such an event could be a breakdown vehicle blocking a lane. In case of an operated tunnel, the blocked lane would probably be closed and the speed limit in the other lanes would probably be reduced. Both these actions are necessary to prevent escalation of the incident, but lead to a reduced availability level as well. Further actions to recover the normal situation would consist (in this example) of salvaging/removing the breakdown vehicle and making the tunnel fully available again by reopening the lane and ending the reduction of the speed limit.

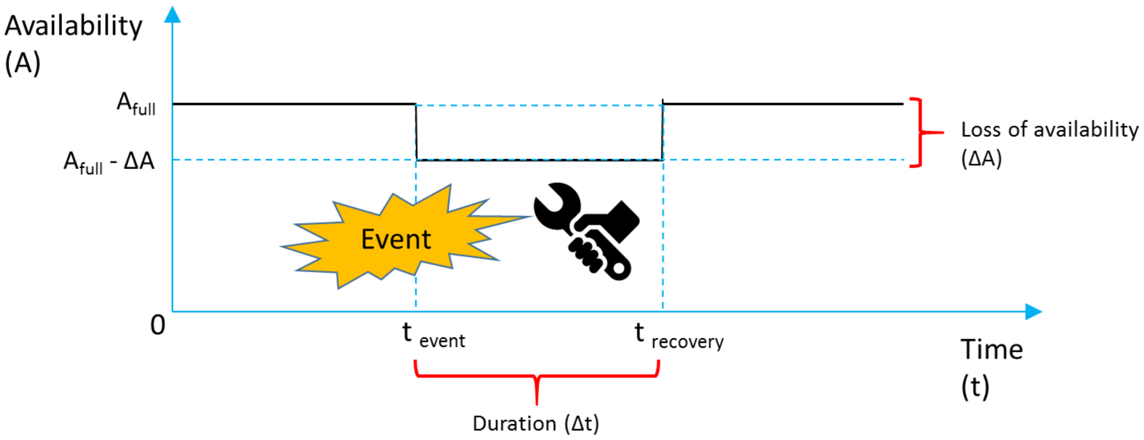

Figure 4. Example of an event leading to temporary loss of availability

The smaller the temporary loss of availability (ΔA) the greater the static resilience of the tunnel system. And the smaller the period of time during which the loss of availability occurs (Δt) the greater the dynamic resilience. Or, put differently, according to [1]: the smaller the total loss (ΔA * Δt), the greater the (mitigation) resilience[7].

In the example of a breakdown vehicle, a measure to improve the dynamic resilience could be an on-site traffic officer, and/or a service level contract with a vehicle recovery company, to manage the incident quickly when it occurs. For tunnels still in the planning phase, a measure to improve the preventive (static) resilience could be an emergency lane in the tunnel, to provide a safe location for a breakdown vehicle to stop, without blocking a lane.

Another example of mitigation resilience is shown in figure 5.

Again, an event occurs that can't be fully absorbed by the tunnel system. In this case, the event leads to closure of the tunnel as a first reaction, but then some temporary mitigating measures are implemented. As soon as these measures are effective (symbolized by the "band aid" icon in the

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[7] Note that if (ΔA * Δt) = 0, the tunnel system is fully resilient to the event (full preventive resilience); no loss of availability to recover from. However, if (ΔA * Δt) → ∞, this would mean that the system cannot recover from the event (no resilience whatsoever). Basically, that would involve an event in which the tunnel system is totally lost, like the flooding of a submerged tunnel, causing the foundation to succumb . Note that such an event would be represented by a different graph than figure 4.

graph) the tunnel can be reopened partly, while actions are taken to fully recover from the event, so that the tunnel can be fully available again. An example for such a scenario could be the complete failure of the camera system (CCTV) so that safe operation of the tunnel is not possible anymore. As a result, the tunnel is closed. Subsequently, traffic officers go on-site to observe the traffic and alarm the tunnel operator in case of an incident. Under these conditions, the tunnel can be re-opened, but maybe not fully, because one or more lanes might be kept closed to make the observation by traffic officers possible and to reduce the probability of an incident. In that case, this reduced availability would remain in service until the camera system is repaired and the tunnel can be fully opened again.

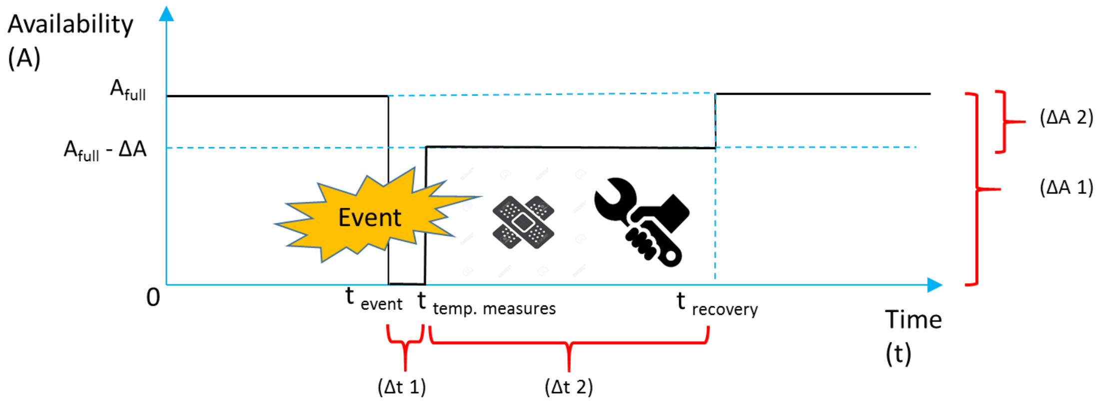

Figure 5. Example of an event with temporary mitigating measures to limit loss of availability

In this case, the performed resilience (limitation of loss of availability) is indicated by the surface (ΔA 1 * Δt 1 + ΔA 2 * Δt 2) . Note that without the temporary measures, the loss would be greater [ΔA 1 * (Δt 1 + Δt 2)]. Thus, the temporary measures add to the resilience considerably.

The resilience in this example could perhaps be further improved by (for instance) the following measures:

- Preventive resilience (static): improve the reliability / redundancy of the camera system.
- Mitigation resilience:
  - Static: shorten the time needed for mobilisation and implementation of the temporary measures (to avoid or limit the full closure of the tunnel).
  - Dynamic: shorten the time needed to repair the camera system (Mean Time To Repair, MTTR).

2.4. SAFETY AS A MANDATORY CONSTRAINT

In the previous section, it was already demonstrated that the safety level of the tunnel plays a role in the availability. In our definition of road tunnel resilience, an acceptable safety level is a mandatory constraint for the tunnel to be available for traffic. This means that as the safety level of the tunnel decreases, mitigating measures may be implemented which include those which may impact the availability. Such measures ensure that the required operating safety level of the tunnel is respected. Such measures can even include closing a tunnel to traffic completely. It should be noted that the impact of closing a tunnel to traffic or restricting the flow of traffic through a tunnel may have safety implications for the road network more broadly (therefore, it could be preferable to prevent failure in the first place!).

Mitigating measures that would limit the availability for traffic (temporarily) include:

- Closure of one or more lanes;
- Reduction of speed limit (tunnel still available, but on a lower service level, with a greater travelling time);
- Closure of the tunnel for specific vehicle categories (e.g. dangerous goods vehicles, trucks or busses), while the rest of the vehicles (e.g. passenger cars) still have access to the tunnel; this means that the banned vehicles have to take an alternative route (diversion), often with a greater travelling time, and introducing a shift of traffic risks to other parts of the network (in terms of road capacity and safety);
- Closure of the tunnel for all traffic (all vehicles have to take an alternative route).

What constitutes acceptable safety varies from country to country, state to state and time to time (or even from tunnel to tunnel within one jurisdiction[8]). Thus, what is considered an acceptable level of safety is a function of many factors including applicable legislation, laws, policies, and practices. Ultimately there are several frameworks available to deal with this matter (see **chapter 3**) but three basic principles are commonly applied:

- When all safety measures (technical and organizational / operational) function well, according to their performance requirements, the safety level complies with the design level or design requirements.
- When a safety measure fails to some degree, immediate action is not always required. For instance, if only one lamp of the tunnel lighting fails, this normally has no significant effect; the lamp can be repaired at the next scheduled maintenance for the lighting, and until then, no mitigating measures are necessary to assure the safety of the traffic. However, if a significant part of the tunnel lighting fails, action is probably required, in the form of mitigating measures (e.g. a reduction of the speed limit) and maybe accelerated repair (before the scheduled maintenance) to limit the duration of the hindrance of the reduced speed limit. The level that requires these kind of actions is the intervention level.
- It is also possible that the safety measure fails to such a degree, that the safety level is not acceptable anymore, not even with temporary mitigating measures. This level is indicated by so called “Minimum Operating Requirements” (MOR). Thus, the tunnel (tube) has to be closed when the safety level drops below the MOR level; an example of such an event could be the failure of the entire tunnel lighting.

Conceptually, the design level of safety should be greater than the intervention level and the intervention level should be greater than the MOR level (unless it is the intention to immediately close a tunnel when the level of safety drops). The approach taken for each tunnel depends upon its unique design, as built and operated performance, applicable laws, regulations, policies and practices, and local safety requirements. The greater the MOR levels are exceeded during normal operations, the more resilient the tunnel will be because there are more opportunities to mitigate the risk of reduced availability and closure due to its inherent higher level of operational performance. Having a tunnel performing at a higher level of operational safety should not be confused with imputing a higher MOR level. The MOR level should be independent of the normal operational safety level of the tunnel. Thus, a tunnel performing at a higher level of operational

[8] For example, very often when a tunnel is being refurbished, the safety requirements become more strict.

safety should not have its resilience reduced by improperly inferring that the MOR level should be raised to match this higher normal level.

Note that the design level could coincide with the intervention level and/or the intervention level could coincide with the MOR level. This depends on regulations, policies or set safety requirements. Also note that the system would be more resilient if the levels are further apart, because there would be more opportunities to avoid reduction of availability in case of failure of a safety measure.

This is illustrated in figure 6, that could represent a case where the tunnel lighting first degrades and then completely fails. At the moment that the performance of the safety measure goes below the intervention level (the "event" represented in the graph) a speed limit reduction is introduced as a mitigating measure (leading to a reduced availability performance). In addition, a period for corrective maintenance is scheduled. However, before the corrective maintenance takes place, the lighting fails completely, causing the safety performance to go under the MOR level, as a result of which the tunnel is closed: zero availability for the traffic until the moment the lighting is repaired.

The example could also represent a case where the tunnel ventilation degrades and fails. Then, the mitigating measure between the intervention level and MOR level could be a ban for dangerous goods vehicles or trucks in general, thus reducing the probability of large fires.

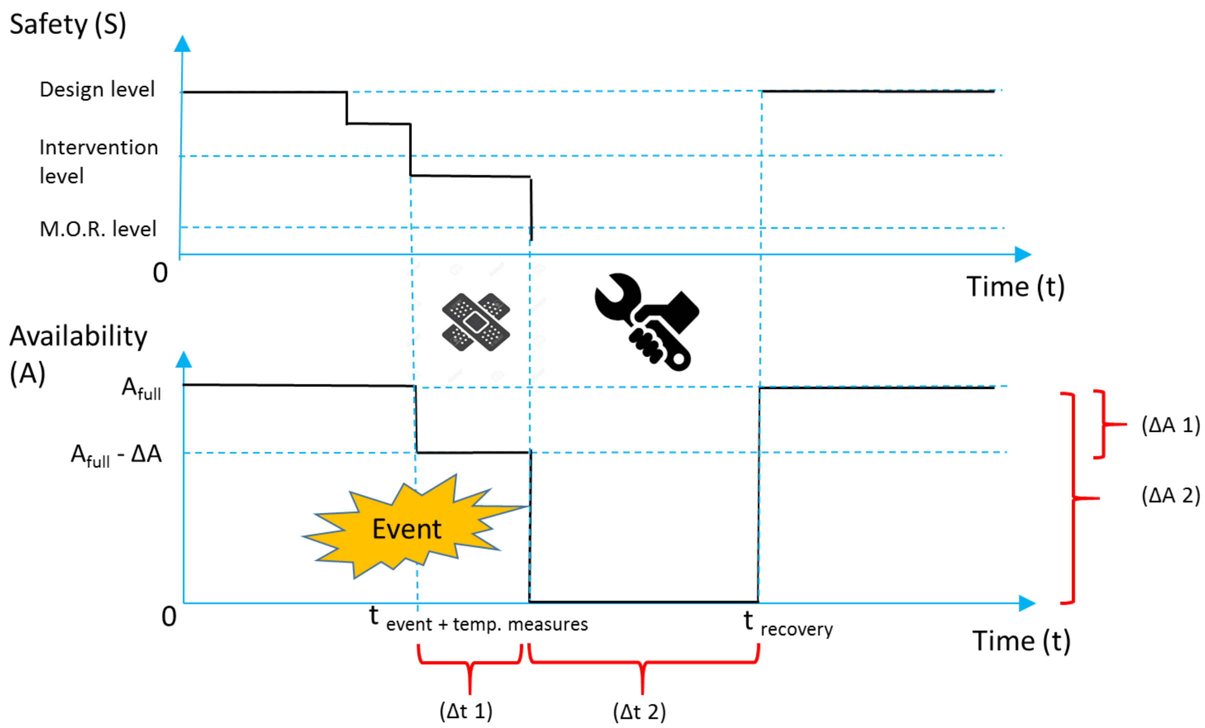

Figure 6. Example of decreasing safety level leading to loss of availability

Note that the "safety level" as presented in the upper graph in figure 6, could represent different parameters. It could be based on a calculated (risk-based) safety level or it could be the performance level of just one safety measure, such as tunnel lighting or tunnel ventilation. Likewise, the intervention level and MOR level could be based on calculated risk or expert judgement, or something else altogether. In other words, the graph explains the principle and does not aim to recommend a specific method or safety requirement (see sections 3.1.3 and 3.3.6 for more information on this topic).

Also note that the graph representing the safety level is interrupted in the period that the tunnel is closed. This is because the safety level has no meaning when the tunnel is closed (no risk, no performance of safety measures).

2.5. ADAPTIVE RESILIENCE

Adaptive resilience is a characteristic that shows over time. It is not related to the performance in one single event, but to the development of the performance when dealing with the same recurring type of events or when dealing with changing circumstances (either positive or negative).

Figure 7 shows an example of the development of the resilience performance of two tunnels for a certain type of events. Note that the parameters presented by the axes of the graph differ from the previous figures. In order to visualize the adaptation over time, the horizontal axis presents time periods (instead of a fluent time course like in the previous figures) and the vertical axis presents the frequency of a certain type of events during those time periods (top part of the figure) and the total loss of availability caused by that type of events during those time periods respectively (bottom part of the figure).

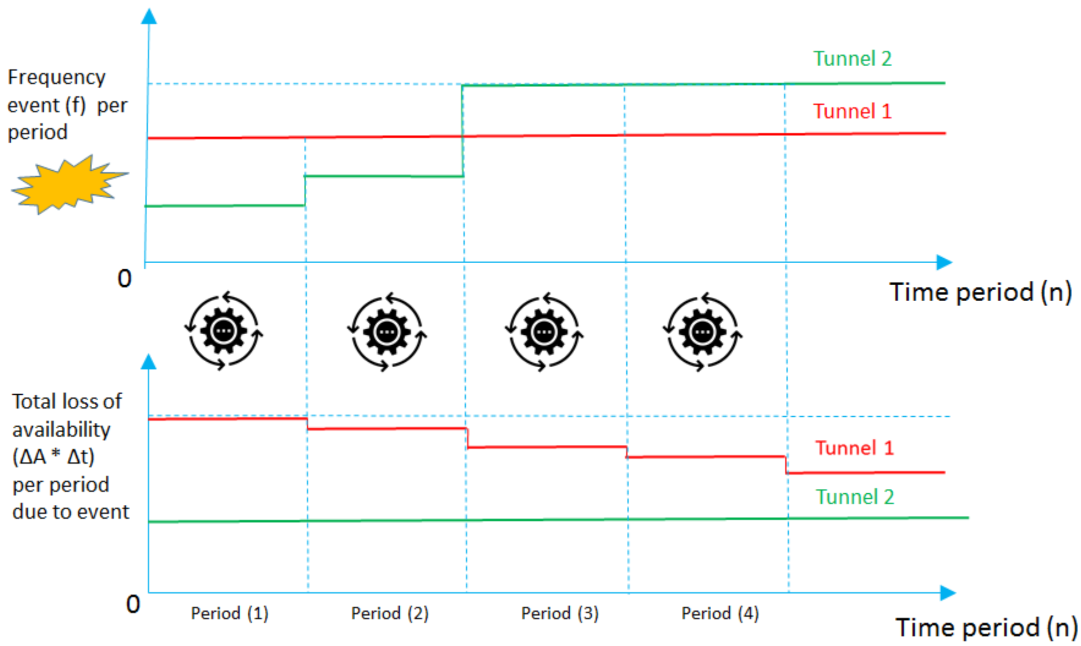

Figure 7. Example of adaptive resilience of two road tunnels

With tunnel 1, the events, for instance rear-end collisions, occur with a constant frequency per time period. Yet, the total loss of availability per period, due to the events, decreases. This means that the resilience performance of that tunnel improves over time, the tunnel system adapts to the occurring events. This could be realized, in this example, by improving the procedure for incident management and/or faster recovery actions through learning experience.

With tunnel 2, the frequency of the occurring events increases in time period (2) and (3), for instance more rear-end collisions induced by a growing traffic load. Despite this increase, the total loss of availability per period remains on a constant level. This means that the resilience performance of tunnel 2 also improves over time. Moreover, it seems that the performed adaptive resilience of tunnel 2 is greater than that of tunnel 1, given the relatively steep rise of the frequency of the events. To explain this performance, one could imagine that, in addition to comparable improvements as mentioned with tunnel 1 (starting in period 2), an on-site emergency response service for an even quicker recovery is implemented (starting in period 3).

2.6. RESILIENCE VERSUS AVAILABILITY

In the previous sections, it was explained that resilience is the ability of the tunnel system to assure availability **under acceptable safety conditions when a (potentially) disruptive event occurs**. The bold part of the previous sentence is stretched here to point out that a high availability over time does not necessarily mean that the tunnel system is resilient. An example is shown in figure 8.

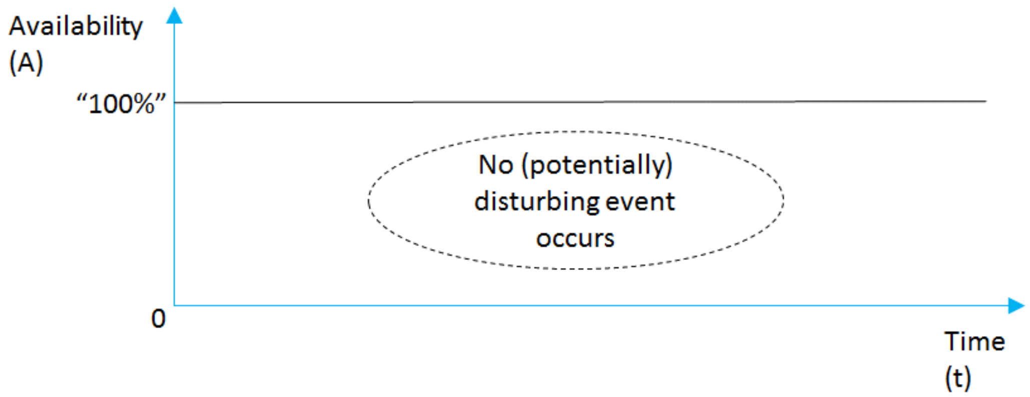

Figure 8. Example of high availability without resilience performance

We see that the tunnel is fully available in the depicted time period. However, we also see that no event occurred that could (potentially) compromise the availability for traffic. Thus, in this case, no resilience was performed and the tunnel was simply available because nothing disturbing happened, which is good luck for the traffic and the tunnel manager. On the other hand, this does not necessarily mean that the tunnel system is not resilient. We only can conclude that the resilience was not tested.

Another example illustrating that a high availability does not equal resilience is when the tunnel is kept open even though the safety level has dropped below the MOR because of a failure. In that case, an unacceptable safety risk is taken, which is not the same as showing resilience. That is why in our definition of resilience safety is considered a mandatory constraint.

So, in order to use "availability" as a metric for resilience, a potentially disturbing event must occur AND one must have well-substantiated (safety-driven) MOR that are complied with.

2.7. RESILIENCE LEVELS

To conclude this introductory chapter on road tunnel resilience, it should be mentioned that there are in fact several levels of (transport infrastructure) resilience that are related:

- Object level;
- Network level;
- Multi-modal level.

The object level would be the tunnel system resilience as discussed above, related to the availability for traffic.

The network level would concern the road network that the tunnel is part of. The resilience on this level would be the ability to still facilitate traffic between various starting points and destinations in case the tunnel is closed (partly) because of a certain event. A criterion for this resilience could for instance be the total increase of travel time. Note that for a optimal resilience of the road network as a whole, the resilience of the tunnel(s) should be balanced with the resilience of other objects that are part of the same route, like bridges, viaducts, retaining walls or earth works.

The multi-modal level would concern other modes of transport as an alternative for road transport, for instance rail or aviation. Resilience on this level would be the ability to process extra travelers that would choose alternative transport, for instance in terms of percentage of customers served.

It can be expected that the impact of a failure of availability of the tunnel decreases on each higher level and will often not be noticed on the multi-modal level.

In line with the goal and scope mentioned in Chapter 1 (and in line with the domain of PIARC TC 4.4 Tunnels) this report logically focusses primarily on the tunnel (object) level. However, the network level is taken into account, through the available alternative routes in the network (that can be considered to be part of the tunnel *system*, as explained in section 1.1). This is relevant for the resilience and availability requirements for the tunnel. After all, the lower the impact of a tunnel closure for the road users (at network level, taking into account travel time, traffic load and traffic safety of the alternative routes) the lower the *criticality* of the tunnel closure and the less strict the road tunnel availability requirements and the resilience requirements to assure this availability need to be. On the other hand, this also implies that the transfer of safety risks to other parts of the network needs to be considered in case a tunnel is (partly) closed. Likewise, developments at network level could have impact on the composition and/or load of the traffic through the tunnel, resulting in a higher probability of disturbing events or damage to the tunnel system. All these aspects require coordination between the tunnel manager and the managers of the other parts of the network (when the whole network is not managed by the same party).

3. RELEVANT LITERATURE

3.1. LEGAL REQUIREMENTS, STANDARDS, POLICIES AND STRATEGIES

3.1.1. Legal requirements

This section is not meant to give an extensive overview of specific legal requirements that are in force in various countries worldwide, but to give a general overview, illustrated by some examples, of how resilience aspects are often addressed in legislation, laws, etc. Each tunnel manager should check out the specific legal requirements for tunnel operation in the country in question.

In (inter)national legal requirements, road tunnel availability and resilience are typically addressed directly or indirectly through (see figure 9):

- Legal requirements on tunnel safety;
- Legal requirements on protection of critical infrastructures:
- Various other legal requirements.

In practice, the role of the legislator and law makers is often limited to assuring boundary conditions for safety and availability, to assure a basic level to serve the societal interests. Specific or detailed performance requirements for the availability and resilience of a tunnel are often considered the primary responsibility of the owners / operators / managers of the tunnels; therefore such requirements are normally not part of legislation and laws.

The application of the legal requirements to a tunnel is usually only tested after an incident that has caused injury and damage. That is, the legal consequences for failure to meet legal requirements are only crystalised after an event. In no jurisdiction are the consequences for injury to tunnel users and damaged property known in advance of an actual incident occurring. The particular and unique circumstances of an event will be explored as part of the legal process in determining the consequences for those with legal responsibility for the actions (or inactions) taken that led to the particular incident under investigation.

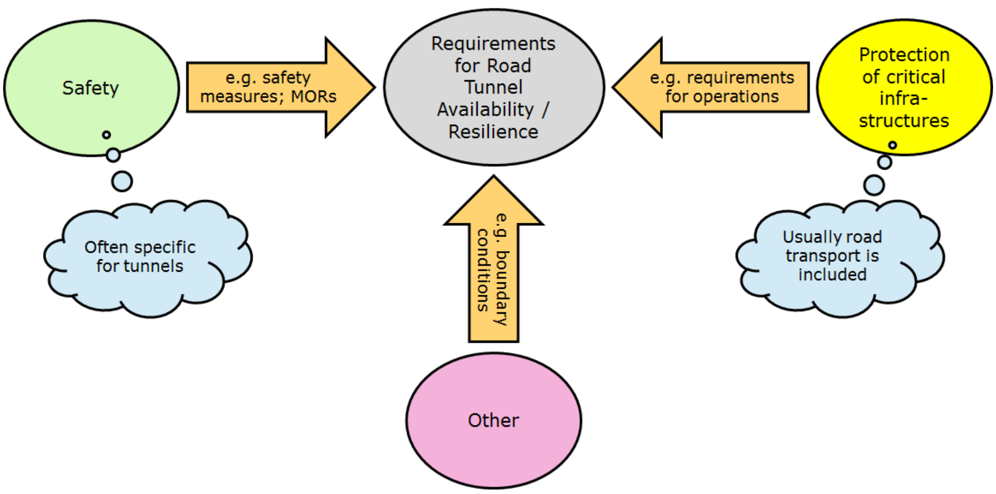

Figure 9. Typical legal requirement topics that address or influence road tunnel availability and resilience

Legal requirements on tunnel safety

Many safety measures that may be legally required have a positive effect on preventing incidents that would compromise the availability of the tunnel. Or the measures can have a positive effect on the degree or the duration of the traffic disruption when an incident happens. Thus, safety measures often enhance resilience.

Also, legal requirements on tunnel safety may contain rules for defining Minimum Operation Requirements (MOR) or even specified MORs; these are boundary conditions for the availability of the tunnel, because if the conditions of the tunnel system go below the MOR, the tunnel should be closed to traffic.

As an example, the European Directive 2004/54/EC [8] contains minimum safety requirements for tunnels longer than 500m in the Trans-European Road Network (TERN). The focus, of course, is on safety measures. But, related to resilience, the considerations in the directive also emphasise the importance of the availability of a tunnel as part of the road network. Moreover, there is a section 3.6 in Annex I of the directive, on tunnel closures. It states that, in case of a closure of a tunnel, the road users should be informed of the best alternative itineraries, by means of easily accessible information systems. Such alternative itineraries shall be part of systematic contingency plans and should aim to maintain traffic flow as much as possible and minimize secondary safety effects on the surrounding areas. Section 3.6 in Annex I also states that Member States should make all reasonable efforts to avoid a situation in which a tunnel located on the territory of two Member States cannot be used due to the consequences of bad weather conditions.

The directive does not contain performance requirements, neither for safety, nor for availability. Lastly, the directive does not specify MOR.

Legal requirements on protection of critical infrastructures

This type of legal requirements is usually not specific for tunnels, but applicable to critical infrastructure in general; based on PIARC report [6] and European Directive 2008/114/EC [7], a critical infrastructure can be described as "an asset, system or part thereof which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact as a result of the failure to maintain those functions".

The primary road infrastructure network in a country (including the tunnels that are part of it) are normally considered as "critical infrastructure".

Usually, requirements are set for the owners / operators of the critical infrastructures, to avoid function loss caused by events like terrorism, security incidents, technological threats and natural disasters. The requirements can address the organization of the owner / operator (even the qualifications of the personnel), the operational procedures, the approach to control risks or other protection measures to be implemented.

As an example, the European Directive 2008/114/EC [7] contains requirements for "European Critical Infrastructures" or "ECIs": critical infrastructures located in Member States of which the disruption or destruction would have a significant impact on at least two Member States. The directive establishes a procedure for the identification and designation of the ECIs and a common approach to the assessment of the need to improve the protection of such infrastructures in order to contribute to the protection of people.

The directive mainly focusses on the energy sector and the transport sector (including road transport and hence road tunnels). The considerations in the directive mention that man-made threats, technological threats and natural disasters should be taken into account in the ECI protection process, but that the threat of terrorism should be given priority.

The primary and ultimate responsibility for protecting ECIs falls on the Member States and the owners/operators of such infrastructures. Domestic coordination between Member State authorities, owners/operators and sectors, as well as international coordination between the Member States concerned, is expected to assure the necessary protection level of the ECIs.

The ECIs are identified and designated on the basis of the transboundary impact a disruption or loss of the infrastructure would have, taking into account criteria like casualties, economic effects and public effects. The severity of the impact must be taken into account, as well as the availability of alternatives and the duration of the disruption.

Among other protection measures, the directive requires Operator Security Plans (OSPs) to be drawn up, implemented and maintained for all ECIs. According to Annex II of the directive, an OSP shall contain:

- Identification of the important assets of the ECI;
- Risk analysis based on major threat scenario's, vulnerability of each asset, and potential impact;
- Identification, selection and prioritization of counter-measures and procedures.

<u>Other legal requirements</u>

In all jurisdictions the combined effect of legislation and other laws sets the criteria by which those legally responsible for the operation, use design and maintenance of tunnels can be held responsible for the consequences of an incident. Collectively these legal requirements set the legal burdens on those responsible to manage a tunnel safely and to drive behaviours which impact the operational safety and resilience of tunnels. The range of controls over tunnels is not limited to the physical safety of tunnel users and property but also extends to other requirements such as environmental (noise, emissions, runoff, etc.), working conditions (occupational health and safety), and security (national security and public interests).

3.1.2. Standards, policies and strategies

The requirements and boundary conditions set by legal requirements are often informed by standards. Standards are generalisations which may or may not be wholly or partly applicable to a particular tunnel. There are (inter)national standards (that may have a legal status themselves by virtue of the operation of the laws within specific jurisdictions) as well as standards developed by owners / operators / tunnel managers, to be used for their own business or as a basis for contracts to be concluded with (for instance) concessionaires (operation and maintenance) or contractors (building or refurbishment). For DBFM tunnel contracts (Design, Build, Finance and Maintain) or concessions, availability requirements are pivotal, because the contractor or concessionaire will get paid on the basis of the availability of the tunnel (or they will get a fine to be deducted from their fee when the tunnel is not available). Intervention levels for maintenance and Minimum Operations

Requirements (MOR) would be equally important for such contracts to assure safe conditions for the tunnel users; failure of safety conditions is usually considered as “non-availability of the tunnel”, resulting in a fine. Standards often help to support these resilience-related interests.

In addition to standards, policies and strategies normally also play a role in the implementation of the legislation or business goals. A policy or strategy would reflect the approach, decisions, actions, and measures a country or organization will take to reach a certain goal and/or to comply with legislation. This means that a policy or strategy can also set requirements for the resilience or availability of a tunnel that the owner / operator / tunnel manager has to comply to.

Listed below are some examples of relevant standards, policies and strategies. Note that, in practice, the distinction between standards (or guidelines), policies and strategies (or general resilience approaches as presented in section 3.2) may be arbitrary, because they are often mixed with one another. For instance, standards are often used as a basis for a policy or strategy, while a policy or strategy may be the origin of certain choices made in a standard. And a strategy is often based on a certain general resilience approach.

<u>Standards and guidelines</u>

- International: there are various standards for Business Continuity Management (BCM), notably ISO 22301: “Security and resilience — Business continuity management systems — Requirements” [16]. This standard specifies the structure and requirements for the design, implementation and maintenance of a resilience management system (comparable to a quality management system, ISO 9001) aimed at developing business continuity appropriate to the amount and type of impact that the organization may or may not accept following all kinds of disruption. To support this, the principles of ISO 31000 on risk management are incorporated, as well as additional resilience aspects. It is a general standard, applicable to all types and sizes of organizations. Translated to a road tunnel system / organization (managed by the tunnel manager), the business would be to provide an available and safe traffic route through the tunnel. The tunnel manager needs to develop business processes to support this goal, making use of technical infrastructure and technical means, as well as operational procedures. The standard provides a framework for these processes; the requirements for performance and properties of the technical means (civil infrastructure, installations, etc.) could then be derived from the process (business), taking into account, in any case, operations and maintenance. For the subsequent design of the technical means based on these requirements, the usual technical standards would be applicable.
- United States of America: NFPA 502, Standard for Road Tunnels, Bridges and Other Limited Access Highways [108]; this standard focusses on measures to assure fire safety: protection of structural elements, fire alarm and detection, emergency communication systems, tunnel closure and traffic control, fire-extinguishing provisions, emergency ventilation, drainage systems, emergency exits, etc.
- The Netherlands: RWS Tunnel Standard (or Dutch National Tunnel Standard) [9]; this is an integral standard for a safe and available (resilient) tunnel system, applicable to state-owned / -operated road tunnels; it contains, among other things, availability requirements, specified failure definitions / MORs, business processes to deal with a comprehensive

variety of hazards / incidents and derived requirements for the tunnel equipment and operational procedures to support this, as well as a management system for improvement.

- United Kingdom: CD 352, Design Of Road Tunnels (formerly BD 78/99) [10]; this standard provides requirements and advice, that shall be complied with in the planning and design of new or the major refurbishment of all road tunnels on the motorway and all-purpose trunk road network in the United Kingdom; related to resilience, among other things, it contains a list of hazards, as well as risk criteria for the undisturbed availability of the tunnel.
- Switzerland: ASTRA 86053, Minimum requirements for the operation of road tunnels, Guide to operational safety of operation [11]; this document is binding for all state-operated tunnels; it describes the temporary permissible deviations from normal operation, as well as the procedure for defining the minimum operating requirements for road tunnels on the national road network; the procedure takes into account the importance of availability.
- Austria: paper no. 32, Minimum Requirements of Operation [21]; this is a user's guide to RVS 09.04.11 Maintenance and Operation; the document is binding for the state owned tunnels in the main road network; it contains guidelines for handling various categories of failure/disruption, prioritized on the basis of the impact on tunnel safety.
- France: the technical instruction IT 2000 [12] includes the rules for containment and/or redundancy for the equipment that directly condition safety (electrical power end lighting, for example). CETU Information Memo 23 [13] defines a methodology to characterize the minimum levels of reliability of technical, human and organizational systems to guarantee the highest level of safety for road tunnel users. In view of the diversity of the equipment present, a global approach by safety functions has been carried out. The operator then has to identify the resources required and combine them to implement these safety functions.

<u>Policies and strategies</u>

- PIARC: Good Practice for the Operation and Maintenance of Road Tunnels [14]; although not explicitly about resilience, the good practices described in this technical report can be considered a valuable guideline for a resilient tunnel; mentions the importance of policies, strategies and performance requirements, covers maintenance and refurbishment, organizational aspects and management systems.
- European Union / RESOLUTE project: European Resilience Management Guidelines (ERMG) [15]; contains framework for the self-assessment and improvement of the resilience of critical infrastructures, through a multilevel gap analysis in respect to the resilience potential; in addition, STREST [103] presents a harmonized approach for a stress test of critical infrastructure against natural hazards (capability of protection and recovery); there are several other projects funded by the European Union that produce guidelines, strategies, methods and tools, see white paper [17]; since the definition of resilience differs per project, the imminent goal is now to harmonize these guidelines into an integral guideline for critical infrastructure; among other things, the aim is to shift from protection to resilience and to shift from risk management to resilience management (more focus on recovery); moreover, the European Member States should develop a strategy to balance between regulation and voluntary efforts by the private operators to enhance critical infrastructure resilience.

- United States of America: National Infrastructure Protection Plan (NIPP 2013) [18]; this plan contains a mission, vision, goals and a management framework (see figure 10) to assure and improve the resilience of national critical infrastructures; the threat categories taken into account (and also adopted in the ERMG [15] are: extreme weather, accidents or technical failure, cyber threats, acts of terrorism and pandemics.

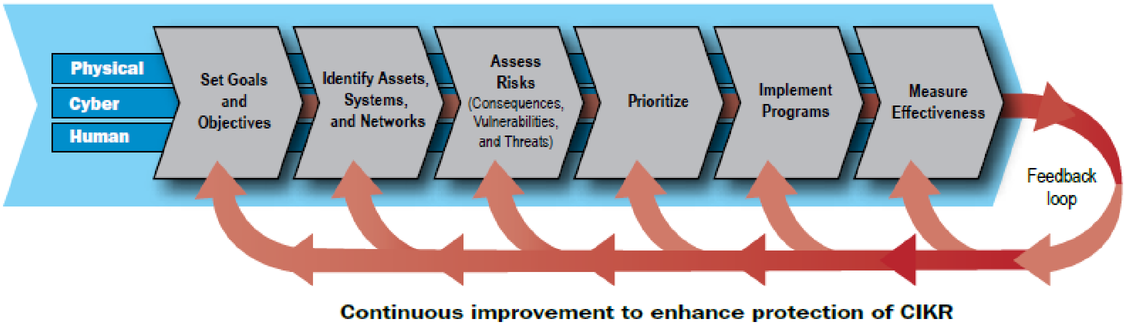

Figure 10. NIPP risk management framework to support and enhance resilience of Critical Infrastructure and Key Resources (CIKR) [18]

- Germany: National Strategy for the Protection of Critical Infrastructures [19]; the strategy summarizes the objectives and the political-strategic approach of the German federal government, as already applied to critical infrastructures[9]; the mission is to continue the results achieved so far on a consolidated basis and to further develop the strategy (aimed at prevention as well as reaction) in view of new challenges; the hazards taken into account are natural events, technical and human failure and terrorism, crime, sabotage and (civil) war; it is emphasised that, in the course of their technological development, countries are increasingly sensitive to disruptions, as they are used to very high safety standards and a high reliability level of supplies; hence, the "vulnerability paradox" is taken into account: the less a country is prone to disruption, the greater the impact when a disruption occurs anyway.
- Switzerland: National Strategy for the Protection of Critical Infrastructures 2018-2022 [20]; the strategy defines goals, as well as measures (17 in total) to meet these goals; the goals and measures are described on a general level and relevant for the operator of a critical infrastructure or the relevant (sub)sector(s); some goals and measures are relevant on a national level; the agencies, parties and operators responsible for the implementation are designated; the importance of coordination between the stakeholders is stressed and taken into account.

3.1.3. Safety as a mandatory constraint

In the previous section, several examples of national standards and guidelines were mentioned that deal with degraded modes and Minimum Operating Requirements (MOR) [9], [11], [13] and [21]. In addition, the MOR of the Somport tunnel on the French-Spanish border can be mentioned as a tunnel-specific example [27].

[9] In contrast to tunnel control centres on federal highways, tunnels are not considered critical infrastructure in Germany

These documents describe the safety conditions under which a tunnel can remain (partly) available for traffic in case of failure of technical and/or operational safety measures.

Although the requirements differ, depending on national legislation and policies by the tunnel managers, the underlying principle is basically the same, as was already explained briefly in section 2.5. Some more details are described below.

- For a safe operation, a number of functions or services have to be fulfilled, both in a normal situation and in an incident situation; all the safety measures, both technical installations and operational procedures, contribute to one or more of these safety functions [9], [11], [13]; the RWS Tunnel Standard [9] identifies "general support", "prevention", "mitigation", "self-rescue", "emergency response" and "traffic management" as functions; likewise, ASTRA 86053 [11] defines "traffic safety", "self-rescue", "intervention of emergency services" and the "possibilities of maintenance and operation" as functions or principles that have to be assured; similarly, CETU memo 23 [13] considers the functions "prevention of incidents and accidents", "detection", "alerting and information", "limitation of consequences" and "ensuring a return to normal".
- A minor degree of failure of a safety measure (technical installation or operational procedure) does not impede normal operation; the performance of the safety functions is still acceptable; repair can take place at a pre-scheduled (convenient) moment.
- A degree of failure that causes the performance to go below a so called intervention level requires compensating or mitigating measures and/or accelerated repair to maintain an acceptable performance of the safety functions; the RWS Tunnel Standard [9] calls the intervention level "failure definition" and CETU Memo 23 [13] speaks of "degraded mode", see figure 11; [9] defines repair priorities (required time spans for accelerated repair) for each failure definition, based on the effect of the failure on tunnel safety and the effectiveness of possible mitigating measures that are taken; [11] and [21] also define priorities for failure and/or repair; an accelerated repair may impede the availability of the tunnel, when this requires closure of the tunnel and the next scheduled maintenance closure is too far in the future; mitigating measures to compensate (part of) the effect of the failure may also impede the availability of the tunnel (for instance lane closure, reduction of speed limit, banning of trucks or dangerous goods) but on the other hand, not taking these measures could mean that the tunnel should be closed entirely (see also section 3.3.7). Thus, the mitigating measures support the resilience of the tunnel.

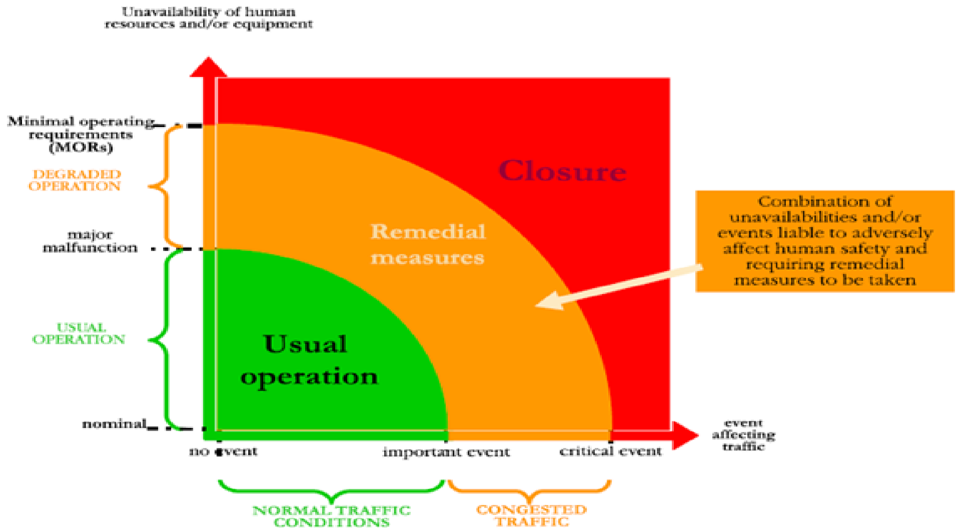

Figure 11. Various degraded operating modes [2], based on [13]

- A degree of failure that can't sufficiently be compensated or mitigated and that causes the safety level to go below the MOR level would require the tunnel to be closed; the tunnel can only be re-opened after the failure has been repaired sufficiently; however, in the decision to actually close the tunnel, the effects of closure on the rest of the road network is also considered [9], [11]; ASTRA 86053 [11] states that, due to the great variety of circumstances and possible failure combinations, it is not possible to define standard MORs; instead, a procedure is described to develop MORs for a specific tunnel; in this procedure, the availability of an acceptable alternative route (including the impact of closure on traffic safety elsewhere on the road network) is taken into account; if an acceptable route is available, then it is advised to close the tunnel; if not, the tunnel manager should go to great length to take measures to keep the tunnel open under acceptable conditions; the Austrian Paper no. 32 [21] also defines possible measures to keep the tunnel open, even for the most severe category of failure; in the RWS Tunnel Standard [9], the tunnel manager has the authority to decide to keep the tunnel open if closure would cause dangerous traffic situations elsewhere on the network[10]; this would require extra measures, not pre-defined in the standard; the tunnel manager is also required to consider closure of the tunnel if repair of a failure takes longer than the repair priority allows for.

3.2. Concepts, methods and approaches

3.2.1. Overarching resilience management concepts

Effective and efficient transport infrastructure management, to ensure safe operation and high availability of the transport network, is a constant challenge for owners and operators of such networks. In view of the high need for mobility of our society and economy and the increasing complexity of infrastructural, technical and organizational aspects, this task is becoming more and more demanding. In addition, the aging of many infrastructure elements, the increasing cost pressure and new challenges like adaptation to climate change are constraints which are gaining

[10] For instance, the alternative route could be temporarily less suitable to process additional traffic because of road works or a traffic incident that has occurred simultaneously. Or the tunnel closure could cause an undesireable cut-through traffic increase in built-up areas with a higher risk of serious incidents (potential collisions with cyclists, pedestrians, children, etc.).

more and more relevance. Therefore, new management approaches related to disruptive events need to be developed, making the infrastructure resilient against all kinds of hazards.

Resilience management has strong similarities with risk management, as defined by ISO 31000 [53], see figure 12.

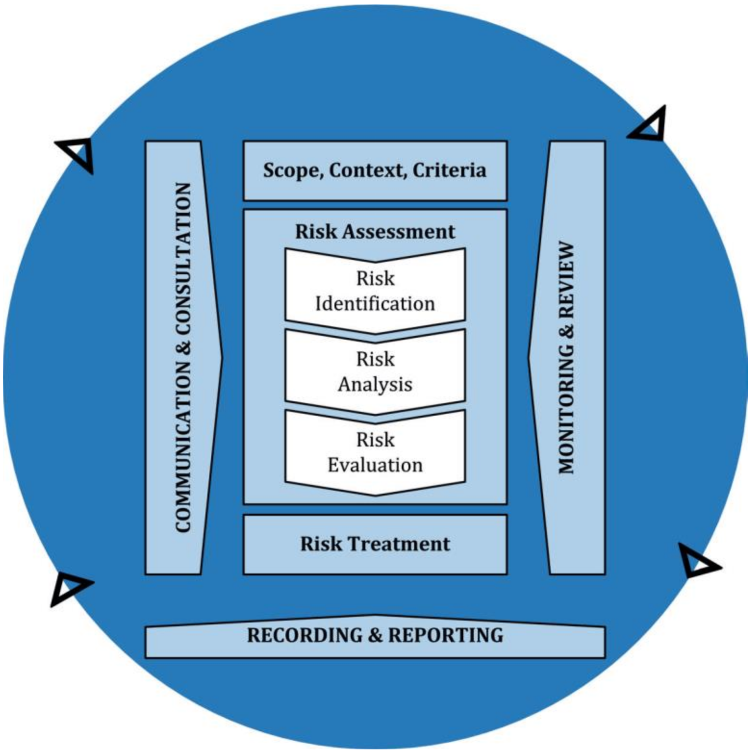

Figure 12. Risk management process according to ISO 31000 [53]

Basically, the concepts of risk management and resilience management are quite simular, both requiring risk assessment and treatment, taking into account hazards, exposure (probability) and vulnerabilities and criticality (impact), see figure 13.

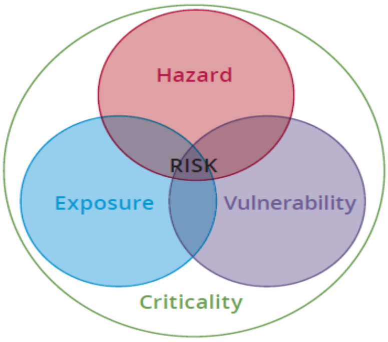

Figure 13. Risks, in terms of hazards, exposure, vulnerability and criticality [67]

Perhaps better put, resilience management can be considered a specific form of risk management, with a more explicit focus on some relevant aspects that would perhaps otherwise not be automatically addressed, for instance [17], [54]:

- Focus not only on prevention, but also on response and recovery;
- Focus on preparedness, taking the occurrence of a disruptive event into account (instead of just lowering the risk without further preparation);

- Focus on system disruptions (maintaining system functionality under various circumstances) rather than individual risk events.

Basically, adequate resilience management approaches are based upon the resilience circle, see figure 14.

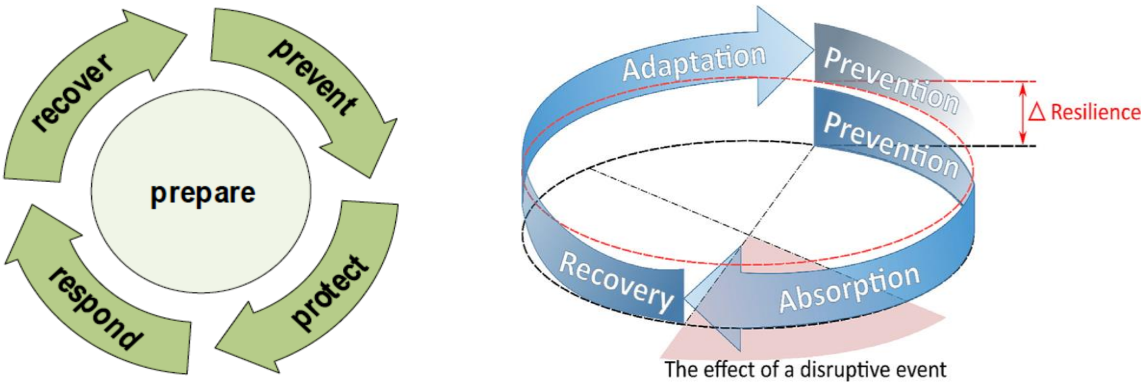

Figure 14. The resilience circle (left: [45], Right: [68]), based on Edwards (2009)

Examples of existing approaches dealing with disturbances of a transport system are [4], [18], [44], [54], [62], [67], [68], [69], [70] and [80]. Most of these approaches either concentrate on the handling of specific single events or on specific hazards of special objects (like safety in tunnels), whereas the consequences for the network level are not considered at all, or to a limited extent only. However, adequate resilience management requires more comprehensive concepts, combining existing approaches for transport infrastructure management (related to disruptive events) to a systematic overarching approach by adding missing elements. So far, such integrated resilience management concepts (that are preferably not too complicated to apply in practice) rarely exist. However ,there are promising recent research activities addressing this topic in a systematic as well as pragmatic manner. As examples, the New Zealand Transport Agency research report "Measuring the resilience of transport infrastructure" [44] and the research project "Resilience of the Road Transport Infrastructure - State of Research and Potentials in the Management of Disruptive Events" [62], elaborated on behalf of the German Federal Highway Research Institute BASt, can be highlighted.

In the BASt study an iterative resilience management process was elaborated, based on previous national and international research approaches on the one hand and existing management systems for motorways on the other hand. Following all stages of the resilience cycle, a modular structured concept was developed, see figure 15.

The approach integrates the object and network levels (see section 2.6) and allows for a general assessment as well as model-supported detailed studies. Moreover, it can be applied to the whole cycle process or on the level of individual modules. In the first case, the workflow of the resilient management process shown in figure 15 is applied to a defined part of a road network as a whole. In the second case, just one module (for instance module 4 "resilience assessment") could be applied at object level just for one selected critical object, for instance a tunnel as part of an route with high traffic load . For each of the key modules of the process a mainly qualitative methodical approach is presented in general terms, which fits into an overarching integrated assessment concept.

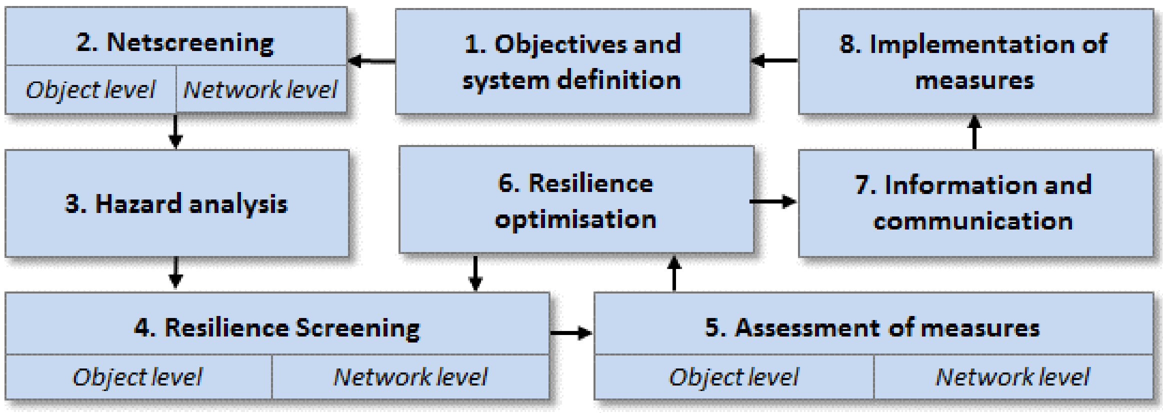

Figure 15. Modules and workflow of the iterative resilience management process [62], based on [80]

The spectrum of disruptive events covered by this approach comprises man-made hazards, hazards due to technical failure, meteorological hazards as well as gravitational, hydrological and geophysical hazards.

A major challenge of the study was the requirement to reduce complex issues to an acceptable level without losing quality. A need for further research was identified concerning the quantification of the effects of a disruptive event, as well as the availability, quality and level of detail of the required input data.

Both the New Zealand Transport Agency [44] and the BASt approach [62] (as well as many other approaches mentioned above) would be fully supportive to – and applicable within - basically any standard for resilience management, like ISO 22301 [16]. The approaches would help to translate the standard requirements to aspects that are pivotal for road tunnel / road network resilience.

Some of the examined literature shows that in the recent years the concept of resilience has been introduced into many technical systems, sometimes in a different manner as explained above. For instance in a Japanese study four functions are proposed to make a technical system resilient: responding, monitoring, anticipating and learning [83].

Responding is keeping the variation of indicators within a permissible range; this can be assured by, for instance, automated control. Monitoring means constantly watching indicators as well as system behavior (for instance by CCTV cameras, which monitor traffic). Anticipating is to predict the system behavior in case an incident is occurring. Both functions, responding and monitoring, are targeting at an incident or a disturbance of the system which has occurred, so they are directed towards the past, whereas the function anticipating is targeting at disturbances of the system behavior in the future. Learning will help the other three to continue to improve their performance. People are indispensable to implement the learning function in the system.

These final aspects address another topic – the role of human behaviour in the context of resilience concepts. The organizational culture is very important to support adequate behavior when resilience is required; this is further addressed in section 3.4.

3.2.2. Resilience criteria and requirements

In the examined literature sources, several criteria / definitions for resilience were found. The definition by **Bruneau et al.** [1] was already discussed in section 1.1 and the corresponding criterion was shown in section 2.3 and on: *the degradation of the quality of the infrastructure (function loss) over time*, see figure 16.

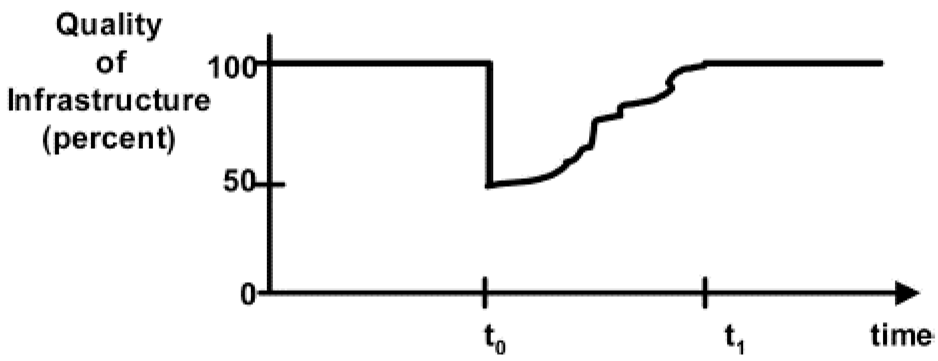

Figure 16. Measure of resilience – conceptual definition according to Bruneau et al. [1]

Mathematically, the resilience R for a disruption of quality Q as shown in the figure can be expressed as:

$$R = \int_{t0}^{t1} [100 - Q(t)]dt \qquad (1)$$

The higher the value of R, the lower the resilience. Theoretically, the value can vary between "0" (full resilience) and "∞" (no resilience).

Note that this criterion is a measure for all the characteristics of resilience according to [1]: the degree to which failure is prevented and the degree to which the consequences of failure and the time to recovery are reduced.

The criterion can be used to express the resilience for one isolated (type of) incident, or the resilience over a certain time period (for instance one year) for all the incidents that occurred during that period.

Moreover, the criterion can be used to express both the resilience of the tunnel system (object level) and the resilience of the road network the tunnel is part of (network level). On the object level, Q can represent the availability of the tunnel; in that case, the value of R would represent the total loss of availability (over a time period). On the network level, Q could represent the service level connected to travel time from "A" to "B"; then, R would represent the total extra travel time (over a time period). Both the availability and the travel time can be impeded by an incident in the tunnel, revealing the resilience of both the tunnel system and the network (for the incident in question). If there are one or more alternative routes when the tunnel is closed, the resilience of the road network can be very high, even when the resilience of the tunnel system is very low. In that case, the availability requirements for the tunnel can be lower than in a situation where there are no alternative routes.

For a road network, or a transportation network in general, **Freckleton et al.** [46] defined resilience as "the ability of the system to maintain its demonstrated level of service or to restore itself to that level of service in a specified timeframe".

Related to travel time, **Omer et al.** described another criterion for road network resilience [24]:

$$R_{t\_network} = \frac{t_{n(\text{before shock})}}{t_{n(\text{after shock})}} \qquad (2)$$

Where:

t_n = the network travel time (the sum of the travel times between the network nodes)

To explain how this criterion works, see figure 17. Article [24] deals with the entry points (bridges and tunnels) of the island of Manhattan (New York, USA) but figure 17 shows a more simplified network for the purpose of demonstrating the principle. This simplified network has 4 nodes: A, B, C and D. The travel times for all possible shortest routes between the nodes are shown. For an undisturbed network, the total of travel times (t_n) would be 160 minutes in this example. When a disruption ("shock") appears between node B and C (for instance a tunnel that is closed because of a fire) the network is disturbed. Because of this, the travel time between nodes B and C and B and D is not only increased because of the longer alternative route via the nodes A and C, but also because the travel time between nodes A and B and A and C increases because of a higher traffic load ("congestion"). As a result, the network travel time (t_n) increases to 245 minutes. Consequently, the network resilience ($R_{t\_network}$) for this particular incident would be 160/245 = 0.65.

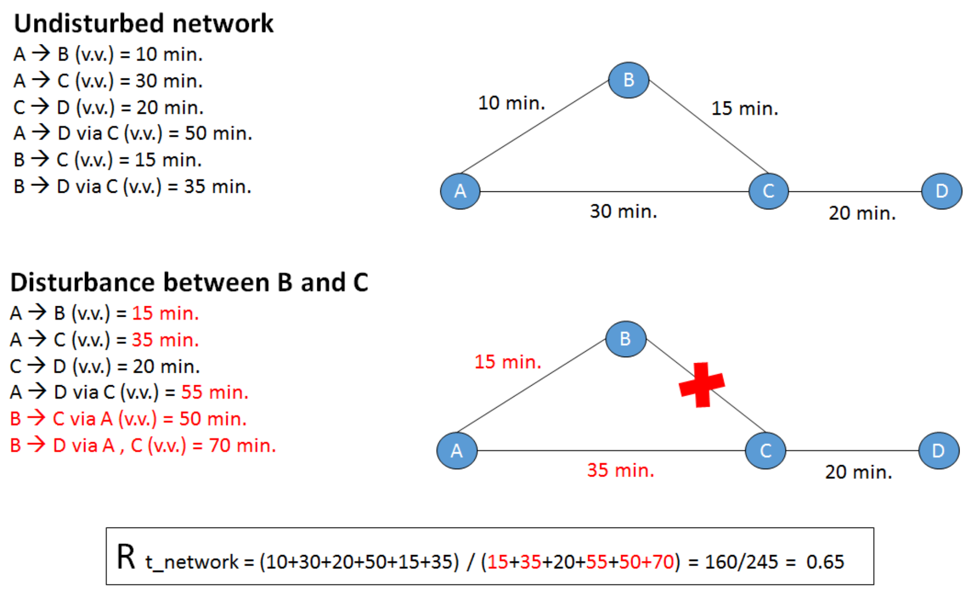

Figure 17. Principle of network resilience according to Omer et al. [24]

Note that, for this criterion, the value of $R_{t\_network}$ can theoretically vary between "1" (full resilience) and "0" (no resilience). Compared to the Bruneau criterion [1] this may come across as "more logical".

In addition to the total network resilience, it is also possible to assess the resilience of a selected part of the network, through the node-to-node resilience, for instance the routes between B and C: $R_{t\_node\_(B\text{-}C)}$. In the example shown in figure 17, $R_{t\_node\_(B\text{-}C)}$ for the disruption between B and C would be: 15/50 = 0.30 . If there were a tunnel between B and C, this could also be a measure for the resilience of the tunnel system, considering availability. For less dramatic incidents than a tunnel fire, the resilience could be higher if traffic were still possible between B and C, but in a limited mode, for instance because of the closure of a single lane in the tunnel.

The example in figure 17 concerns a single specific incident, but it is also possible to measure the R_t (network or node-to-node) over a specified time period Δt, taking into account all incidents or (a) specific type(s) of incident(s) [24]:

$$R = \frac{\int_0^t R_t(t)dt}{\Delta t} \qquad (3)$$

This would, like the Bruneau criterion, formula (1), cover all resilience characteristics (degrees of prevention and limitation of consequences and recovery time).

In contrast, **D'Lima and Medda** defined a simpler criterion for resilience [25]: the speed at which a system returns to equilibrium after a disturbance away from equilibrium.

Thus, compared to the previous examples, this criterion only takes into account the recovery time after a failure / disturbance has occurred. This may seem like a limitation, but the advantage is that it is a simple criterion to apply. Moreover, managing resilience on the basis of just this criterion may be enough to reach the desired goal, especially when:

- the measures to enhance prevention or limitation of consequences are already in place or not indicative for the performance of the system;
- or when such measures are not possible and/or difficult to implement.

In [25] D'Lima and Medda describe a mathematical model, that was used to assess the resilience of the London Underground, based on this criterion. Taking the number of travelers on a certain underground line as a characteristic to describe the state of the system, they used the model to simulate how long it will take before the system state is back to normal after a certain disruption. A disruption would cause the number of travelers on the relevant line to decrease and the number of travelers on other, alternative lines to increase; and "back to normal" (equilibrium) means that the number of travelers would equal the number again that would normally be expected around that specific time of day. Translated to a road network, the time it takes to get the traffic flow back to normal again after a disruption would be the equivalent measure. Translated to a tunnel, this would be the time it takes to get the tunnel fully available again after an incident; or, put differently, the total time of reduced availability. Again, the criterion can be used for a single incident, or for a series of incidents (or type of incidents) over a certain period of time.

As a last example in this section, **Huibregtse et al.** use a criterion that focuses on the prevention side of resilience [26]: *the amount of change the system can accommodate until an unacceptable situation arises.*

This seems like a suitable criterion to apply to long-term developments the tunnel system has to cope with, like an increase of traffic load, the rise of the sea water level, or the increase of (the intensity of) rainfall or other climate change consequences. In [26], Huibregtse et al. describe an aspect of climate change in The Netherlands, namely the increase in the frequency of extreme rain showers. This increases the probability that a tunnel below ground level will be flooded (creation of a water puddle at the deepest point of the tunnel) if the capacity of the drainage system (gutters, pipes, cellars and pumps) is insufficient to cope with the intensity of the rain shower.

Given the accepted probability, the resilience of the drainage system can be defined as the difference between the accepted probability (P_{fa} , normally the design criterion) and the actual probability (P_f), see figure 18:

$$R = P_{fa} - P_f \qquad (4)$$

As the probability increases, the resilience will decrease over time, until the actual probability exceeds the accepted value. The development in time can be estimated on the basis of statistical data, trends and models. Note that in this example, an exceedance of the accepted value would not lead to immediate flooding of the tunnel (the graph is about probability).

For traffic developments, a similar graph could be set up for the probability of traffic congestion (v/c ratio = volume/capacity ratio over time).

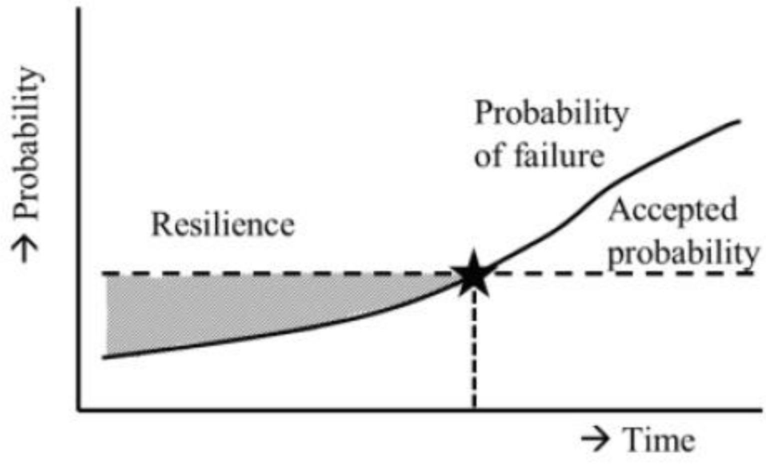

Figure 18. Resilience as the comparison between the probability of failure of the considered system and the accepted probability of failure [26]

The literature sources as discussed above do not present any actual performance requirements for resilience. Only the concepts are explained and results of analyses are presented. However, tunnel managers may draw inspiration from this information to set up their own performance requirements.

<u>Assessment of expected resilience and measurement of actual resilience performance</u>

To conclude this section on resilience criteria, please note that there is a difference between the *expected resilience* and the *actual resilience performance*. The actual resilience performance can only be measured after a certain disruptive event. However, normally the tunnel manager or other stakeholders want to assess the expected resilience of the tunnel system before the event actually takes place, to evaluate if the requirements will be met or that additional improvement measures are needed. For this assessment, various methods are available, that can be divided in two main groups: qualitative and quantitative [46], [47], [48].

Qualitative methods are used to evaluate the resilience of a transportation infrastructure in a descriptive way, for instance: “high“, “medium“ or “low” resilience, based on one or more metrics. These methods may be fitting at object level, but are not suitable for assessing the resilience of more complex and interdependent transportation networks.

Quantitative methods (analytical and simulation models) can compute system resilience at network level, also accounting for the intermodal components. Analytical models can include event tree, fault tree, scenarios analysis, failure and effect analysis, Bayesian analysis or an analytic hierarchy process (AHP). These methods might be too complicated to apply in very large transportation networks, characterized by many possible scenarios. Therefore, nowadays, simulation models are often used to quantify the transportation network resilience[11]. By identifying vulnerable components and comparing different scenarios, simulation models appear to represent a better tool for supporting decisions and addressing, for instance, maintenance activities that should be undertaken for a more resilient transportation network. However, it should be mentioned that the randomness of the factors that play a role in the resilience may cause some uncertainties in the outcome of the assessment. Therefore, additional studies on the effect of these uncertainties (sensitivity analyses) should also be carried out. Likewise, the influence of relevant interdependencies between the road network and other modalities should be studied, as well as interdependencies between systems within the same modality (for instance the tunnel in relation to the control centre / traffic centre).

On the basis of the above mentioned assessments, performance requirements for the tunnel system can be derived (both for technical and operational measures) in order to meet the desired level of availability / resilience for relevant events.

Once a certain event actually takes place, the actual resilience performance can actually be measured and evaluated on the basis of one or more pre-determined metrics or criteria related to, for example:

- the degree of prevention (did the event lead to loss of availability or not?);
- the consequences when loss of availability is not prevented, at object level (for instance the number of closed lanes in the tunnel) and at network level (for instance the extra travel time during the impeded availability of the tunnel);
- the duration of the consequences, again at object level (for instance the period of time that the tunnel was not fully available) and at network level (for instance the total period of time before the normal traffic flow is restored again, or the total amount of vehicles that experienced extra travel time because of the event).

These criteria actually concern the *external* performance of the tunnel system, representing the impact for the traffic / tunnel users. However, also the *internal* performance of various relevant tunnel system elements, that are meant to support the external performance, may be measured and evaluated. For instance:

- the reliability of installations (failure on demand or not?);
- the time that passed before event was detected;
- the time that passed before mitigating measures were taken and/or the effectiveness of these measures;
- the time that passed before the incident management was started and time needed to fully recover from the incident;
- the time needed to repair the damage to the tunnel system, caused by the event;

[11] And microsimulation can be used to assess performance over short lengths of a network, such as intersections.

- the compliance of the actions to the procedures and the effectiveness of the procedures;
- the timely availability of the staff and other resources required for the actions following the event.

Although not focused on tunnels (but on computer networks), the EU research report “Measurement Frameworks and Metrics for Resilient Networks and Services – Technical report” [49] specifies some external and internal metrics and indicators that can be inspirational for the tunnel manager to set up a measurement plan.

The evaluation of the performance on the basis of the measurements could subsequently trigger improvement and/or give feedback information for a re-assessment of the resilience with the qualitative and quantitative methods as mentioned above. The measurement of the performances during one specific event may not give an adequate feedback on the overall resilience of the tunnel system. For this, a more permanent measurement covering various events would be more suitable (for instance, the overall resilience performance in a one year period). However, even one event can give useful information to evaluate and improve certain elements of the tunnel system.

3.2.3. Availability criteria and requirements

In the examined literature sources, several criteria / definitions and requirements for the availability of a road tunnel were found.

A first example is the criterion proposed by Khetwal et al. [22], [23]:

$$Q = \left(\frac{\#\ of\ open\ lanes}{Total\ \#\ of\ lanes}\right) \times \left(\frac{Reduced\ speed\ limit}{Normal\ speed\ limit}\right) \qquad (5)$$

In this formula, Q represents the (quality of the) functionality of the tunnel in terms of availability for traffic. Note that a full availability (Q = 1 or 100%) means that all lanes of the roadway are open and the normal speed limit is in force. In case of an incident, for instance a break-down vehicle or a small collision, some or all tunnel lanes may be closed and/or the speed limit may be reduced on the lanes that remain open, thus reducing the availability (the value of Q). When all lanes are closed, the value of Q equals 0. On the other hand, if the traffic flow in the tunnel comes to a full stop because of a traffic jam (for instance because of an incident downstream of the tunnel) the tunnel is still fully open. Thus, the criterion reflects the tunnel operation, not the traffic situation and not the tunnel resilience in terms of the ability to offer enough road capacity for the traffic load.

If you plot Q as a function of time, you typically get graphs as already shown in section 2.2 and subsequent sections.

Note that Q can calculated as a momentary value, as well is an average value over a certain time period:

$$Q = \int_{t0}^{t1} [Q(t)]dt \,/\, \Delta t \qquad (6)$$

Also note that the criterion can be used per tunnel tube or per driving direction. In a bi-directional tube, some lanes in one direction can be closed, whilst all the lanes in the opposite direction can be open. In this case, it would perhaps be more logical if Q would be calculated per driving direction, but on the other hand, the value of Q for the total tube (both directions) could also be a good basis to evaluate the performance of the tunnel operations. The same goes for unidirectional tunnels / twin tubes.

The advantage of this criterion is, that it can easily be recorded by the tunnel operator, for instance through the data of the lane control system, that is often/normally used to close a lane or to reduce the speed limit.

The RWS Tunnel Standard [9] offers similar criteria for availability:

$$\text{Full availability (A\_full)} = \frac{[\text{Time all lanes open with no traffic restrictions in both directions}]}{[\text{Total time}]} \quad (7)$$

$$\text{Limited availability (A\_limit)} = \frac{\begin{matrix}[\text{Time not all lanes open and / or traffic restrictions are in force,} \\ \text{but traffic in both directions is still possible}]\end{matrix}}{[\text{Total time}]} \quad (8)$$

$$\text{No availability (A\_no)} = \frac{[\text{Time traffic is not possible in at least one direction}]}{[\text{Total time}]} \quad (9)$$

In these formulae (7), (8) and (9), “traffic restrictions” would mean either a temporary reduced speed limit (like in the criterion by Khetwal et al.) and/or a temporary ban for transports of dangerous goods or trucks in general. Such a temporary ban could be in force as a mitigating measure in case of, for instance, a (partial) failure of the tunnel ventilation, thus excluding the risk of a large fire, allowing the tunnel to remain open for passenger cars.

Note that this criterion is on the level of the tunnel system as a whole, incorporating all tunnel tubes in both directions. If traffic is not possible in one direction, this status is considered as “no availability”, even if traffic is still possible in the other direction.

For each availability criterion, the RWS Tunnel Standard sets requirements the tunnel system has to comply to. These requirements are very strict, because, given the high traffic volumes in The Netherlands, a (partial) closure of a tunnel in the primary road network would almost immediately cause a regional or even national traffic congestion. Hence, taking into account the network level, the possible availability categories for tunnels are “high” or “very high”. As an example, in the category “very high”, traffic should be possible in both directions for 98% of the time on a yearly basis and fully available in both directions for 93% of the time. Consequently, the allowed no-availability is limited to 2% per year. All events compromising the availability are included in this requirements, like traffic incidents, fires, failure of equipment, maintenance (planned and unplanned), flooding and training and exercise of tunnel staff and emergency response services.

The British Standard CD 352 [10] has different availability requirements, founded on risk-based criteria, see figure 19.

Probability	Severity				
	Traffic disrupted for up to 20 minutes	Traffic disrupted for between 30 minutes and 90 minutes.	Traffic disrupted for between 90 minutes and one day	Traffic disrupted between one day and one month	Traffic disrupted for more than one month
1 in 100 years	Broadly acceptable	Broadly acceptable	Tolerable	Tolerable	Unaccept-able
Once every 10 - 100 years	Broadly acceptable	Tolerable	Tolerable	Unacceptable	Unaccept-able
Once every 1 - 10 years	Tolerable	Tolerable	Tolerable	Unacceptable	Unaccept-able
> 1 - 10 times per year	Tolerable	Tolerable	Unacceptable	Unacceptable	Unaccept-able
> 10 times per year	Tolerable	Unacceptable	Unacceptable	Unacceptable	Unaccept-able

Risk Classification	REQUIRED ACTIONS
Broadly acceptable	Ensure assumed control measures are maintained and reviewed as necessary
Tolerable	Additional control measures needed to reduce risk to a level which is 'as low as reasonably practicable' (ALARP) for the population concerned.
Unacceptable	Activity not permitted. Hazard to be avoided or risk reduced to 'Tolerable'.

Figure 19. Risk criteria for the availability of a road tunnel, according to British Standard CD 352 [10]

To comply with these risk criteria, a risk assessment has to be carried out, taking into account relevant events that could compromise the availability of the tunnel, and considering the probabilities and consequences of these events. Based on the results of this assessment, measures should be taken, including ALARP[12] measures, so that the risks are at least "tolerable". To support the risk assessment, [10] offers a comprehensive list of events (hazards) to consider, such as vehicle related incidents, equipment failure, weather conditions and security incidents.

Not found in the examined literature sources, but also possible according to the Working Group, is an availability criterion based on travel time, for instance[13]:

$$\text{Availability} = \frac{[\text{Shortest possible travel time through tunnel,based on speed limit}]}{[\text{Actual travel time through tunnel}]} \qquad (10)$$

[12] "ALARP" stands for: As Low As Reasonably Practicable. It means that residual safety risks shall be reduced as far as reasonably practicable. In other words: if safety risks can easily be be further reduced by simple measures without disproportional cost, these measures shall be implemented.

[13] This criterion is a variation on the congestion index, originally defined as the ratio of the delay time to the acceptable travel time.

Again, this criterion could be momentary or average over a certain time period, for the tunnel as a whole or per driving direction, etc. This criterion would require the start and end of the tunnel route to be defined, for example between two nodes of the road network closest to the tunnel.

3.3. MEASURES TO IMPROVE RESILIENCE IN VARIOUS EVENTS

3.3.1. General

To categorize the possible measures to enhance road tunnel resilience, we again use the framework developed by Bruneau et al. [1]. As already mentioned in section 2.1, Bruneau et al. define the following characteristics of a resilient system:

- Reduced failure probabilities;
- Reduced consequences from failures, in terms of lives lost, damage, and negative economic and social consequences;
- Reduced time to recovery (restoration of a specific system or set of systems to their ‘‘normal’’ level of performance).

Thus, measures to enhance resilience contribute to one or more of these characteristics, see figure 20.

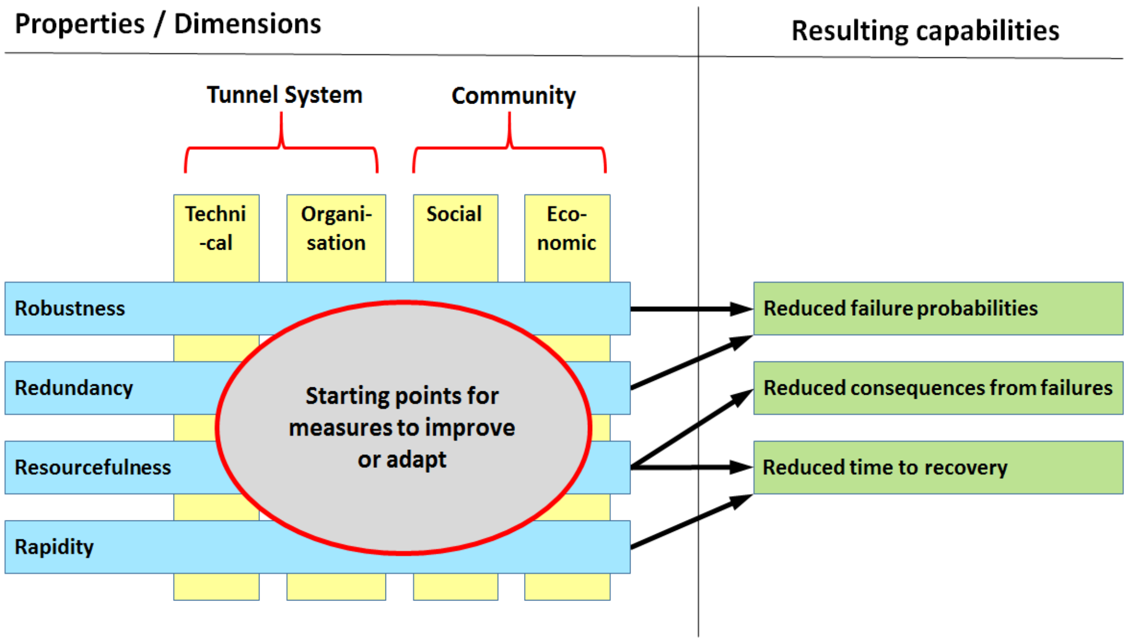

Figure 20. Resilient tunnel system in relation to resilient community according to Bruneau et al., based on [1]

From the perspective of the tunnel manager (considering the tunnel system) the measures can be technical or organizational (operational). From the perspective of society, the community also could take measures to deal with situations in which the tunnel is not available, to reduce the social or economic impact. Although the actions by the community members are outside the scope of this study, the tunnel manager could indeed support these actions by communicating effectively and efficiently to the road users about the scheduled or actual availability situation of a tunnel (incidents, or scheduled maintenance, etc.) as well as the possibilities for alternative routes. This is considered an organizational / operational measure that is included in the scope.

Beside a distinction between technical or organizational dimensions, possible measures by the tunnel manager can be related to one of the four properties of a resilient system, as defined by [1]:

- Robustness: strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function;
- Redundancy: the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of functionality;
- Resourcefulness: the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis; resourcefulness can be further conceptualized as consisting of the ability to apply material (i.e., monetary, physical, technological, and informational) and human resources to meet established priorities and achieve goals;
- Rapidity: the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption.

Based on this, it is possible to identify measures that would have a positive effect on road tunnel resilience in general, that is, for most or many possible events the tunnel system has to cope with when assuring availability for traffic, see table 1.

Basically, these measures would support the resilience of the road tunnel for all events that are discussed in the following sections. However, a similar table will be presented in each section to describe more specific measures for the event in question, whenever this has added value to this general table. To avoid unnecessary repetition for the reader, the cells in the tables in the following sections will read “See table 1 (no additional measures)” if no specific additions for the events in question have added value.

In general, the choice and implementation of measures should be based on performance goals, the strategy of the tunnel manager and cost effectiveness, either on the level of the organization of the tunnel manager or on society level (societal benefits of a higher availability of the tunnel).

Typically, the strategies of the European Union [17] invite the tunnel manager to pay more attention to recovery beside protection, to shift from risk management to resilience management. Perhaps seemingly in contrast to this, but in effect from a shared view, the RWS Tunnel Standard [9] has chosen the principle that measures to prevent non-availability are preferable over measures to mitigate non-availability, as long as prevention is technically feasible and cost-effective. Nonetheless, procedures and measures for recovery should always be in place, even if the probability of the event in question is low (“action perspective” for the tunnel manager).

Table 1. **Possible measures to improve resilience** **Event category: General** **Event:** *General*		**Literature sources in which measure is addressed**
Measures to prevent the negative effects on availability (reduced failure probabilities)	Tunnel system with sufficient capacity to withstand incidents / events (structural strength, fire resistance, traffic volume, equipment capacity and reliability (redundancy), staff size and capabilities, etc.)	[1], [2], [9], [26]
	Availability requirements for service / resource providers, like power supply, data connections, etc.	[45]
	Diagnostic technologies and methods, to detect developments, damages or failures before they affect availability (inspections, tests, automatic monitoring systems or procedures, etc.)	[1], [9]
Measures to limit the degree of the negative effects on availability that are not prevented (reduced consequences from failure)	Training of tunnel personnel (operators, traffic officers, etc.) and emergency response personnel.	[9], [45]
	Systems and procedures for early detection of incident, to limit escalation.	[1], [2], [9]
	Plans and resources for Incident- and emergency response, to limit escalation (including mitigating measures that will allow the tunnel to remain open as much as possible).	[1], [2], [9]
	Monitor situation after incident, to assess if closure of lanes or other mitigating measures that impede the availability can be limited (instead of immediate full closure of the tunnel).	[9]
	Open the emergency lane (when present) temporarily for traffic.	[45]
	Temporary bidirectional traffic in unidirectional tunnel, including necessary equipment.	[9], [45]
	Provide more than one tunnel tube per driving direction, so that a disturbance / blockade in one tube does not lead to a complete stop of the traffic flow in the direction in question.	[9]
	Provide one or more suitable (in terms of road capacity and safety) alternative routes when tunnel is closed, and/or suitable alternative modes of transport.	[2], [9], [11], [14], [24], [25], [45]
	Communicate to road users about actual or scheduled tunnel closures and alternative routes as soon as possible / way in advance.	[1], [9], [41], [86]
	Traffic management measures at network level.	[9], [45]

Table 1. (continued) **Possible measures to improve resilience** **Event category: General** **Event:** *General*		**Literature sources in which measure is addressed**
Measures to limit the duration of the negative effects on availability that are not prevented (reduced time to recovery)	Plans and resources in advance for Incident- and emergency response, to limit duration of recovery: rapid detection, rapid incident management and (when required) rapid inspections, tests, problem analysis, damage repair, etc.	[1], [2], [9]
	Service level agreements or accelerated-procedure contracts with parties involved in the incident management and repair (like the vehicle salvaging company, the emergency response services or the calamity contractor) to quickly normalize / recover the normal situation.	[1], [9], [45]
	Stock repair parts (for the quick repair of frequent damages or failures)	[9], [45]
	Use of modular systems for several tunnels	[45]
	In-house maintenance personnel	[45]

As a final general remark, please note that human behaviour should always be taken into account when planning, designing and implementing measures to improve resilience. For instance, adequate driving behaviour in tunnels is important for the prevention of incidents and adequate response behaviour by tunnel users in case of an incident can limit escalation and/or the duration of the disturbance.

3.3.2. Extreme weather conditions, climate change and other natural hazards

Extreme weather conditions may have a disruptive impact on road tunnel operation. Within the Working Group, various weather events were discussed that are presumed to represent a significant risk to tunnel operation, such as the following examples:

- High temperature, reducing the availability of electronic equipment;
- Low temperature, freezing the tunnel's fire-fighting main;
- Flooding from heavy rainfall, storm water surge or rising sea level;
- Higher groundwater level (due to increased rainfall), causing tunnel ramp structures to lift or flood;
- Snow and ice, causing collisions;
- Heavy winds and meteorological pressure, overpowering the capacity of a longitudinal ventilation system, or damaging the power lines of the tunnels's power supply;
- High salt/chloride concentrations in the air close to the sea, potentially damaging tunnel installations;
- Fog, being detected as smoke or by causing collisions;
- Wind screen fogging, causing collisions;
- Droughts, interrupting the supply of water for firefighting;
- Sandstorms, blocking the tunnel entrance with sediment or damaging ventilation equipment.

Climate change may increase the risk of disruptive weather conditions due to increased frequency and/or increase the intensity of the events. Climate change may also have an impact on other natural hazards, like:

- Bush fires, interfering with the smoke detection or with the tunnel ventilation system;
- Rock falls (thawing permafrost), physically damaging the tunnel structure or the access road; on the other hand, note that a tunnel is sometimes a measure in itself to protect the traffic from rock fall and avalanches.

Other natural hazards to take into account may include earthquakes, tsunamis and volcanic eruptions.

For most of these events, no reference has been found in the literature (although many aspects are taken into account in design standards, for instance to assure a robust structure). The literature sources that were found concentrate on tunnel flooding from heavy rainfall, storm water surge or rising sea level , winter conditions and wind screen fogging (see tables 2, 3 and 4). In addition, some literature was found on rockfall and earthquakes (see table 5).

Table 2. **Possible measures to improve resilience** **Event category: Weather conditions** **Event:** *Flooding (through rainfall or (sea) water level rise)*		**Literature sources in which measure is addressed**
Measures to prevent the negative effects on availability (reduced failure probabilities)	Flood relief structures or flood gates in the vicinity of the tunnel	[28], [29], [30], [26], [100]
	Design of tunnel portals to allow higher water levels in the vicinity, design for greater storm surges	[28], [30], [26], [31]
	Design of drainage gutters and pipes, pump capacity and volume of pump cellars against intensity and duration of rainfall	[9], [30], [32]
	Abandon or relocate coastal highways, move critical infrastructure inland	[26]
	Sealing of tunnel walls and floors more efficiently to reduce seepage	[28]
	Urban situation / climate change: plant green rooftops, to absorb precipitation, reduce storm water discharge, and alleviate the urban heat island effect	[100]
Measures to limit the degree of the negative effects on availability that are not prevented (reduced consequences from failure)	Monitoring of water level	[45]
	Design of the safety installations to allow minimum damage in case of the tunnel being flooded.	[33], [34], [35]

Table 2 (continued). **Possible measures to improve resilience** **Event category: Weather conditions** **Event:** *Flooding (through rainfall or (sea) water level rise)*		**Literature sources in which measure is addressed**
Measures to limit the duration of the negative effects on availability that are not prevented (reduced time to recovery)	Design of the safety installations to allow minimum damage in case of the tunnel being flooded.	[33], [34], [35]
	Installation of an air-inflated "tunnel plug" to block the tunnel structure from flooding.	[36], [37], [38]
	Temporary extra pumps, to pump the water out of the tunnel after the flooding (e.g. through a calamity contractor)	[9]

Table 3. **Possible measures to improve resilience** **Event category: Weather conditions** **Event:** *Ice, snow, low temperatures*		**Literature sources in which measure is addressed**
Measures to prevent the negative effects on availability (reduced failure probabilities)	Sprinkle de-icing agents in advance (e.g. on the basis of the weather forecast and/or the road surface temperature measurement system) to prevent icy road conditions.	[9], [42], [43]
	Preventive avalanche blasting.	[45]
	Snow fences.	[45]
	Heater for the fire-fighting main (fire extinguishing water pipe system) to prevent freezing.	[9]
Measures to limit the degree of the negative effects on availability that are not prevented (reduced consequences from failure)	Frequent removal of ice and snow to limit nuisance / danger for traffic.	[9], [42], [43]
Measures to limit the duration of the negative effects on availability that are not prevented (reduced time to recovery)	[-]	[-]

Table 4. **Possible measures to improve resilience** **Event category: Weather conditions** **Event:** *Wind-screen fogging*		**Literature sources in which measure is addressed**
Measures to prevent the negative effects on availability (reduced failure probabilities)	Detection of critical conditions	[39], [40], [41]
	Ventilation	[39], [40], [41], [107]
Measures to limit the degree of the negative effects on availability that are not prevented (reduced consequences from failure)	Static or dynamic traffic signs	[39], [40], [41]
	Traffic management	[39], [40]
Measures to limit the duration of the negative effects on availability that are not prevented (reduced time to recovery)	[-]	[-]

Table 5. **Possible measures to improve resilience** **Event category: Natural hazards** **Event:** Earthquake and rock fall		**Literature sources in which measure is addressed**
Measures to prevent the negative effects on availability (reduced failure probabilities)	Rock fall protection measures (securing unstable slopes or rock banks)	[45]
	Dimensioning / designing the tunnel structure for higher seismic loads	[45], [105]
	Rock fall or avalanche galleries,	[73]
Measures to limit the degree of the negative effects on availability that are not prevented (reduced consequences from failure)	See table 1 (no additional measures); in particular an alternative or temporary route seems crucial, since it will take a long time to repair damage [73].	[-]
Measures to limit the duration of the negative effects on availability that are not prevented (reduced time to recovery)	See table 1 (no additional measures).	[-]

3.3.4. Traffic incidents and long-term traffic developments

Traffic incidents, like congestions, breakdown vehicles, lost objects, stray animals or persons or various types of collisions, are very common on the road in general and also in road tunnels. Moreover, these incidents almost always lead to some degree of decreased availability of the road: one or more blocked lanes and/or a reduced traffic flow. Therefore, traffic incidents form an important (if not the most important) category of events to be resilient for. Prevention is of course important (also considering safety), but a rapid recovery of the full availability (detection, incident management and clearance of the road) is equally important, especially given the fact that a tunnel usually has a limited cross section as compared to the open road, thus reducing the probabilities to pass the incident under safe conditions. Often, one or more lanes in the tunnel will be closed to prevent escalation of the incident.

The importance of an alternative route in case of a (partial) tunnel closure was already pointed out in section 3.3.1, but the reverse could also be of interest: when a traffic incident occurs elsewhere on the road network, the route through the tunnel might be used as an alternative. When this is considered useful in terms of network resilience, it should be taken into account in the planning/design phase of the tunnel, along with a possible future increase of the traffic load.

Literature on traffic incidents in tunnels, that is relevant for resilience, is scarce. Particularly notable is the 2019 PIARC report "Prevention and mitigation of tunnel-related collisions" [41]. In this report, a typology of tunnel-related collisions is defined, covering single-vehicle collisions (collisions with the tunnel infrastructure or with obstacles on the road) and multi-vehicle collisions (head-on collisions, rear-end collisions and side- or side-swipe collisions). Moreover, over more than 80 possible measures were identified (technical or operational) to either prevent all these types of collisions or to mitigate the mechanical impact of the collisions, thus limiting injuries and material damage and reducing the time required normalize the situation. The measures are ordered according to their functionality, as lines of defense in accordance with the well-known bow tie model, see figure 21 (and table 7).

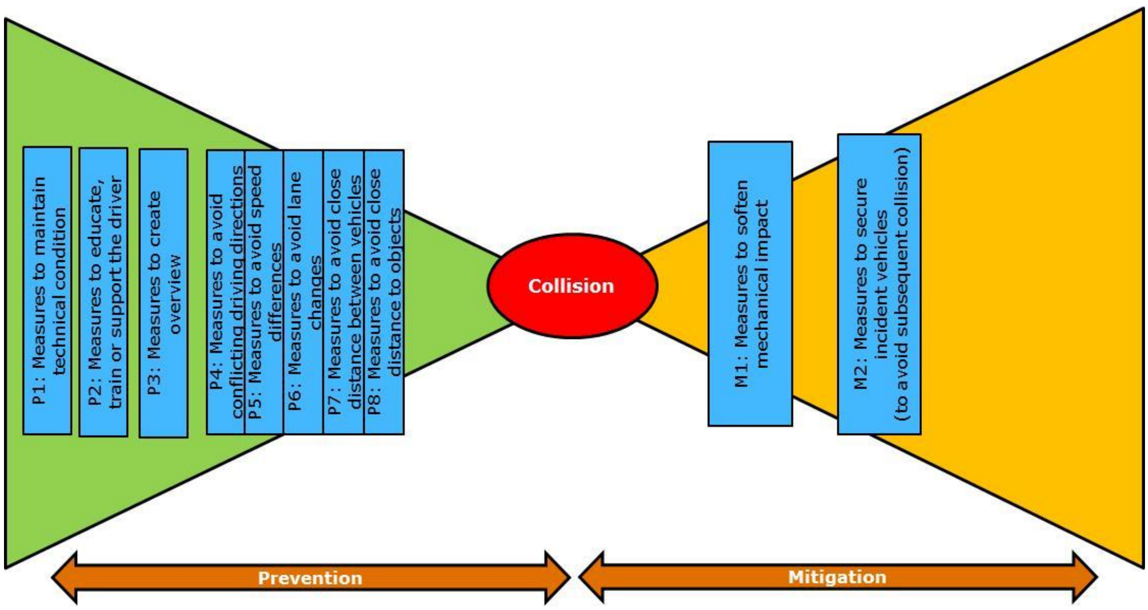

Figure 21: Bow tie model for the prevention and mitigation of collisions [41]

Moreover, based on the collection of real cases, literature and expert opinion, the measures are assessed with respect to their effect on collision risk, other safety aspects, the practical aspects of their implementation and their cost-effectiveness. A detailed description for every measure, including the result of the above mentioned assessments, is included in an appendix of the report.

A summary of the measures found in literature to improve resilience for traffic incidents are summarized in table 6 (congestion) and table 7 (collisions). Of course, there are more types of incidents, like stand-still vehicles or lost load that would require early detection and lane closure. However, since these measures are mentioned in table 6 as a preventive measure to prevent a collision, the tables cover more or less the whole spectrum in practice.

Table 6. **Possible measures to improve resilience** **Event category: Traffic incidents** **Event:** *Congestion*		**Literature sources in which measure is addressed**
Measures to prevent the negative effects on availability (reduced failure probabilities)	Sufficient road capacity, taking into account future traffic developments, and/or temporary traffic that might use the tunnel in case of a disturbance elsewhere on the road network.	[2], [9]
	In operated tunnels: an extra lane, that temporarily functions as an emergency lane, until the moment in the future that the increased traffic load requires its commissioning as a normal lane.	[2], [9]
	Tidal-flow tube (next to other tunnel tubes) that can be used during peak hours, in the dominant direction of the traffic load during the peak period in question (outside peak hours the tube is normally closed).	[2], [9]
Measures to limit the degree of the negative effects on availability that are not prevented (reduced consequences from failure)	Traffic management measures, for instance: - Promote traffic outflow at exit ramps downstream of the tunnel (e.g. through traffic lights on the underlying / secondary road network); note that this might not be beneficial for the traffic on the secondary network; - Limit influx of traffic at entrance ramps upstream of the tunnel (e.g. traffic metering); note that this is only beneficial for the traffic already on the primary road network; - Set lower speed limit upstream of the congestion (through the lane signals) to harmonize / optimize traffic flow; - Re-direct traffic to alternative routes, (e.g. through dynamic message signs).	[9], [41], [45]
	Traffic information services through public communication means, so that road users can take a different route or decide to postpone their trip.	[41]
Measures to limit the duration of the negative effects on availability that are not prevented (reduced time to recovery)	(No additional measures).	[-]

Table 7. **Possible measures to improve resilience** **Event category: Traffic incidents** **Event:** *Collision*		**Literature sources in which measure is addressed**
Measures to prevent the negative effects on availability (reduced failure probabilities)	Good maintenance, to assure the good technical condition of the road and the tunnel (as well as the vehicles).	[41]
	Training and education of the drivers; additional focus on driving behaviour in tunnels; information campaigns.	[41]
	SMART cars; intelligent transport systems	[41]
	Measures to create good overview for the drivers, like self-explaining roads, sufficient sight distance or good tunnel lighting.	[41]
	Measures to avoid conflicting driving directions, like unidirectional tunnels or rumble strip or flexible marker posts to separate lanes with opposite driving directions.	[41]
	Measures to avoid speed differences, like automatic slow vehicle detection in combination with lane control system or avoidance of steep gradients,	[41]
	Measures to avoid lane changes (at unsuitable locations), like route information signs well ahead of tunnel portal, overtaking ban for heavy goods vehicles or avoidance of lane reductions.	[41]
	Measures to avoid close distance between vehicles, like dynamic warning signs controlling the time gap between vehicles or stand-still vehicle detection.	[41]
	Measures to avoid close distance to tunnel infrastructure or obstacles, like rumble strips, wide cross-section, large height clearance, detection of over-height vehicles or early detection of objects on the road.	[41]
Measures to limit the degree of the negative effects on availability that are not prevented (reduced consequences from failure)	Measures to soften the mechanical impact of the collision, so that the incident will be less severe, like safety barriers or lower speed limit.	[41]
	Measures to secure incident vehicles (to avoid subsequent collisions), like automatic detection systems or lane (or tunnel) closure.	[41]

Measures to limit the duration of the negative effects on availability that are not prevented (reduced time to recovery)	See table 1; no additional measures. Note that many of the above mentioned measures also contribute to a limited duration, because less severe consequences (by prevention or mitigation) take less time to normalize.	[-]

3.3.5. Fires or release of dangerous goods

Incidents like fires, explosions or the release of toxic substances are rare, but may cause major damage to the integrity of the structure and/or the equipment of a tunnel and may hence cause a long lasting interruption or disturbance of operation. These kind of incidents are very dangerous to people inside a tunnel as well and therefore have been in the focus of tunnel safety management for a long time, in particular since the major fire incidents in the years 1999 and 2000 in the Mont Blanc, Tauern and Gotthard Tunnel and the subsequent implementation of the EC Directive 2004/54/EC in 2004 [8]. Hence the hazards associated with these incidents are also subject to national regulations and guidelines and addressed systematically by quantitative risk assessment approaches [90].

These hazards are on the one hand also linked to traffic incidents (as discussed in the previous section) because a collision could cause a fire or the release of dangerous goods. Hence, measures which are effective for traffic safety also have a positive effect on preventing such an escalation. On the other hand, these hazards can also be caused by technical failures or even by intentional human actions. This means that additional measures may be required to support prevention and/or recovery. Considering both the high level of potential damage and disruption on the one side and the (very) low probabilities on the other side, a trade-off has to be made between the life cycle cost and the effectiveness of such measures (damage risk reduction). The assessment of the effectiveness should not only take into account the probability of damage, but also the synergy effects associated with tunnel safety, asset protection and assuring availability for traffic, in order to support a decision making process focused on integrated solutions. And of course, regulations and policies also play a role in the decision. The outcome of such a trade-off normally depends heavily on the specific situation and may include to accept the damage risk or to take measures like, for instance, passive or active fire protection [91].

With respect to dangerous goods, reference has to be made to the ADR regulations [109], which define the requirements and conditions for the road transport of dangerous goods in general and through tunnels in particular. These regulations are applied in Europe and in many other countries. Similar regulations exist as well in North American, Australasian countries and other parts of the world.

A summary of the measures found in literature to improve resilience for fires and dangerous goods incidents are summarized in table 8. To explain the category in which some measures are mentioned, please note that in case of a fire, however small, the tunnel tube in question will normally be closed immediately for safety reasons. Moreover, the neighbouring tube might also be closed for the emergency response services, to provide access to the incident tube (through cross connections, for example). If fire protection measures are implemented (like passive or active fire protection) the tunnel will still be closed until the fire has been extinguished and the people have evacuated (or have been taken out), the road has been cleared, the damage has been repaired and/or the tunnel installations have been tested. Thus, these fire protection measures will not limit the degree of loss of availability after the incident. However, since these measures will limit damage, the required time for full recovery (emergency response and repair) will be shortened, thus limiting the duration of loss of availability.

Although many or most of the fire and dangerous goods incidents are traffic related and therefore bound to happen in the tunnel tubes / traffic tubes, a fire in a technical room or the control centre can also cause a situation in which the availability of the tunnel is threatened. Therefore, such events are also addressed in table 8.

Table 8. **Possible measures to improve resilience** **Event category: Fire or release of dangerous goods** **Event:** *Fire or release of dangerous goods*		**Literature sources in which measure is addressed**
Measures to prevent the negative effects on availability (reduced failure probabilities)	Measures preventing vehicles in critical conditions from entering the tunnel (e.g. thermo-scanner, visual control).	[45]
	Measures preventing traffic incidents which may cause a fire or a release of toxic substances (see table 6).	[41]
	Measures regulating the transport of dangerous goods through road tunnels, like ADR tunnel regulations. (Note that restrictions mean a permanent non-availability for the dangerous goods vehicles in question, in favour of providing a more secure availability for the other traffic).	[9], [45], [109]
	Limit potential fire load in technical rooms, to avoid large fires (e.g. during maintenance works) that could damage critical installations, leading to closure of the tunnel for safety reasons; protect installations in technical rooms by separate fire compartments and fire proof cabinets.	[9]
Measures to limit the degree of the negative effects on availability that are not prevented (reduced consequences from failure)	Provide for independent tunnel tubes, in a way that failure/damage to the structure or the equipment in one tube does not lead to subsequent failure in the other tube (thus increasing the possibility that a fire in one tube does not cause closure of all the tubes).	[9]
	In case of fire in the control centre / evacuation of operators: leave tunnels open for traffic when traffic centre is evacuated, but set a lower speed limit through the lane control system and send traffic officers on site and/or switch to operation from the local control centres at the tunnel sites.	[9]

Table 8 (continued). **Possible measures to improve resilience** **Event category: Fire or release of dangerous goods** **Event:** *Fire or release of dangerous goods*		**Literature sources in which measure is addressed**
Measures to limit the duration of the negative effects on availability that are not prevented (reduced time to recovery)	Passive fire protection of the structure, cables and installations (like fire protection boards / heat-resistant cladding, high temperature-resistant ventilation units, self-extinguishing cables, etc.).	[9], [45], [108]
	Active fire suppression systems (FFFS)	[45], [91], [92], [102], [108]
	Structural measures for explosion protection; and ATEX measures for electrical equipment in explosive surroundings (like explosive vapour in pump sumps).	[9], [45]
	Measures providing firefighting resources in order to extinguish fires in an early stage, like patrolling fast intervention unit or portable fire extinguishers (for the public) inside tunnel.	[45], [9], [108]
	Incident detection, fire detection, or dangerous goods detection system	[2], [9], [10], [45], [102], [108]

3.3.6. Physical attack or cyber-attack (security issues)

Security issues refer to intentional man-made hazards, such as physical attacks or cyber-attacks. Physical security issues are as old as mankind, but, despite of this, not always taken into account properly [6]. Cyber security considerations are relatively "new", but rapidly becoming more important. In this respect, the ongoing digitization of technical systems, including tunnel and road network systems, presents opportunities, but also threats. Tunnel control centers are integrated in networks with increasing complexity, which makes them more vulnerable with respect to cyber-attacks.

Public literature on road infrastructure (cyber) security is relatively scarce (for obvious reasons) but the matter is addressed in the PIARC reports [6] and [28], as well as in other sources [72], [94] and [95]. Tunnels and/or control centers are specifically taken into account in the Dutch "COB Living document on cyber security" [94] and in the German research project "Cyber safe" [95].

Both documents provide basic knowledge as well as in-depth information about IT-security, in line with the PIARC reports. The main objectives are to sensitize operators and other personnel, to allow an assessment of the current status of IT-security and to implement measures to improve the level of security.

Note that physical security and cyber security measures are related and complementary. Physical measures also support cyber security, for instance by preventing access to a control system building, thus preventing unauthorized login attempts "at the source".

A selection of notable measures found in literature to improve resilience for security incidents is summarized in table 9. These measures can be validated in practice through security exercises, including “mystery guests” in the field of physical security and “ethical/friendly hacking trials” in the field of cyber security.

Table 9. **Possible measures to improve resilience** **Event category: Physical attack or cyber attack** **Event:** *Physical attack or cyber attack*		**Literature sources in which measure is addressed**
Measures to prevent the negative effects on availability (reduced failure probabilities)	General: take measures to prevent unauthorized persons and vehicles who could endanger road traffic or the functionality of the tunnel from gaining access to the tunnel system assets (tunnel, service building, control centre, service areas, information systems, control systems and communication systems). These measures are to be based on a risk analysis and/or scenario-analysis, normally resulting in a differentiation of required measures, depending on the probability and possible effect of a security breach on safety and/or availability (different level security zones within a building that are accessible with different/additionally required passes, highly protected control systems, etc.).	[6], [9], [94], [95]
	General: regular enhancement of security awareness among the tunnel / traffic centre personnel / staff, through training and instructions	[6], [9], [45], [94], [95]
	General: implement access restriction procedures (related to buildings, objects, areas, data, information, documents, systems) for personnel/staff and other parties; perform a frequent evaluation and update of (registration of) access rights.	[9], [45], [94], [95]
	General: implement a layered security, a combination of physical and logical lines of defence, see below.	[9], [94]
	Physical: provide physical barriers (like fences, gates, bollards, ditches and locks on doors and windows) between public areas and object-bound areas, as well as between the outside and the inside of the building/ object, as well as between the possible security zones within the building/object.	[6], [9], [94]
	Physical: provide “natural surveillance” (social control) from the public road as well as formal site surveillance (e.g. camera observation, including sufficient lighting).	[9], [94]
	Cyber: provide a private stand-alone communication and data network between the computers and control systems in the traffic centres and the tunnels, isolated from the internet and other networks (to prevent access by hackers through internet).	[9], [94]

Table 9 (continued). **Possible measures to improve resilience** **Event category: Physical attack or cyber attack** **Event:** *Physical attack or cyber attack*		**Literature sources in which measure is addressed**
Measures to prevent the negative effects on availability (reduced failure probabilities) (continued)	Cyber: restriction of remote access to IT-systems; realize all connections / communication with other networks ("from outside to inside") through a controlled route, e.g. through a permanently monitored jump server on which the security is properly arranged.	[94], [95]
	Cyber: implement protocols/limitations for the use of USB-sticks and other data carriers in relation to tunnel related computers/control systems (e.g. virus scan).	[94]
	Cyber: provide logical access security for the computer / control systems: (regularly to be changed) user name, password, validation code, etc.	[94], [95]
	Cyber: provide anti-malware and regularly required software updates (patches) to further limit break-in possibilities for hackers.	[94], [95]
	Cyber: set security requirements for the purchase / procurement of IT products and services.	[95]
	Cyber: implement procedures and instructions for the management and maintenance of computer and control systems; the nature and characteristics of maintenance activities introduce certain security risks by themselves, that should be taken into account and controlled.	[94]
Measures to limit the degree of the negative effects on availability that are not prevented (reduced consequences from failure)	General: Arrange the formal powers to be able to act on time when a (possible) security incident actually takes place.	[94]
	General: provide standardised procedures (and training) for the quick detection of a possible incident, for the alerting of the parties involved in the protection of the areas / control systems / communication systems and for the mitigation or neutralisation of the threats.	[94]
	Cyber: ICT measures to detect (and alert for) unauthorized access to the communication or control system or abnormalities within the systems, viruses, etc.; regular scans and tests.	[94]
	Cyber: frequent and thorough back-up (and deletion) of data and software to limit the damage of a possible cyber security incident.	[94], [95]

Measures to limit the duration of the negative effects on availability that are not prevented (reduced time to recovery)	See table 1; no additional measures. Note that many of the above mentioned measures also contribute to a limited duration, because less severe consequences (by prevention or mitigation) take less time to normalize.	[-]

3.3.7. Failure of technical or operational safety measures or other parts of the tunnel system

Tunnel operation requires not only reliable equipment but also qualified personnel. The unavailability of equipment or the absence of an operator or other members of the tunnel staff (for instance as the result of a pandemic) can have a significant impact on the availability of a road tunnel.

For this reason, measures relating to the reliability of equipment and systems must be implemented. These may be measures which limit the risk of equipment unavailability or compensatory measures which aim at limiting the unavailability time.

Regular monitoring of equipment and preventive maintenance can considerably limit the risk of failure.

Similar measures can be implemented for operating personnel. These include the implementation of a consistent training program in order to have interchangeable teams, as well as measures to protect the health of the personnel; see, for instance, PIARC report [110] on the COVID-19 pandemic. The objective is to prevent and/or to compensate for any absence of personnel that could lead to temporary closure of the tunnel or operation in degraded mode.

Finally, standardized procedures can be implemented to assess vulnerability and verify the level of cybersecurity of a system. Early detection introduces the opportunity to address the issues before the attackers can exploit the weakness of the system.

The measures found in literature to improve resilience for technical or organisational failure of the tunnel system are summarized in table 10.

Note that, in case of degraded mode operations (like closing lanes or banning dangerous goods or trucks in general to compensate for the failure of tunnel equipment) the transfer of safety risks to other parts of the network needs to be considered and controlled, as already mentioned in section 2.7.

Table 10. **Possible measures to improve resilience** **Event category: Failure of tunnel system** **Event:** *Failure of technical or operational (safety) measures*		**Literature sources in which measure is addressed**
Measures to prevent the negative effects on availability (reduced failure probabilities)	Reliability and redundancy of equipment and operational staff (e.g. possibility to operate a tunnel from an alternative location when the control centre fails; or continuous scanning / observation of traffic in case of failure of detection systems).	[2], [6], [9], [14], [21]
	Technical inspections.	[42], [50], [51], [52]
	Optimized balance between preventive and corrective maintenance, so that the availability of the tunnel is maximized.	[9]
	Medical / hygienic / organisational measures to protect staff / personnel against diseases / infections / pandemics.	[45], [110]
	Defence against cyber-attacks; robustness principles.	[6]
Measures to limit the degree of the negative effects on availability that are not prevented (reduced consequences from failure)	Degraded-mode operations (not going below minimum operating requirements). This may include: - Reduced speed limit (e.g. in case of road damage or failure of tunnel control centre, tunnel lighting or CCTV); - Closure one or more lanes (possibly in combination with tunnel metering) to reduce the number of vehicles in the tunnel (e.g. in case of failure of ventilation or measures supporting a safe escape route); - Temporary ban of dangerous goods vehicles or heavy goods vehicles in general (e.g., to prevent large fires in case of failure of the tunnel ventilation or to prevent collisions with the tunnel structure in case of failure of the system to detect over-height vehicles).	[13], [21], [27], [11] [9]
	Repair of failure at a time when there is little traffic (e.g. during the night or weekend) so that the nuisance is limited.	[9]
	Repair at a time of an already scheduled tunnel closure (when this can be justified considering the safety and traffic flow conditions in the mean while)	[9]
Measures to limit the duration of the negative effects on availability that are not prevented (reduced time to recovery)	Rapid repair, to limit the time period in which the tunnel is closed or in a degraded-operations mode).	[9]

	Re-prioritise the allocation of available personnel, in favour of operating the tunnel than other tasks (temporary lower service level elsewhere on the network).	[9]

3.3.8. Tunnel maintenance and refurbishment

Maintenance and refurbishments are necessary to keep the technical condition of the tunnel on the required level and to adapt to new requirements and developments that occur over time. Indeed, also the technical installations that play a role in assuring resilience will (to some degree) lose their functionality without maintenance. Moreover, a refurbishment is an opportunity to upgrade the tunnel system and increase the resilience performance, taking into account current and future goals and circumstances.

On the other hand, maintenance and refurbishment works on road tunnels have a direct impact on the availability of the tunnel systems and lead to hindrance for traffic, both at the tunnel and/or elsewhere on the road network. Thus, a certain resilience to limit this nuisance is also required.

In this context, improving resilience could entail best practices in order to limit the duration of the maintenance or refurbishment; or implementing compensating measures to reduce hindrance. In addition, tunnel administrators could develop long-term strategies with the goal of reducing the impact of maintenance or refurbishment projects, for example by limiting the amount of required maintenance operations.

The available literature on the subject indicates that there are no clear-cut solutions which are applicable to all road tunnels. Instead, the emphasis lies on the decision-making process. In order to decide on strategy and tactics, it is paramount to gather sufficient and correct data, to determine and consult all stakeholders early in the project and to clearly document the roles, schedules, compensating measures, et cetera in a decisive plan.

As a result, the information gathered from the literature functions as a guide to development of such a plan. What are factors which one should take into account while planning maintenance and refurbishment? What are the advantages and disadvantages of different strategies and tactics? These are among the questions to which the literature provides some insight.

In relation to maintenance and refurbishment, availability is closely tied to tunnel safety. Therefore, tunnel safety is a recurring theme throughout the different literature sources. This applies not only to safety of the road users, but also to the personnel that performs the maintenance or refurbishment works. Besides the implementation of proper safety measures, it is also important to offer sufficient training to regular tunnel personnel, such as tunnel operators, in order to deal with a (temporarily) modified tunnel system.

The measures found in literature to improve resilience for the negative effects of maintenance and refurbishment works are summarized in table 11.

Table 11. **Possible measures to improve resilience** **Event category: Maintenance and refurbishment** **Event:** *Maintenance and refurbishment*		**Literature sources in which measure is addressed**
Measures to prevent the negative effects on availability (reduced failure probabilities)	Set requirements for the maximum allowed reduced availability or non-availability per year caused by maintenance (preventive or corrective) and validate the design and maintenance scheme against these requirements.	[9]
	Define and document the minimum operating requirements and the necessary safety measures to ensure safe exploitation of the tunnel while carrying out the refurbishment or maintenance works. These measures should take into account both the safety of the road user and the safety of the maintenance staff.	[55], [13], [57], [58], [59], [14]
	Choose low maintenance solutions for the technical measures in the tunnel system, e.g. passive rather than active safety measures, to reduce the probability of failure; and choose simple technical solutions rather than complex ones; this will reduce both the frequency and the amount/duration of the maintenance.	[9]
	Locate equipment in technical areas outside the tunnel tube as much as possible; make sure that these areas are accessible for maintenance without hindering traffic in the tunnel tubes.	[9]
	Apply redundant systems, so that repair can take place during scheduled maintenance closures in case of failure.	[9]
	Apply “separation of concerns” between different installations; no shared functionality, to support maintenance / replacement of one installation without compromising the functionality of the other installation.	[9]
	Regular inspections and tests form the basis for maintenance and refurbishment measures and lead to the minimisation of hindrances by damages and failures.	[2], [61], [105], [106]
	Create an optimal balance between preventive and corrective maintenance (including inspections and tests) leading to the required reliability of the equipment (to prevent failure) and availability against acceptable maintenance costs; risk-based maintenance is a good approach to support this.	[9]
	A data based tunnel maintenance system (TMS) can aid to reduce traffic hindrance.	[14]

Table 11 (continued). **Possible measures to improve resilience** **Event category: Maintenance and refurbishment** **Event:** *Maintenance and refurbishment*		**Literature sources in which measure is addressed**
Measures to limit the degree of the negative effects on availability that are not prevented (reduced consequences from failure)	Design and establish a proper Quality Plan for each road tunnel. This plan includes a Control Plan, Safety & Risk Management, documentation to operate the tunnel, reviews of tunnel operating procedures, use of separate services tunnel, the importance of road policies and design standards, consideration of future widening tunnel structure and materials. Maintenance & Operation, Tunnel Management System, Training & Emergency Exercises and Renovation of Tunnels. The described documents and processes are fundamental for tunnel resilience.	[14]
	Provide training to control centre operators and field personnel on the new defined action plan.	[9], [57], [59]
	Plan refurbishment or maintenance works during low-traffic periods. Take into consideration both the micro-level (daytime) and macro-level (weeks or months).	[9], [56], [60], [86], [87]
	Carefully consider alternative itineraries and/or different modes of transport. They should aim to maintain traffic flow as much as possible and minimise secondary safety effects on the surrounding areas. Inform road users of the best alternative itineraries, by means of easily accessible information systems.	[56], [8], [86]
Measures to limit the duration of the negative effects on availability that are not prevented (reduced time to recovery)	Consider different methods for refurbishments, such as a single 'big-bang refurbishment', or a series of 'micro-refurbishments', or 'parallel construction' (building the new systems while the old systems keep functioning). Each method has certain advantages and disadvantages regarding traffic hindrance. Develop a long-term refurbishment & maintenance strategy.	[56], [60], [61]

3.3.9. Technological and societal developments

Long-term developments, like climate change and traffic developments were already considered in section 3.3.2 and 3.3.3 respectively.

In addition, the Working Group examined literature sources on:

- The development of SMART mobility (intelligent transport systems) [41], [66];
- The growing use of new energy carriers (NECs) for vehicles [63], [64], [65], [104].

SMART mobility is in effect a measure in itself to improve resilience and availability, mainly because it will help to prevent traffic incidents, see section 3.3.3 and [41]. The developments also influence security (see section 3.3.5) and failure risks and maintenance (see sections 3.3.6 and 3.3.7). The technology to enable SMART mobility consists of [66]:

- In-care technology (sensors, logic, actuators, communication systems);
- Vehicle-to-vehicle communication (V2V);
- Vehicle-to-infrastructure communication (V2I or V2X; “X” being the tunnel system in this case).

The V2V - and V2X communication is enabled through public communication networks, like 3G, 4G or 5G (now being implemented). The technology is still in full development, and various studies are still being conducted, so, at the moment, it is not possible to oversee the consequences for the requirements for the tunnel system and the impact in practice on resilience and availability. The scope and characteristics of the required tunnel installations and operational procedures to support and manage safety and traffic flow will certainly change in the future, but if is unclear whether we will end up with, for instance, less tunnel equipment that requires less maintenance and thus also adding to resilience. Moreover, it is also unclear how this development effects the management of the consequences of disruptive events (like failure of the V2V-/V2X communication system or a vehicle fire in the tunnel) that could take place despite all the preventive measures incorporated in SMART mobility. The Working Group feels that the “vulnerability paradox” [19], as mentioned in section 3.1.2, should be taken into account here when considering resilience in further developments.

New energy carriers (NECs) mainly include batteries (electric cars), natural gasses and hydrogen [63]. The hazards associated with these energy carriers (fire, explosion or toxic release, see section 3.3.4) are not new, but, compared to traditional vehicles, conventional loads or dangerous goods[14] that normally appear in traffic, the risk profile for the tunnel system, in terms of probability, effects and vulnerability considering safety, availability and asset protection, may be different, possibly requiring extra measures to assure or improve resilience. Many of these aspects are still being studied further.

As an example, fires of electric vehicles have some similarities and some differences when compared with fires of traditional vehicles. The fire similarities are the temperature and the heat release rate, approximately 5 MW for a passenger car [64], [65], [104].

The fire differences are:

- Release of hazardous gases (like HF, H3PO4) [64] [104];
- Release of toxic metals (like Cobalt, Manganese and Lithium) [64];
- Thermal runaway of car batteries [64], [104];
- Possible release of Oxygen from the batteries themselves, that can, in combination with thermal runaway, cause an extinguished fire to re-ignite [104].

Provided that electric vehicles could safely be extinguished with water, there are a few potential ways how to deal with thermal runaway:

- To bring water directly into the casing of the battery, making use of only recently invented tools, to cool down the battery, thus preventing an extinguished fire to re-ignite; the advantage of this method is that only a little amount of water is required for a great

[14] Note that, for instance, hydrogen driven vehicles would also require bulk transports (tankers) of hydrogen to supply the fuel stations. These tankers will also make use of the roads and (when allowed) road tunnels.

effectiveness [104], but the implementation of this tool would require approval from fire fighters;

- To drown the battery, but in a tunnel this would mean that the entire vehicle would have to be drowned, which would require a much bigger amount of water than for extinguishing a traditional vehicle fire [64] and most likely new tools as well;
- To cover an electric vehicle with a non-burning cover to cut off an external access of oxygen, but this appears not to be very effective [104]
- To let the battery/car burn out; but this is not the best way to enhance the resilience of a tunnel.

All and all, for now, the safety for the fire brigade is still a concern and the repression of an electric vehicle fire is more difficult and takes more time than with a conventional vehicle fire, so that (to some degree) there seems to be a negative effect on the availability of the tunnel.

3.4. ORGANIZATIONAL ASPECTS AND MANAGERIAL CAPABILITIES

In regard to organisational aspects available to tunnel managers to support and enhance tunnel resilience, our literature review did not identify any specific documentation on this topic. However, the PIARC report, "Good Practice for the Operation and Maintenance of Road Tunnels" [14] has some relevance to organisational aspects of tunnel management and tunnel resilience. The report describes management plans, processes and practices that if well developed and implemented can contribute to tunnel resilience. This report emphasises the importance of using a Quality Plan for tunnel operations and provides guidance on the content of such a plan. "Performance management plan" could be an alternative description of the aim. Measures to improve tunnel resilience, from the perspective of a tunnel manager, can easily be incorporated in the development of the plan.

As an example, the RWS Tunnel Standard [9] has basically applied this approach, by taking the incident management processes (including performance requirements) as a starting point for the development and design of the tunnel system as a whole, thus ensuring resilience (see figure 22).

Further, there is an obvious connection between the Quality Plan as mentioned by [14] and the Operator Security Plan (OSP), as mentioned by the European directive 2008/114/EC [7], see section 3.1.1, as well as the Business continuity plans and procedures as mentioned by ISO 22301 [16], see section 3.1.2. The Working Group intends to explore this topic more widely in the following phases of the development of a full technical report on road tunnel resilience.

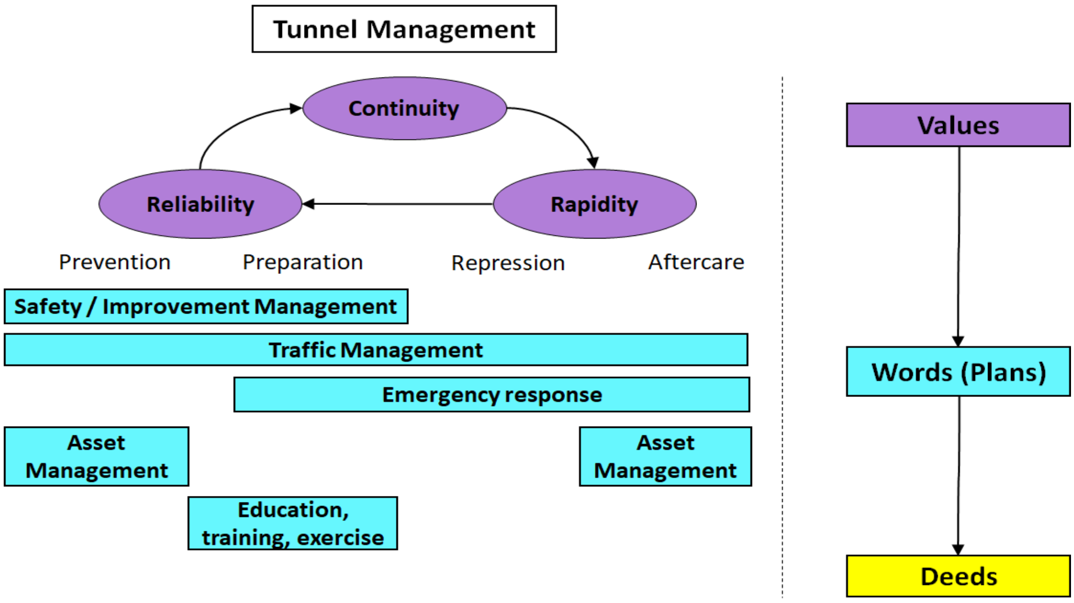

Figure 22. Principles of tunnel management organisation, aimed at a continuous safe traffic flow [9]

On the other hand, as important as management plans are, Japanese literature (Haga, [81], [82]) points out that rigid procedures and instructions do not work in strongly anomalous disaster situations, like the Japanese earthquake in 2011. People were then forced to behave beyond established procedures, training, hierarchical structures, rules and law; when and where resilience was required, they had to act autonomously, based on their own judgement. To support this individual and organisational resilience, a "just culture", in which people are not blamed for their mistakes and errors, is critically important. "Just culture" describes "an atmosphere of trust in which people are encouraged, even rewarded, for providing essential safety-related information, but in which they are also clear about where the line must be drawn between acceptable and unacceptable behavior" [J. Reason , 1997]. In a just culture, after an incident, the question asked is "what went wrong", rather than "who caused the problem". Thus, it is the opposite of a "blame culture".

4. COLLECTION OF CASE STUDIES

4.1. INTRODUCTION

As a result of the working method described in section 1.4.2, a total of 18 case studies were collected from 13 countries worldwide. An overview is presented in table 12, including a reference to the appendices in this report where the case studies can be found. The indicated resilience topics correspond with the topics/sections in chapter 3, to make a connection with the scope of the literature review.

Table 12. Overview of collected case studies on road tunnel resilience

Id.	Country	Title	Resilience topic(s)	Appendix
1.	Australia	Transurban's Resilience Approach, Australia	a. Organisational aspects and managerial capabilities b. Failure of technical and operational measures / COVID-19	B
2.	Austria	Maximize availability at an acceptable safety level during the refurbishment of the Karavanke road tunnel between Austria and Slovenia	a. Fires or release of dangerous goods b. Maintenance and refurbishment	C
3.	Belgium	Implementation of real time ADR detection in the Beveren Tunnel near Antwerp, Belgium	Fires or release of dangerous goods	D
4.	France	To continue operating after damages caused by over-height truck Fourvière Tunnel, Lyon, France	a. Traffic incidents b. Maintenance and refurbishment	E
5.	France	Implementation of photovoltaic panels L2 ring road crossing the city of Marseille, France	Technological and societal developments	F
6.	Germany	RITUN – Resilient Road Tunnels	Concepts, methods and approaches	G
7.	Germany	Rehabilitation of the A 81 Engelberg Tunnel	a. Natural hazards b. Fires or release of dangerous goods c. Maintenance and refurbishment	H
8.	Italy	Improving Road Tunnel Resilience by SCADRA (Supervisory Control Acquisition Dynamic Risk Analysis)	Failure of technical and operational measures	S
8.	Japan	Concept of measures and design methodology for recovery from earthquake damage to a mountain tunnel in Japan	Natural hazards	I
9.	Netherlands	Societal cost-benefit analysis for a water mist system, to enhance the availability of the Leidsche Rijn Tunnel in Utrecht, The Netherlands	a. Fires or release of dangerous goods b. Concepts, methods and approaches	J

Table 12. Overview of collected case studies on road tunnel resilience (continued)

Id.	Country	Title	Resilience topic(s)	Appendix
10.	Netherlands	Approach to maximize availability during the refurbishment of the Heinenoord Tunnel near Rotterdam, The Netherlands	a. Maintenance and refurbishment b. Concepts, methods and approaches	K
11.	South Africa	Extreme wind conditions at the Huguenot Tunnel near Cape Town, South Africa	Extreme weather conditions / Natural hazards	L
12.	South Korea	Improving fire safety of mid-length expressway tunnels in South Korea	a. Fires or release of dangerous goods b. Maintenance and refurbishment	M
13.	Spain	Madrid Calle 30 Ring Road Resilience Approach, Spain	Organisational aspects and managerial capabilities	N
14.	Switzerland	Additional tunnel tube to support refurbishment, Switzerland	Maintenance and refurbishment	O
15.	Switzerland	Reopening of the Gotthard road tunnel after Fire Damage, Switzerland	a. Fires or release of dangerous goods b. Maintenance and refurbishment	P
16.	United Kingdom	Second Tube for Tyne Tunnels, Newcastle, UK	a. Longer-term traffic development b. Maintenance and refurbishment c. Fires or release of dangerous goods	Q
17.	United Kingdom	Saltash tunnel, UK	a. Failure of technical and operational measures / MOR b. Maintenance and refurbishment c. Fires or release of dangerous goods	R

It can be noticed that these case studies form a varied collection, covering most of the broad scope of topics presented earlier in the report. Only the topic (cyber) security is not addressed by a case study. “Legal requirements” are not addressed directly as main topic, but many case studies mention such requirements as the cause of (or the boundary condition for) the implementation of the described measures. Some case studies deal with more than one topic, allowing for some cross-references to be made. Although the geographical context of a certain country may be specific (like legal requirements) the Working Group feels the principles and approaches described in the case studies are mostly quite universal and therefore broadly applicable.

The following section and subsection will highlight some of the results and learned lessons derived from the case studies, through the views of the various topics.

4.2. Results, points of interest and lessons learned

4.2.1. Concepts, methods and approaches

Various case studies give a description of methods and approaches to enhance road tunnel resilience. First of all, we have the case study presented in Appendix G, on the German **RITUN** research project. RITUN provides a methodology to increase the resilience and availability of road tunnels, while complying with the minimum requirements of tunnel safety as a mandatory constraint.

The methodology is risk-based, focussing on both prevention and recovery, and consists of 3 steps[15]:

1) Identification of potential hazards and resulting damage scenarios, through an all-hazard approach;
2) Determination of the effects of the damage scenarios on the tunnel operation, as well as on the local and regional traffic; these effects are considered in the context of the Minimum Operating Requirements (MOR);
3) Selection of measures to enhance the resilience, by either prevention or mitigation of the effects; for this step a measure catalogue was developed, presenting a qualitative indication of the effectiveness and cost-effectiveness of various measures, focussing on the availability of the tunnel, but also taking into account side-effects on safety and objects and traffic outside the tunnel.

A quantitative method to assess the effectiveness and cost-effectiveness of possible measures to enhance road tunnel resilience is presented in Appendix J: a **Societal Cost-Benefit Analysis (SCBA)** according to the Dutch OEI method (Overview Effects Infrastructure). Although the relevant case study deals with the decision whether or not to install a Water Mist System (WMS) in the Leidsche Rijn Tunnel in The Netherlands (to enhance availability through resilience for fire incidents), the method is applicable in general to any measure. The method is particularly suitable when a high investment is involved and one requires an objective assessment of the overall effects on society level to make an educated decision (e.g. because the investment is funded with tax payers money). One of the basic principles of the method is that all the effects of the implementation of the measure, both costs and benefits, should be quantified (monetized) as much as possible, to enable an objective (or objectified) evaluation. However, the method allows to take effects into account that can only be described in a qualitative way.

In the case study, the SCBA compared the life cycle cost (**LCC**) of WMS (purchase, installation, additional works, operation and maintenance) with the expected value of the benefits during this life span, being the prevented damage to the tunnel, as well as the prevented economic damage that results from the required closing of the tunnel to carry out repairs. On the other hand, installation and maintenance of WMS also require tunnel closures that cause economic damage; this was also taken into account. Last but not least, the expected value of the monetized societal benefits of saved lives by WMS (and reduced medical care for injured people) were also considered

[15] These steps fit into the overall iterative resilience management process as presented in figure 15 in section 3.2.1. The RITUN steps cover the steps 3, 4 and 5 in figure 15.

and monetized. Appendix J provides details on how all of this was done. A comparable analysis was performed for the installment of WMS in the Tyne Tunnels in the United Kingdom (see Appendix Q).

Another method to evaluate possible measures to enhance the resilience of road tunnels (in general or for a specific event) is the **Multi Criteria Analysis (MCA)**. This method allows to score alternatives for a certain measure against various qualitative and/or quantitative criteria, as a basis for the selection of the optimal or preferable solution. Typically this is done in a matrix, with the alternatives on one axis, the criteria on the other and the scores in the cells. The method allows to weigh the scores, depending on the importance of the aspect/criterion. An example of the application of an MCA can be found in Appendix K, dealing with the refurbishment of the Heinenoord Tunnel in The Netherlands. The MCA was used to select the optimal scenario for the execution of the refurbishment works, considering, among other things: safety, nuisance for the traffic (accessibily of the region), required time span (calendar time) for the works and resulting total project cost. In this consideration, safety was a constraint for every scenario, but the required temporay measures to assure safety (both for the construction workers and the traffic) often limited the possibilities to carry out the work, resulting in higher cost and a longer time span. In this case, the limitation of nuisance for the traffic was the most important criterion for the selection of the optimal scenario, more so than project cost (although the cost had to be feasible and reasonable).

To conclude, it must be mentioned that methods like SCBA, LCC and MCA are certainly not new; they are used world-wide as a tool to support a decision making process. Thus, the case studies merely demonstrate that they are also applicable to (and useful for) measures to enhance resilience.

4.2.2. Extreme weather conditions and other natural hazards

Three of the collected case studies deal with natural hazards that can endanger the operation of a road tunnel.

First of all, Appendix L presents a case study on **extreme wind conditions** at the Huguenot Tunnel near Cape Town, South Africa. The western portal of this tunnel is accessed via the 530m long, high-altitude Hugo’s River Viaduct. During high wind seasons, the ‘Black South Easter’ wind causes a lot of disruption on the viaduct by blowing over empty trucks and small delivery vehicles. This causes an unsafe situation (possible casualties or injuries) as well as a blockade for all traffic into the tunnel. After such an incident, the standard procedure is that the tunnel will be closed for trucks until it’s safe to travel again. But, in addition, the road has to be cleared before the tunnel can be (safely) reopened to the other traffic (passenger cars); this includes emergency response and the removal of the (damaged) trucks. To avoid such incidents (thus improving both safety and availability) pre-warning measures were implemented. A weather station was installed on the viaduct, wind speeds were measured and a correlation was determined between the wind speeds and the incidents that occurred. Based on these results, the viaduct is now pro-actively closed for trucks when wind speeds exceed 84 km/h. To further improve the situation in the future, it is considered to construct a framed mesh on the viaduct to disrupt the wind flow, thus preventing or limiting the dangerous effects for trucks.

A second case study dealing with natural hazards is presented in Appendix I, and concerns measures and a design methodology for recovery from **earthquake damage** to the Tawarayama Tunnel, a mountain tunnel in Japan. Although it was first assumed that mountain tunnels are pretty much resilient against the effects of earthquakes, the Tawarayama tunnel was damaged during a series of earthquakes in 2016. For the damage repair, aimed at the prevention of similar damage in the future, one faced the problem that no references or standards were available yet for suitable measures. To solve this problem, the damages were categorized (based on severity) and measures were developed and implemented for each category. Examples are: reinforcement for the concrete tunnel lining, replacement or strengthening of temporary support structures for the rock/soil around the lining (like spray concrete and bolts) and crack injection. To support the rationale behind the selection of measures, a guideline or decision framework was also developed for future cases of earthquake damage (flow charts).

A third case study, presented in Appendix H, is about the rehabilitation of the A 81 Engelberg Tunnel near Stuttgart, Germany. The natural hazard in this case is the **swelling rock** in which the structure of the two tunnel tubes is embedded. This rock contains the mineral anhydrite. Water percolating into the mountain transforms the anhydrite into gypsum, which presses against both tunnel tubes over a length of approximately 180 m. Over the years, it became apparent that the reinforced concrete and the previous refurbishment measures were not sufficient to withstand this pressure in the long term. Therefore, additional measures are being undertaken in the 180m rehabilitation zone, to make the structure more resilient against the pressure forces, thus securing the availability of the tunnel in the future:

- Reinforcement of the support floor of the roadway, to withstand the horizontal pressure on the tunnel lining (already completed);
- The installation of a steel skeleton, consisting of intermediate ceiling and wall reinforcements, to withstand the vertical pressure; as a special feature, the skeleton is designed as a 3-joint construction, that can be adjusted (relieved) when the pressure gets too high in the future, thus adding even more to the resilience of the structure.

The rehabilitation works, as described above, will be combined with a complete upgrade of the safety and operation systems, notably the ventilation system. See also sections 4.2.3 and 4.2.6.

4.2.3. Traffic incidents and long-term traffic developments

One case study specifically deals with the recovery process after a traffic incident, namely a **collision of an over-height truck** in 2017 against the intermediate ceiling in the south tube of the Fourvière Tunnel in Lyon (France), severely damaging the ventilation ducts (see Appendix E). Since the Fourvière Tunnel has a high traffic load, the first aim was to carry out the repair as quickly as possible under safe conditions, with as little disruption for the traffic as possible. The second aim was to take measures to prevent similar collisions from occurring in the future; one decided to implement a system to detect and stop over-height vehicles before they enter the tunnel. The case study describes every phase of the recovery in detail, with a focus on the specific resilience aspects (also see section 4.2.6).

The case study in Appendix Q is about the realization of a second tube for the Tyne tunnels to cope with the **increase of the traffic load**. However, the second tube not only enhanced the resilience for long-term traffic developments, but also the resilience for **(traffic) incidents in general**. For instance, the risk of head-on collisions was virtually eliminated, since the two tubes allow for unidirectional traffic instead of bi-directional. Moreover, a second lane in each direction increases the possibility that a tube can remain partly open when a traffic incident happens. And when any kind of incident in one tube requires a longer period of time to recover from, the neighbouring tube can temporarily be operated in a bi-directional mode again. Lastly, the second tube allowed for the original tunnel to be upgraded as a whole, notably to enhance fire safety (see section 4.2.4).

4.2.4. Fires or release of dangerous goods

Scenarios involving fires and/or the release of dangerous goods have always played an important role in road tunnel considerations. This probably explains why many collected case studies (at least partly) deal with these scenarios:

- The Karavanke Tunnel between Austria and Slovenia (see Appendix C);
- The Beveren Tunnel in Antwerp, Belgium (see Appendix D);
- The Engelberg Tunnel near Stuttgart, Germany (see Appendix H);
- The Leidsche Rijn Tunnel in Utrecht, The Netherlands (see Appendix J);
- The upgrade of mid-length expressway tunnels in South Korea (see Appendix M);
- The Gotthard road tunnel in Switzerland (see Appendix P);
- The Tyne Tunnels in Newcastle, United Kingdom (see Appendix Q);
- The Saltash Tunnel, United Kingdom (see Appendix R).

Many of these case studies describe **upgrading projects**, aimed to comply with relevant (new) regulations or tunnel standards, like the Karavanke Tunnel, the Engelberg Tunnel, the mid-length Korean expressway tunnels, the Tyne Tunnels and the Saltash Tunnel. Often, the upgrading is safety driven, to comply with (international) regulations. However, the safety measures also contribute to resilience and thus availability, for instance because fire incidents are prevented and/or the recovery phase after a fire incident (emergency response, repair and normalisation) will be shorter when the incident can be controlled better, leading to less casualties and material damage. This means the upgrades relate to **the preparation and improvement** capabilities of resilience. The measures often include improvement of the ventilation and emergency exits to the neighbouring tube or an escape corridor. In case of the Tyne Tunnels, a watermist system (WMS) was installed. Additional measures at the Karavanke Tunnel included thermo scanning and truck metering. In some cases, temporary measures (like an on-site fire brigade or speed limit reduction) were implemented as a quick mitigation before the final upgrading took place. Although the upgrading projects contribute to resilience, the case studies also make clear that during the related works the availability of the tunnel is compromised, thus introducing the paradox that traffic disruption is caused during the works, to avoid possible future disruption by fire incidents. Therefore, many case studies describe the efforts to carry out the works in a resilient way, limiting the disruption for the traffic as much as possible (also see section 4.2.6).

The case study on the **Gotthard road tunnel** describes how good **preparation** helped to speed up the **recovery** after the fire incident in 2001. This preparation was based on experiences with typical damage that occurred in earlier fires and resulted in standard procedures and standard measures, for instance a standard temporary support system for the intermediate ceiling when it is damaged in a fire. Such a support system can be installed very quickly and helps to carry out inspections and repair works under safe conditions, thus speeding up the process. The standard procedures also include a plan for the production and logistics for the parts and components that are needed for the repair, as well as an identification of the required expertise, so that the involvement of the experts and enterprises that know what to do can be organized very quickly. Indeed, the organization of the repair already started when the fire was still burning. All this helped to reopen the tunnel within 2 months.

As already mentioned in section 4.2.1, the case study on the **Leidsche Rijn Tunnel** (Appendix J) involves a **decision making process** about the installation of a watermist system (WMS). The question was, if such a system would enhance the resilience for fire incidents in a cost-effective way, taking into account the reduction of damage (including casualties and injuries) and the related reduction of non-availability of the tunnel because of repair works. A Societal Cost-Benefit Analysis (SCBA) was carried out to support the decision. The SCBA showed that, in this case, WMS is not cost-effective and therefore it was decided not to install such a system. See the appendix for details on the content of the analysis.

Last to be mentioned in this category, the case study on the **Beveren Tunnel** describes measures to enhance the resilence for **dangerous goods incidents**. This involves the testing of a real-time ADR detection system, based on intelligent cameras. The Beveren Tunnel was recently degraded from ADR category “A” to “D”, to comply with the legal safety risk criterion that was exceeded, due to traffic load increase in combination with the fact that the tunnel safety systems should be upgraded . This means that the tunnel is not available anymore for a large amount of dangerous goods transports to and from the sea harbor of Antwerp. Since it is the aim to have no traffic restrictions for the tunnel, this can be considered a loss of availability caused by a decreased safety level (as explained in section 2.4). A scheduled refurbishment will realize the required upgrade, so that ADR category “A” could be restored, but even then this category will remain under pressure, because the traffic load continues to increase. Therefore, the ADR detection system will be used in a study to obtain a better overview of daily and seasonal fluctuations of the different categories of dangerous goods transports. Based on these results, a new traffic management system will be developed (involving dedicated toll) to reroute traffic on a macroscale, so that local ADR transport will not use the Beveren Tunnel during general peak hours and the safety risks will be lowered sufficiently, even when ADR category “A” is applicable. In addition, the ADR detection system is expected to support the descision making by the tunnel operator and fire brigade during emergency response, possibly leading to a faster recovery after a fire incident.

4.2.5. Failure of technical or operational (safety) measures

When considering a failure of the tunnel system, technical failures might first come to mind. However, the operational (safety) measures can also fail to a degree that the service and/or availability level of a road tunnel is compromised. **The COVID-19 pandemic**, threatening the heatlth of the (critical) tunnel personnel, was already mentioned in section 3.3.6 as an example. One of the case studies, on the resilience management approach of **Transurban**, an Australian road network management group, also touches on this example (see Appendix B). Disease transmission risks were mitigated successfully. Most personnel shifted to working from home, but control room operators continued to work from the control room. Measures to assure a safe environment in the control room included an identification of all transmission risk points, a sanitisation process for entering the control room and applying a “virtual” change over process between control room shifts. To assess the organisation’s capability under these COVID-19 restrictions, a virtual desktop exercise was conducted. The conclusion was that Transurban was able to successfully deal with a major event with most of the team working remotely.

Closely related to the availability of the tunnel in relation to the failure of tunnel system measures are the **Minimum Operating Requirements (MOR)**, as explained in section 2.4. MOR are also addressed in the case studies on the RITUN methodology (see section 4.2.1 and Appendix G) and the upgrading of the Saltash Tunnel (see Appendix R). In the **RITUN** context, the MOR define the conditions, including temporary measures, under which a tunnel can still be operated - maybe in a degraded mode - at a tolerable safety level after an event occurred that caused a certain damage to (or failure of) the tunnel system. This is taken into account when assessing the consequences of a certain disturbing event on the availability of the tunnel and the selection and implementation of the measures to reduce this risk. As part of the upgrading of the **Saltash Tunnel**, a risk-based MOR system, able to provide real time information on the tunnel safety level (based on the technical condition of the systems) was developed and implemented. Both degraded system and a sudden system failure scenarios were considered and a set of practical mitigation and compensatory measures were defined enabling a continued safe operation of a tunnel in case of degraded systems or sudden system failures (e.g. lane closure, speed limit, traffic management, etc.). Thus, the MOR system improves resilience by increasing the availability of the tunnel.

Lastly, the Italian case study on the **SCADRA system** (Supervisory Control Acquisition Dynamic Risk Analysis) in Appendix S also describes an automated support system for resilience. Starting point is a SMART tunnel, with sensors collecting real-time data on traffic conditions, weather conditions and the technical status of the tunnel systems and installations. Based on these data, the SCADRA calculates the safety risk level of the tunnel at regular pre-established intervals and in case of sudden changes (dynamic risk assessment). When the actual risk level is sufficiently low, it is possible to consider energy-saving strategies ("safe energy mode"). On the other hand, when the actual risk level threatens to exceed the acceptable level, the systems informs the operator to implement operational measures to lower the risk, like lowering the speed limit, enforcing a certain distance between vehicles or enforcing an overtaking ban for trucks. This way, closure of the tunnel under certain circumstances can be prevented. Moreover, the emergency response services can be better informed and better prepared for possible emergencies in the actual situation, intervention times can be reduced and maintenance planning can be optimized.

4.2.6. Tunnel maintenance and refurbishment

In the collected case studies, the following reasons for refurbishment or maintenance were presented:

- An upgrading of the tunnel is required, for instance to enhance fire safety:
    - Karavanke Tunnel (Appendix C), the Engelberg Tunnel (see Appendix H), the mid-length expressway tunnels in South Korea (see Appendix M), the Tyne Tunnels (see Appendix Q) and the Saltash Tunnel (see Appendix Q);
- Damage to the tunnel has to be repaired:
    - Fourvière Tunnel (see Appendix E), Tawarayama Tunnel (see Appendix I), Gotthard Tunnel (see Appendix P);
- Tunnel installations and systems are end of life:
    - Heinenoord Tunnel (see Appendix K) and three Swiss tunnels (see Appendix O): the Belchen Tunnel, the Gotthard tunnel and the Rosenberg Tunnel.

Whatever the reason, maintenance and refurbishement works are an disrupting event, compromising the availability of the tunnel and causing disruption to traffic. Therefore, the works should be executed in a resilient way, making use of the resilience capabilities already present in the tunnel system, possibly in combination with the implementation of temporary or permanent mitigating measures when this is required to reach the aimed service / availability level during the works.

Most case studies involving maintenance or refurbishment works describe that various alternatives were considered to limit disruption to traffic. The multi-criteria analysis (MCA) applied for the Heinenoord Tunnel in The Netherlands was already described in section 4.2.1 (also see Appendix K). Normally, safety is a basic condition for all alternatives.

The described solutions to execute the works with limited disruption (compared to full closure with detour route during the entire period) include:

- The construction of an **additional tube**, to process the traffic during the time period that the works take place in one of the current tubes. This is a well-known strategy when the additional tube is part of the upgrading measures (like with the Tyne Tunnels, see Appendix Q); usually, the additional tube is constructed first, then the traffic is led through the new tube while a current tube is fully closed for refurbishment; after all current tubes are refurbished, the tunnel is fully opened again, with the new tube providing additional traffic capacitiy, and possibly the opportunity to introduce uni-directional traffic in all tubes for safety reasons. However, the Swiss case study on "**refurbishment tubes**" in Appendix Q, involving the Belchen Tunnel, the Gotthard tunnel and the Rosenberg Tunnel, presents another interesting variant: for these tunnels, an additional tube was constructed for temporary use during the refurbishment alone. In these cases a permanent use of the additional tube is not allowed, because an increase of traffic capacity would require additional formal approval according to Swiss legislation (a study demonstrating the necessity for extra traffic capacity would have to be conducted). An additional tube for temporary use during maintenance and refurbishments only is maybe not a solution one would think of right away, for reasons of cost-effectiveness. However, in the planning stage for these additional tubes, a societal cost-benefit analaysis (SCBA) was carried out to demonstrate that this is indeed cost-effective, also taking into account the duration of the works in combination with a long detour route, resulting in much extra travel time for the traffic during this period.
- **Temporary bi-directional traffic** in one tube while another tube is closed for refurbishment or repair (as implemented with the Fourvière Tunnel, see Appendix E). A variation on this concept is setting an **alternating driving direction** in a tunnel tube, as implemented with the Karavanke Tunnel (see Appendix C): one direction at the time, the other traffic waits until the direction is changed again.
- **Closure of one or more lanes** in a tube to provide an area in which the works are carried out next to the traffic; this normally requires a temporary reduction of lane width in combination with a speed limit reduction and an adequate safety zone between the workers and the traffic. In the case of the Engelberg Tunnel in Appendix H, the working space is fully enclosed for optimal protection of the workers.
- **Ban for trucks**, allowing only "light traffic" to make use of the tube under maintenance or refurbishment; this is usually combined with the above-mentioned measure of closing one or more lanes to allow for working space. This has several advantages: light traffic requires a smaller lane width (more workspace, more working efficiency) and the risk of large fires

is limited, which is an advantage when, for instance, the ventilation is not fully functional during the works. A ban for trucks was applied with the Karavanke Tunnel and the Fourvière Tunnel.

- **Full closure only in in low-traffic periods**, like during nights or weekends; this was applied with the Karavanke Tunnel and will be applied with The Heinenoord Tunnel (in this case, almost the entire refurbishment will be carried out under this regime; this is made possible, among other things, by applying the concept of “parallel assembly”; see Appendix K for detsails).

A supporting measure could be to provide signs (at strategic locations) **displaying the actual travel time** for various alternatives, to support the choice for the optimal route by the traffic participants during the works (as implemented with the Engelberg Tunnel).

Note that many of the above-mentioned measures can in fact also be applied to maximize availability during the recovery from disturbing events other than maintenance and refurbishment works.

Further, it is worth mentioning that the case study on the Heinenoord Tunnel also shows that maintenance and refurbishment works should be possible outside the traffic space in the tunnel tube as much as possible, to limit the loss of availability of the tunnel. For this reason, a service gallery will be constructed as part of the refurbishment scope. The gallery will house 40% of the tunnel equipment; most of the other equipment (50%) will be in the service buildings; only 10% of the equipment will remain in the traffic space in the tubes. This not only helps to limit the hindrance during the refurbishment, but it also enhances the resilience for future works.

To conclude this section: additional case studies on (resilience aspects of) maintenance and refurbishment of high-trafficked (urban) road tunnels can be found in the report [113] by Working Group 1 of TC 4.4 on Tunnels.

4.2.7. Technological and societal developments

A case study that highlights resilience aspects not yet mentioned is the implementation of **photovoltaic panels for the power supply** of the L2 ring road crossing the city of Marseille, France (see Appendix F). This is a 12km long road, mostly in cut-and-cover tunnels. One would perhaps think that the photovoltaic panels would enhance the reliability of the power supply, thus enhancing the resilience for failure of the tunnel system, as described in sections 3.3.6 and 4.2.5. But the reliability of the power supply was already very high, through redundant connections to the public power grids. Hence, the increase of reliability is merely theoretical (but still positive). A bigger advantage is that the power supply through the photovoltaic panels will lead to cost reduction. This can be considered an improvement of resilience, because the same performance is delivered against lower cost; this is a form of adaptive resilience through technological development. But, perhaps the most important perspective for the measure is that, according to the company that manages the road, resilience also must be perceived through social acceptability, in particular for road infrastructure. The implementation of photovoltaic panels contributes to this social acceptability by the use of clean energy which minimizes the overall carbon footprint of the infrastructure. This lowers the probability that the infrastructure and its usefulness will be questioned in the future. In other words: this is an example of a societal development to be resilient for.

Related to this case study, it is important to mention that **sustainability** (enhancement of circumstances for people, planet and profit in an integral way) becomes more and more important for society, hence also for road tunnel operations. PIARC report [114] presents guidelines to take this into account (while planning measures to enhance resilience).

4.2.8. Organisational aspects and managerial capabilities

Two of the collected case studies deal with the organizational and managerial aspects of resilience:

- Transurban's Resilience Approach, Australia (see Appendix B);
- Madrid Calle 30 Ring Road Resilience Approach, Spain (see Appendix N).

The **Transurban Group** develops, operates, manages, and maintains toll road networks in Australia and North America. Overall, it operates 21 toll roads which include 12 tunnels. The case study examines the managerial approach used by Transurban Group to maintain and improve resilience of its toll roads that has application to road tunnels. In Appendix B, some aspects of the approach are highlighted, like the four pillars for resilience (assess, prepare, respond, assure), the multi- level response management structure (assuring both flexibility and capability to deal with events) and the continuous training and exercises to enhance the resilience capability. A section in the case study addresses how Transurban coped with the COVID-19 pandemic (as already explained in section 4.2.5).

The **Madrid Calle 30 Ring Road** is the most important and the busiest road infrastructure in Spain, running through a complex urban environment, and includes circa 48 km of tunnels. The case study in Appendix N describes further characteris of the road, the structure and organization of the control rooms, the emergency response, as well as the monitoring of the critical systems and installations to assure a safe and continuous operation. Further, the judicial context is explained, from legislation to comply with, to the concession contracts under which the operation takes place. This complex convergence of technical, organisational, legal and contractual preconditions is managed through an Operating Manual and a Quality Plan.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSIONS

This report presents an overview of the topic resilience of road tunnels and critical infrastructure in general, through a literature review and a collection of case studies.

The literature sources and case studies confirm that resilience is an important consideration for road tunnels, in order to ensure the availability for traffic under various circumstances. Thus, the tunnel manager should (to a suitable degree) take measures to either prevent the negative effects of incidents on the availability, or to mitigate the negative effects, or to make sure the full availability is quickly recovered. More focus on recovery is a trend in legal requirements, standards and policies, since one should always be prepared for the required actions when prevention fails, even when the probability of failure is low. The magnitude of the measures to ensure resilience for certain events depend on the strictness of the availability requirements, and the risk imposed by the incidents that these availability requirements are not met. The availability requirements, in turn, normally depend heavily on the importance of the tunnel as a connection in the road network: the more nuisance when the tunnel is not fully available (in terms of, for instance, total extra travel time for all affected vehicles taking an alternative route), the stricter the availability requirements.

The report (Chapter 3) presents many approaches and measures, found in literature, tunnel managers can implement to assure or enhance the resilience of the road tunnel for various events or incidents. And, since specific literature on road tunnels seems to be rare, this report also seems to have added value in a way that it combines the many topics related to resilience in a tunnel context[16].

The presented approaches are broadly applicable, and in fact independent of the content or strictness of the requirements for availability and safety. This is confirmed by the collection of case studies (Chapter 4 and appendices). Moreover, there are many possible measures to enhance resilience, not necessarily requiring large investments. Therefore, the resilience concept could also have added value for tunnels in Low and Middle Income Countries (LMICs).

In addition to management systems and measures, a “just culture”, in which people are not blamed for their mistakes and errors, proves to be crucial to enhance the resilence of an organization and hence a tunnel system.

Further it was observed that a lot of measures enhancing tunnel safety (notably preventive and mitigating measures) may also be effective to improve tunnel resilience. Therefore, resilience aspects may be valuable additional parameters in the decision making process with respect to tunnel safety measures, in particular when planning refurbishment and upgrading projects.

Not all resilience topics identified as relevant by the Working Group are sufficiently covered by literature yet. For instance, the following topics would deserve some more attention:

[16] Several aspects of resilience are certainly not new tot he tunnel industry and are traditionally taken into account through codes, standards and practical guidelines presenting experience with the design, operation and maintenance of road tunnels. However, the consideration of these aspects appears to be spread over many different literature sources that are not always explicitly recognizable as part of the resilence concept.

- Planning, measuring and improving road tunnel resilience in practice: quality plans / performance management plans and performance measurement systems ("dashboard" to support resilience management);
- Measures to enhance the resilience for refurbishments (Increasing availability / reducing traffic nuisance during refurbishment works);
- Mitigating measures / alternative measures to assure an acceptable safety level in case of failure of safety provisions (technical or operational) that are normally operational;
- The effectiveness, Life Cycle Costs (LCC) and cost-effectiveness in practice, of the resilience improvement measures found in literature.

The collection of case studies appears to cover many of these topics in more detail, thus providing added value. Although the case studies cover a broad variety of topics and problems related to various phases of the tunnel life cycle, a general conclusion to be drawn from the examples would be that a good analysis, a balanced decision making and a thorough preparation is essential for a successful implementation of measures to improve resilience. This does not necessarily mean that the decision making process or the chosen measures are complex; sometimes the problems and solutions are obvious and simple. It just means one has to get a good-enough overview of the relevant aspects in relation to the impact of the measures. Furthermore, a good focus on the resilience goal to be achieved is important.

5.2. RECOMMENDATIONS

5.2.1. Recommendations for decision makers

Given the importance tunnels normally have in the road network, resilience is an aspect that should be considered adequately. Based on the literature review, the following basic roadmap to manage and improve road tunnel resilience could be used as a starting point:

- Start by setting requirements for the availability of the tunnel and/or resilience for certain events, in terms of protection and recovery, in line with the importance of the tunnel in the total road network; section 3.2 presents some criteria that can be used for these requirements;
- Next, start measuring the performance related to these requirements;
- Parallel to this, start an assessment of hazards, probabilities, vulnerabilities and impact on the availability (on the object level as well as on the network level); section 3.1 presents some approaches that can be useful for this;
- Then determine, on the basis of the acquired measurements and/or the results of the assessment, what (if any) additional measures are required to improve availability / resilience (in addition to the already implemented measures); section 3.3, as well as the collection of case studies, can be helpful in the selection of measures; taking the incident management processes as a starting point for the design of the tunnel system would provide a good basis to ensure resilience;
- Implement the required additional measures and provide for the necessary resources for all measures to be effective (power supply, information supply, staff, materials, equipment, assets, financial budget, etc.);
- Continue to measure the availability / resilience performance, to monitor if requirements are still met or if the implemented additional measures are effective; if not, adapt or improve the measures;

- Last but not least, evaluate periodically if the requirements for availability and resilience are still "fit for purpose"; adjust the requirements when relevant.

5.2.2. Recommendations for PIARC

In line with the above conclusions, the Working Group recommends to:

- Further develop the basic road map described in section 5.2.1, possibly including "supporting tools", to better facilitate a practical implementation of measures to manage, evaluate and improve resilience performance in every phase of the lifespan of the road tunnel (from planning to operation);
- Further analyse the effectiveness and cost-effectiveness of the resilience measures, as found in the literature review and the collection of case studies; since many prevention measures are also tunnel safety measures, that already have been described many times in the past, we recommend to focus on mitigating measures, supporting the recovery phase after an event occurred. When relevant and possible, the sustainability aspects of the measures should be addressed as part of the (cost-)effectiveness).

The Working Group will take these recommendations into account while further developing the full technical report on road tunnel resilience.

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7. GLOSSARY

Term	Definition
AADT	Annual Average Daily Traffic; normally calculated as to total number of vehicles (in both directions) on a road per year, divided by 365.
ADR	Accord Européen relatif au transport international des marchandises Dangereuses par Route; translated in English : « Agreement concerning the international carriage of Dangerous goods by Road”. Related to road tunnels, the ADR category indicates which dangerous goods are allowed in the tunnel (and which are not). ADR category “A” means “no restrictions”. In popular language, “ADR” often refers to (the transport of) dangerous goods in general, like “ADR traffic” or “ADR detection”.
ALARP (safety)	“As Low As Reasonably Practicable”. It means that residual safety risks shall be reduced as far as reasonably practicable. In other words: if safety risks can easily be further reduced by simple measures without disproportional cost, these measures shall be implemented [source: PIARC TC 4.4 WG2].
HGV	Heavy Goods Vehicle
MCA	Multi Criteria Analysis
SBCA	Societal Cost-Benefit Analysis
LCC	Life Cycle Cost
QRA	Quantitative Risk Assessment
WMS	Water Mist System
Resilience (general definition)	The ability of a system, community or society exposed to a hazardous event, a trend or a disturbance, to resist, absorb, accommodate, adapt to, transform, learn and recover from the induced effects in a timely and efficient manner that maintain their essential function, identity and structure. [source: PIARC TC 1.4, report 2021BN1.4EN, adapted from IPCC, 2019 and UNDRR 2017]
Road tunnel system	Whole of the structure, installations, internal and external infrastructure, operation and management organization of a road tunnel [source: PIARC Road Dictionary].
Road tunnel system resilience (specific definition, adapted to road tunnels and their primary function)	The ability of the tunnel system to prepare, plan for, resist, absorb, recover from, more successfully adapt to actual or potential negative effects of events or developments affecting the availability of a road tunnel in a timely and efficient way. In this context, an acceptable safety level is a mandatory constraint for the availability of the road tunnel [source: PIARC TC 4.4 WG2].
Preventive resilience (road tunnel system)	The ability of the tunnel system (as a result of adequate planning and preparation) to resist/absorb actual or potential negative effects of events or developments in a timely and efficient way, so that the availability of the tunnel is not compromised. In this context, an acceptable safety level is a mandatory constraint for the availability of the road tunnel [source: PIARC TC 4.4 WG2].
Mitigation resilience (road tunnel system)	The ability of the tunnel system (as a result of adequate planning and preparation) to mitigate actual or potential negative effects or developments in a timely and efficient way, so that the loss of availability

Term	Definition
	of the tunnel is reduced, either by limitation of the degree of loss (static resilience) or the duration the loss (dynamic resilience). In this context, an acceptable safety level is a mandatory constraint for the availability of the road tunnel [source: PIARC TC 4.4 WG2]. Note: this concerns the mitigation of (or the recovery from) the negative effects that could not be prevented / absorbed by the preventive resilience of the tunnel system.
Adaptive resilience (road tunnel system)	The ability of the tunnel system (as a result of adequate planning and preparation) to adapt more successfully to actual or potential negative effects of events or developments in a timely and efficient way, so that the loss of availability of the tunnel is better (or more efficiently) prevented or reduced. In this context, an acceptable safety level is a mandatory constraint for the availability of the road tunnel [source: PIARC TC 4.4 WG2]. Note 1: what is considered an acceptable safety level may change over time as well; thus, adaptive resilience may also be required to adapt to changing / increasing safety requirements. Note 2: “adaptive resilience” can also be defined as “adaptive capacity”: the ability or potential of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities, or respond to consequences of impacts of environmental variability and change. It includes adjustments in both behaviour and in resources and technologies [source: PIARC TC 1.4, report 2021BN1.4EN, adapted from PIARC Framework, 2015 and IPCC 2018].
Static resilience	Part of mitigation resilience, see definition above. The term “static resilience”, as a measure for the degree of the temporary loss of function as the result of a certain event, was first defined by Rose [3].
Dynamic resilience	Part of mitigation resilience, see definition above. The term “dynamic resilience”, as a measure for the duration of the temporary loss of function as the result of a certain event, was first defined by Rose [3].
Availability	The ability of an item to be in a state to perform a required function under given conditions at a given instant of time or during a given time interval, assuming that the required external resources are provided. Notes: 1. This ability depends on the combined aspects of the reliability, the maintainability and the maintenance supportability. 2. Required external resources, other than maintenance resources, do not affect the availability of the item [source: EN 13306 / PIARC Road Dictionary]. In this study, the availability for traffic (under safe conditions) of a road tunnel is considered.
Event	An incident, man-made or from natural causes, that has an impact on infrastructure, for example earthquakes, tsunami, floods, sea level rise (as a result of climate change), extreme weather, road traffic accidents, terrorist act, vehicles striking structures [Source: PIARC TC 1.4, report 2021BN1.4EN / State Highway Network Resilience National Programme Business Case – 2014].
Disruption	An event that considerably interrupts normal life, business, functions, operations, or processes, whether anticipated or unanticipated. [Source: PIARC TC 1.4, report 2021BN1.4EN / New Zealand “National Disaster Resilience Strategy” 2019].

Term	Definition
Consequence	Outcome of an event affecting objectives. A consequence can be certain or uncertain and can have positive or negative direct or indirect effects on objectives. Consequences can be expressed qualitatively or quantitatively. Any consequence can escalate through cascading and cumulative effects [Source: ISO, 2018].
Intervention level (tunnel safety)	Definition or description of the allowed degree of failure of safety provisions or the allowed decrease of the safety level before action is required to keep the (additional) safety risks acceptable for the tunnel users; relevant action may consist of temporary measures to mitigate the additional risks caused by the failure and/or quick repair within a certain time span [source: PIARC TC 4.4 WG2].
Minimum Operating Requirements (MOR) (tunnel safety)	Definition or description of the minimum required safety conditions or level for the operation of a road tunnel; if the conditions become worse than the minimum required, and no immediate (temporary) measures are possible to get the conditions above the minimum again, the tunnel should be closed for traffic [source: PIARC TC 4.4 WG2].
Critical Infrastructure	An asset, system or part thereof which is essential for the maintenance of vital societal functions, health, safety, security, economic or social well-being of people, and the disruption or destruction of which would have a significant impact as a result of the failure to maintain those functions [Source: PIARC Task Force C.1 on Infrastructure Security, based on European directive 2008/114/EC].
Object (level)	Refers to the physical elements of infrastructure i.e. pavements, bridges, earth structures, tunnels, furniture etc. [Source: PIARC TC 1.4, report 2021BN1.4EN]
Risk	Effect of uncertainty on objectives or system operation. Risk is often characterized by reference to the likelihood of potential events, consequences, or a combination of these and how they can affect the achievement of objectives or system operation. Risk is often expressed in terms of a combination of the consequences of an event or a change in circumstances, and the associated likelihood of occurrence [Source: ISO, 2009].
Risk Analysis	Process to comprehend the nature of risk and to determine the level of risk. Risk analysis provides the basis for risk evaluation and decisions about risk treatment [Source: ISO, 2009].
Risk Evaluation	Process of comparing the results of risk analysis against risk criteria to determine whether the level of risk is acceptable or tolerable [Source: ISO, 2009].
Risk Treatment	Process of developing, selecting and implementing controls or options for addressing risk [Source: PIARC TC 1.4, report 2021BN1.4EN; adapted from ISO, 2018].
Hazard	A potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation. Hazards can include latent conditions that may represent future threats and can have different origins: natural or induced by human processes [Source: PIARC TC 1.4, report 2021BN1.4EN / Sendai Framework 2015].
Exposure	The presence of people, livelihoods, environmental services and resources, infrastructure or economic, social, or cultural assets in places

Term	Definition
	that could be adversely affected by a hazard [Source: PIARC TC 1.4, report 2021BN1.4EN / Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, IPCC, 2012].
Vulnerability	The degree to which a system is susceptible to, or unable to cope with, adverse effects of hazards, including climate change, variability and extremes [Source: PIARC TC 1.4, report 2021BN1.4EN / PIARC Framework, 2015].
Criticality	The relevance of an infrastructure element or section to the availability of a transport infrastructure system [Source: PIARC TC 1.4, report 2021BN1.4EN, based on All-Hazard Guide for Transport Infrastructure, 2015].

APPENDICES

APPENDIX A: FORMAT FOR THE CASE STUDIES

For the description of the case studies, the following format was used as a guideline.

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	
Author(s)	
Date of preparation	
Description of the case study	
Objectives	
Technical challenges	
Non-technical challenges	
Evaluation (effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)	
Lessons learned and recommendations	
Further information	
References or interesting web links	

APPENDIX B: CASE STUDY: TRANSURBAN'S RESILIENCE APPROACH, AUSTRALIA

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Transurban's Resilience Approach, Australia
Author(s)	George Mavroyeni, Australia
Date of preparation	22 April 2021
Description of the case study	

Transurban Group develops, operates, manages, and maintains toll road networks in Australia and North America. Overall, it operates 21 toll roads which include 12 tunnels. This case study examines the managerial approach used by Transurban Group to maintain and improve resilience of its toll roads that has application to road tunnels.

The resilience of tunnels and road network is driven by Transurban's business resilience which it defines as, "having the capability and capacity to respond effectively to any threat, incident, emergency, disruption or crisis that has the potential to impact the organisation, our customers or the community in which we operate – prioritising the safety of people, the protection of our reputation and the ability to continue to operate critical services." These objectives are achieved by:

- Understanding the potential risks that might disrupt its business and operations, its customers, stakeholders and the communities in which it operates.
- Building a capability that enables it to effectively respond to, and recover from, any such disruption no matter the scale or nature of the event that has occurred.

Transurban undertakes significant planning to be able to quickly contain incidents and to protect people and property, planning for a loss or failure of critical dependencies, such as buildings, technology infrastructure and systems, critical suppliers, people and equipment and planning to communicate with employees, customers, stakeholders and communities during emergencies, disruptions or crisis.

In planning for resilience, Transurban uses a strong focus on consequences of events without much regard for the likelihood of events. This approach enables it to better prepare for any event.

Transurban uses four pillars for resilience.

1. Assess – identify the priorities and scope of resilience preparedness and response capability.
2. Prepare – minimise the negative impact to the organisation by preparing and exercising a range of strategies, response plans and procedures across all areas of business operations.
3. Respond – capability and capacity to respond effectively to disruptions by optimising the performance of response teams, communications, and tools.
4. Assure - provide assurance to stakeholders that the organisation is prepared and capable to respond effectively to events that might adversely impact roads, customers, business and stakeholders.

Transurban has established a multi- level response management structure that it applies to all of its businesses, see figure 1.

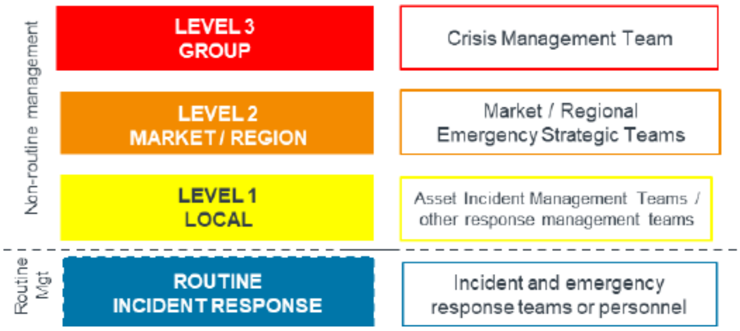

Figure 1. Transurban response management structure

This structure provides Transurban with the flexibility and capability to deal effectively with any event. At the **Routine level**, operational teams deal with the day to day incidents/events (technical in nature). Their objective is to contain local incidents and make safe, enabling the continuity of road operations. At **Level 1**, the teams are more tactical with a focus on business unit / asset operations to contain a situation and minimise the impact. Asset Incident Management Teams comprise of representatives from operations, planning, logistics and communications business units, as well as any specialist input that might be required, such as Technology, Health, Safety and Environment and Legal. The teams work to detailed plans and procedures. Each plan and procedure has an owner who is responsible for ensuring the documents remain relevant and fit for purpose. These documents include details of the various team member roles and their objectives, and provide the necessary guidance and instructions for team members to follow. At **Level 2**, the Emergency Strategy Team in each Market or region is strategic in its approach and its priority is managing the impact to the Market with a key focus on stakeholder management, as well ensuring likely and worst case scenarios are considered. This team has representatives from people & culture, legal, communications, customer, finance, technology and operations business units. The practice is to initially set up the Emergency Strategy Team with full membership to enable diversity of thought when considering potential impacts and issues, then downsize the team commensurate with the priorities of the response. This ensures that a broad assessment of the situation has been undertaken and can enable the team to adapt as required. The Emergency Strategy Team is supported with a plan and role cards to enable the team to carry out its responsibilities. The plans are deliberately brief so that team members can readily understand their role and what is expected of them. The team works to an agenda that is designed for critical thinking. For example, what can we do now to avoid a worst-case scenario or what can we do if we are in a worst-case situation? The operations representative provides the team with a situation report outlining the status of the incident, the planned activities of the Incident Management Team and any challenges to be addresses. This approach enables the Emergency Strategy Team to remain focussed on the strategic issues and avoid being caught up in the detail being addressed by the Asset Incident Management Team. At **Level 3**, the Crisis Management Team plays a strategic role with a focus on the enterprise impacts, such as long-term strategic change, national stakeholder management, Transurban wide impact and ongoing business viability.

While Transurban has the capability to quickly set up the above multi-level response management structure, it has found from experience that all levels do not need to be in-place for all events. Transurban uses its structure flexibly to manage events of varying degree of risks.

Transurban maintains and improves its resilience capability through training and exercises. The exercise scenarios are designed to be as realistic as possible and typically involve key stakeholders either as participants or as observers. This assists all relevant parties to better prepare for events. The exercises involve the primary role players and also back-up/alternative role players so that the risk of key players being absent during an event is mitigated. Significant resources are invested in running exercises and there is a budget for these exercises. Annually, Transurban conducts multiple exercises, both internally and with external stakeholders to facilitate training, system testing and capability. Exercises are undertaken to test new systems, processes and risks (such as risks associated with electric vehicles).

Resilience during COVID-19

COVID-19 impacts forced 95 per cent of the Transurban workforce to work from home, however, control room operators continued to work from the control room.

In March 2020, Transurban developed an initial traffic control room covid safety plan. Some of the actions in this plan are listed below:

- preparing where possible all traffic control room operators to work from home
- testing of the alternate traffic control room
- identifying all transmission risk points
- establishing a ‘virtual’ change over process between control room shifts
- sterilising the control room at each shift change over
- sanitisation process for entering the control room.

The plans are reviewed periodically according to the changing COVID risks in each region with consideration of State government guidelines, and Transurban risk assessments.

Throughout COVID-19, Transurban has continued to maintain a program of exercising to ensure response teams such as the Asset Incident Management Team remain capable of responding to an event. For example, a virtual desktop exercise was conducted in November 2020, to assess the organisation’s capability to successfully deal with events under COVID-19 restrictions (see figure 2). This particular exercise involved an external stakeholder, which added to the complexity of the scenario. The conclusion was that Transurban was able to successfully deal with a major event with most of the team working remotely.

Figure 2. Virtual desktop exercise under COVID-19 restrictions

Objectives
To identify managerial practices used by Transurban Group for resilience of the road network it manages and operates that can apply to road tunnels and open roads and would be of interest to the broader road network community.
Technical challenges
Differing requirements for each jurisdiction (e.g. emergency services requirements, Deed requirements).
Non-technical challenges
Ensuring the response management structure remains fit for purpose, cognisant of emerging and changing risks, and capable of effectively responding to a diverse range of events that could adversely affect the resilience of a road network.
Evaluation **(effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)**
Transurban has established a management structure that is flexible and easily set up to deal with any event. It maintains capability and efficacy of its response management structure by training and conducting frequent exercises. Transurban demonstrated its capability to respond to incidents during the Covid-19 crisis by conducting an exercise virtually and with strict arrangements for the traffic control room operations.
Lessons learned and recommendations
It is important to effectively adapt to a changing environment in order to be well prepared to respond effectively to any event. Road users and Governments have an expectation that their road network (including key infrastructure such as tunnels) is available for use at all times. Closing infrastructure to resolve an operational issue is the very last option, however, safe operations will always be the number one priority. Need to be well prepared for unexpected disruptions, such as a Covid-19 crisis.

Transurban has demonstrated that it can meet its business resilience objectives by setting up an appropriate response management structure, with plans, procedures and training for event management, and by conducting frequent exercises to continually improve its response plans and procedures and its capability. The involvement of external key stakeholders in exercises is important in order to develop response capability more broadly and to give stakeholders confidence that the network manager/operator is well prepared to deal with events that adversely impact the safe availability of the network. A standardised response arrangement that is used by all of an organisation's business units, irrespective of geography, leads to consistent outcomes for that organisation.
Further information
[-]
References or interesting web links
https://www.transurban.com/

APPENDIX C: CASE STUDY: MAXIMIZE AVAILABILITY AT AN ACCEPTABLE SAFETY LEVEL DURING THE REFURBISHMENT OF THE KARAVANKE ROAD TUNNEL BETWEEN AUSTRIA AND SLOVENIA

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Maximize availability at an acceptable safety level during the refurbishment of the Karavanke road tunnel between Austria and Slovenia
Author(s)	Bernhard Kohl, Bernhard Klampfer
Date of preparation	September 30, 2021
Description of the case study	

Since 1991, the Karavanke Road Tunnel provides one of the most important highway connections between Austria and Slovenia as part of the European route E61 (A11 in Austria, A2 in Slovenia). The following figure shows the location in the South of Austria and the North of Slovenia respectively.

Figure 1: Location of the Karavanke Road Tunnel in the Austrian and Slovenian highway network (source: ASFINAG)

Currently the tunnel with a length of about 7,9 km is operated as a single tube tunnel with one lane per direction and does not have any emergency exits.

Because of these shortcomings with respect to the EC directive 2004/54/EC on the minimum safety requirements for road tunnels, in the long term a second tube will be available. As the decision-making, permitting and construction process for this major project involving two states is taking many years, measures had to be implemented in the meantime to comply with the applicable safety regulations and at the same time to maintain or even increase the availability of the internationally important traffic route.

Figure 2: Northern Portal of the Karavanke Road Tunnel

Due to the lack of reasonable detour routes the connection between the two countries through the Karavanke mountains is of high relevance for both freight and passenger traffic. If the tunnel is closed for operation, traffic has to be redirected to the secondary road network over a mountain pass or via the highway network with significantly longer distances. Both options result in a considerable increase in travel time and significant bottlenecks in periods of peak traffic.

Although the AADT with currently about 10,000 vehicles per day and a predicted increase up to 15,000 in 2038 is not very high, there are significant traffic peaks up to 37,000 vehicles per day in the main touristic seasons, especially during the weekends in spring and summer, as shown in Figure 3.

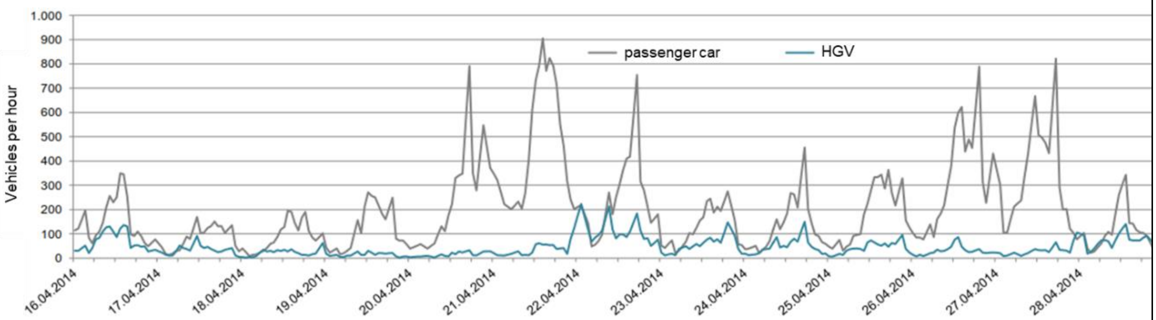

Figure 3: Distinct traffic peaks (statistics from the year 2014)

With regard to the EC directive 2004/54/EC and as a result of executed quantitative risk assessments, there was an urgent need for improving the original conditions and implementing additional risk mitigation measures, especially for periods of high traffic. Particularly they had to focus on fire risk, as this turned out to be significantly higher than acceptable (i.e. the fire risk of the corresponding reference tunnel, which is the reference case for risk evaluation in Austria). On the one hand, this was caused by the absence of emergency exits. On the other hand, the initially installed combined ventilation system (sections with longitudinal ventilation combined with sections with smoke extraction) did not meet the requirements to ensure a smoke free escape route (see also section “Technical challenges”). Furthermore, the consideration of periods with a very high traffic volume lead to a substantial increase in risk.

On these grounds, adequate safety measures had to be implemented until the second tunnel tube would be available for unidirectional operation in the long turn. The decision on additional risk mitigation measures was taken on the basis of the results of the quantitative risk study, applying the Austrian Tunnel Risk Model TuRisMo. Beyond that, due to the strategic relevance of this route for international traffic, aspects of availability were of high relevance as well when it came to the final selection of the most suitable measures. Thus, a holistic approach, considering safety as a basic requirement of operation as well as availability criteria were applied to finally select the measures .

Thus the main focus was put on measures able to prevent and mitigate fire risk, as major fires in a single tube tunnel without emergency exits like Karavanke tunnel are a dominant risk factor for life safety as well as for the availability of the tunnel. In the end, the following measures were implemented:

- Fire Brigade at tunnel portal
  A fire brigade unit located at the tunnel portal is able to intervene very quickly after every incident - collision or breakdown. By implementing this measure a significant reduction of the intervention time could be achieved, thus increasing significantly the efficiency of fire fighting. In particular fires developing from technical failures (which are the vast majority of vehicle fires) can be extinguished in most cases in an early stage, thus reducing the probability of fire scenarios harmful to health or tunnel structure. This measure was implemented as short term measure in an early stage, until the improved ventilation system, the thermo scanner and the truck metering systems were installed and fully operable. As it is an organizational measure, no adaptions of the construction or equipment was necessary, thus no negative effects regarding availability resulted from the implementation of this measure.
- Thermo scanner
  Thermoscanners (see example in figure 4) were installed in front of both tunnel portals. A thermo scanner allows to detect overheated vehicle parts (e.g. brakes, engine, exhaust), what may indicate a potential fire hazard. Locating the detection system in front of the tunnel, such vehicles can be detected and sorted out. If no real fire can be identified, the vehicle has to pass through the scanner again, after a short period of cooling down.
- Truck metering system
  During periods of high traffic the number of HGV entering the tunnel is restricted to a maximum of about one vehicle per minute. This measure does not reduce the absolute number of trucks per year, but it results in a reduced number of HGV driving through the tunnel simultaneously. Thus, the potential source of bigger fires during periods of peak traffic with a high number of passenger cars potentially affected is limited to a certain degree.
  Nevertheless, the limitation of HGV traffic by operating the truck metering system may implicate congestions during traffic peaks.
- No HGV traffic during periods with extremely high traffic
  A truck-driving ban is an efficient measure to reduce both, fire risk as well as the risk of a significant damage of tunnel structure, significantly during periods of extremely high traffic - in the summer months, during weekends or whenever the traffic volume exceeds a certain predefined threshold. However, as the Karavanke Tunnel is of high importance for international freight traffic, a total truck-driving ban should be implemented in exceptional situations only. This is why the tunnel operator cannot decide independently on it, but the public authorities of Austria and Slovenia have to order such a ban.
- Speed limit of 60 km/h
  If the thermo scanner and the truck metering system are not available for whatever reason, a speed limit of 60 km/h instead of 80 km/h allows reaching an adequate safety level too. It results in a slight increase of travel time, without significantly effecting the overall capacity.
- Improvement of ventilation system

As the original ventilation system, which combined transversal and longitudinal ventilation, did not meet the requirements of actual rules and standards, a substantial adaption was required (see section “Technical challenges”).

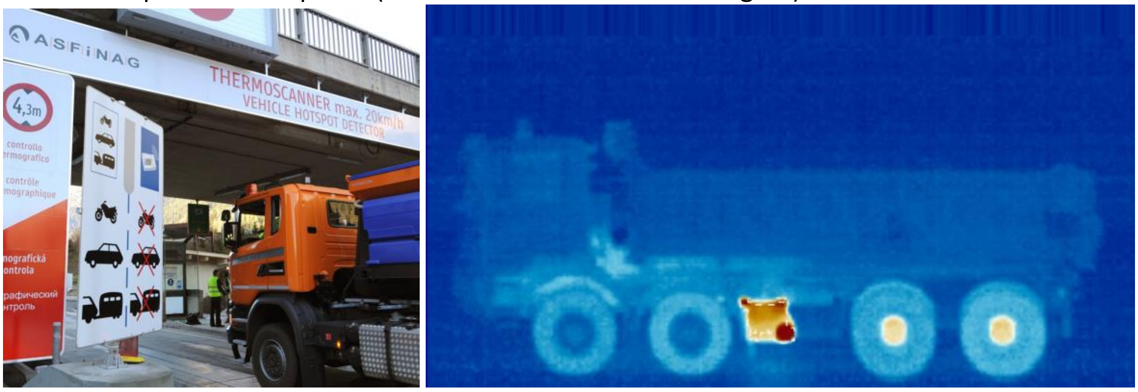

Figure 4: Truck passing a thermo scanner (similar to the one installed at the Karavanke Road Tunnel) and the resulting visualization of the temperature distribution

Objectives

The main objective of the implemented measures was to comply with the safety requirements according to the EC directive 2004/54/EC. Nevertheless, many safety measures and their implementation implicate an impact on availability too, both in a positive and in a negative manner. In order to ensure a holistic and comprehensive decision-making process, it is crucial to consider aspects of availability too.

On the one hand, the objective was to implement measures that create positive synergy effects in relation to availability, e.g. by avoiding severe damage to the tunnel structure and installations with potentially long recovery processes.

On the other hand, negative effects on availability resulting from the initial implementation of measures as well as from regular maintenance shall be minimized.

Technical challenges

In the course of the refurbishment aiming to comply with national and international legislation, the tunnel ventilation had to be updated substantially.

Initially a combined ventilation system was installed in the Karavanke Tunnel. In the first 3,3 km from both portals a transversal ventilation system was used. The remaining part with a length of about 1,2 km in the middle of the tunnel was equipped with a longitudinal ventilation system only .

Due to insufficient exhaust capacity and inadequately sealed leaks, the transversal ventilation suffered inefficiency in the inner parts of the cross-ventilated sections. It only worked properly in the first 2.000 m long sections on both sides of the tunnel, where two flaps had to be opened. In the inner parts up to ten flaps needed to be opened simultaneously, thus in case of a bigger fire the smoke would have been displaced over very long distances and smoke free escape routes could not be provided.

This is why the original ventilation system did not comply with the requirements of the ventilation guideline RVS 09.02.31, which was introduced afterwards.

Three alternatives for an upgrade of the ventilation system were analysed:

1. The intermediate ceiling is closed over the middle section to ensure an entirely transversally ventilated tunnel with an upgraded ventilation machinery.

2. The middle section remains longitudinally ventilated but the length is reduced to approximately 600 m. In order to avoid a fast smoke propagation due to an increased initial airflow velocity in the tunnel, jet fans located on the longitudinally ventilated middle section limit the velocities to a maximum of 1,5 m/s.
3. Semi-transversal ventilation is installed also in the middle section of the tunnel by means of a continuous air exhaust duct through the entire tunnel, while next to the duct enough space remains to position jet fans.

Finally, alternative 3 was realized, as it allows ensuring a continuous smoke extraction over the complete tunnel length. Thus, the requirements and conditions according to RVS 09.02.31 are complied with.

During the refurbishment works inside the tunnel, considerable traffic hindrance was inevitable. Therefore, all activities had to be organized in a way to be able to maintain the availability as much as possible. For this purpose, the construction process was divided into phases with different degrees of traffic hindrance, e.g. speed limit of 60 km/h, closure of one lane with alternating one-way traffic or even total closure of the tunnel for a limited duration.

As the traffic volume varies considerably throughout the time, during a week as well as during a year, the impact on traffic could be minimized very well by scheduling periods of total closure of the tunnel in phases of light traffic.

Non-technical challenges

Due to the criticality of the Karavanke Tunnel in the international road network, the availability for traffic operation is of vital importance. To make matters even more challenging the interests as well as rules and regulations of both involved countries, Austria and Slovenia, had to be considered. This asked for intensive bilateral coordination throughout the entire planning, construction and operation processes. Due to territorial integrity, the national border represents the border in terms of operation and maintenance of the tunnel too.

Evaluation
(effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)

Most of the implemented measures focus on a reduction of the risk with regard to fire. Especially the adapted ventilation system, the permanent attendance of the fire brigade and the thermo scanner have a substantial impact on the resulting fire risk.

Nevertheless, every measure shows its effects on a variety of aspects. The main objective was to look at the tunnel and the surrounding road network in its entirety.

In the decision-making progress the compliance with the minimum safety level just represents a mandatory constraint in order to be allowed to operate the tunnel. The final choice of measures is the result of a holistic approach considering several issues, especially in relation to the availability of the tunnel.

In this context, some measures implicate positive synergy effects:

- Fire events may result in severe damages to the tunnel structure and installations with long recovery processes. According to an evaluation of tunnel fires in the ASFINAG road network, a thermo scanner has the potential to decrease the number of HGV fires due to breakdowns by almost 50 %. By avoiding damage to the structure and the installations caused by tunnel fires resulting from technical failures, the long term expected value for the overall repair time can be reduced and the availability increased accordingly.

In contrast, the implementation of measures can have negative effects in terms of availability too: ▪ The installation of the safety-related facilities requires, at least partly, the closure of single lanes or even the entire tunnel. Thus, the travel time increases due to detour and/or congestion. For this reason, organizational measures, like a fire brigade at the tunnel portal, and measures, which do not require the installation of equipment inside the tunnel, like the thermo scanner and the truck metering system, were implemented preferably. ▪ The regular maintenance and periodic replacement of the safety-related facilities inside the tunnel lead to reduced availability too, as long as an extra closure is required. Consequently, detour and/or congestion result in an increased travel time too. ▪ In this regard it is important to note, that the motorway section of the Karavanke Tunnel requires purchasing an additional toll ticket. Therefore, the non-availability of the tunnel directly results in a considerable loss of income for the operator.
Lessons learned and recommendations
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Further information
With the ongoing progress of the construction of the second tunnel tube, the cross passages to the existing tunnel are built gradually. This procedure allows to use the cross passages as an emergency exit already during construction phase. Thus, the length of the escape routes is reduced considerably. Nevertheless, such a practice is not implemented in the Slovenian part of the tunnel due to legal issues. When the second tunnel tube is completed and ready for operation, a modernization and refurbishment of the existing tube is necessary. In order to maintain traffic through the Karavanke tunnel during this period, the traffic will be directed in the new tunnel tube in bi-directional operation. For this purpose all the equipment is designed to be able to deal not only with uni-directional traffic, as during normal operation, but also with bi-directional traffic. In the face of potential upcoming closures of one of the tunnel tubes, as a result of scheduled activities in the tunnel or unscheduled events, this allows to maintain the availability under controlled conditions.
References or interesting web links
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APPENDIX D: CASE STUDY: IMPLEMENTATION OF REAL TIME ADR DETECTION IN THE BEVEREN TUNNEL NEAR ANTWERP, BELGIUM

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Implementation of real time ADR detection in the Beveren Tunnel near Antwerp, Belgium
Author(s)	Heidi Cuypers
Date of preparation	July 19, 2021

Description of the case study

The Beveren Tunnel - part of the R2 (ring around Antwerp -, is a tunnel with a length of 1.1 km that consists of two unidirectional tubes (each with two lanes and an emergency lane). The tunnel crosses the Waasland Canal (see figure 1). The tunnel was opened to the public in 1991.

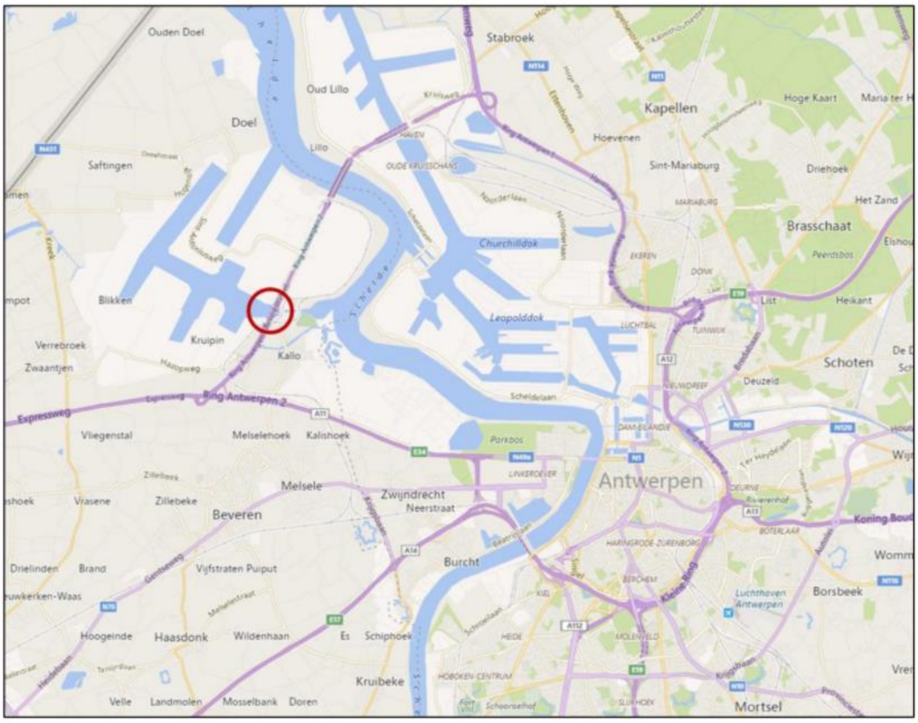

Figure 1. Location of the Beveren Tunnel

With an average traffic volume of 784 vehicles per hour per tube - with a max of 1.456 vehicles per hour per tube during peak hours - traffic volume in the Beveren Tunnel is relatively low compared to its capacity. However, the tunnel has several safety issues because it is situated in an industrial zone of the port of Antwerp. There are five main reasons for these safety issues:

1. The percentage of HGV (heavy goods vehicles) varies between 22% (during peak hours) and 39% (during normal daytime hours).
2. The amount of ADR (dangerous goods vehicles) is as high as 2% of the total amount of HGV
3. Between 2012 and 2019, the traffic volume increased by no less than 53%

4. Coming from the city of Ghent, there is a motorway exit immediately leading to the industrial zone of the port of Antwerp, after the exit portal of the tunnel. This leads to fluctuating traffic backlash into the tunnel on the right lane around 5:00 a.m. and 1:00 p.m., which are the typical hours of shift change in the industry zone. The incident rate of the Beveren Tunnel per vehicle-kilometre (vkm) is the highest in Flanders (Dutch-speaking region in Belgium).
5. Also, organised bus transport services are offered during these peak hours by several companies. In April 2020, a serious accident involving two busses, three HGV's and one passenger car led to one fatality and 49 injured people, of which five were seriously injured.

Renovation of the Beveren Tunnel is in the study phase, but apart from the 'normal' civil and electro-mechanical upgrading, the issue of the high amount of HGV's and ADR will remain. Since the region of Flanders, in which the port of Antwerp is situated, uses the Dutch QRA-tunnels model (Quantitative Risk Analysis model), the acceptance criterion for the societal risk shows a high sensitivity to the combination of the high amount of ADR vehicles and incident rates.

Since the QRA-tunnels model showed that the Beveren Tunnel could not meet the acceptance criterion, several (temporary) measures were already taken prior to the actual renovation.

1. The ADR category of the tunnel is changed from A to D
2. A traffic management system is installed for the tube coming from Ghent to prevent fluctuating traffic backlash into the tunnel at the exit leading to the industry zone at the port of Antwerp
3. Barriers are installed to provide a hard stop of vehicles entering the tunnel in case of smoke, fire or an ADR incident
4. A real time ADR-detection system was installed that will immediately provide a list of dangerous goods trucks still present in the tunnel in case of an accident.

The case study will elaborate on measure number 4, since - as far as the author knows - it is not implemented in tunnels yet.

Objectives

A new real-time ADR detection system is currently being tested in the Beveren Tunnel. The possible installation of this system on a permanent base is twofold:

1. Based on the results of a study pertaining to internal tunnel safety, using the Dutch QRA-tunnels model, the ADR category of the tunnel was recently decreased from A to D. Unfortunately, the rerouting of ADR transport had a considerable impact on the external safety of the surrounding area, as shown in an analysis according to the Dutch RBM-II method. Also, several companies located in the harbour were less than happy with the current detour. The current tunnel renovation plans allow for a reinstalling of the former category A, but only for a limited amount of time (a couple of years), due to the steady increase of traffic intensity and ADR. Therefore, a study will be launched to obtain a better overview of daily and seasonal fluctuations of the different categories of ADR and also of the general traffic. Based on these results, a new traffic management system will be developed. This new traffic management system could reroute traffic on macroscale (a system of dedicated toll will be introduced in the future in the whole tunnel-system around Antwerp to redirect traffic through the various tunnels) and/or try to avoid that local ADR transport will use the Beveren Tunnel during general peak hours. The possibility to reinstall category A (at least most of the time during the day) is a boundary condition that will get proper care in this study.

2. It will facilitate the decision tree of the tunnel operators and emergency services by offering real-time detection of ADR transport and the nature of its cargo (flammable fluids, flammable gasses, explosion, toxic gasses). The aim is to offer a real-time list of the number of dangerous goods trucks and the nature of their cargo, being blocked in the tunnel in case of an accident and that might be the cause of a subsequent calamity (pool fire, leakage of toxic gasses, explosion, …). This measure will have no impact on the outcome of the risk calculations by QRA-tunnels (because the model conservatively does not take into account the positive effects of the emergency response), but it will assist the decision-makers in the operator room and the arriving emergency services in case of a serious accident by obtaining a better overview of potential hazards and their nature. It will therefore mainly lead to increased safety for the emergency services in a tunnel which has a high amount of HGV and dangerous goods (in case we can reinstall category A).

Technical challenges

To collect real-time data of dangerous goods, present inside a specific tunnel, cameras use image recognition algorithms based on artificial intelligence and machine learning techniques. This results in highly accurate, automated counts, but it also opens up the possibility to monitor the ADR traffic in real time. Machine learning algorithms may take a long time to train properly, but when the training process is completed, applying the algorithm is fast and allows for near real-time applications.

Near real-time detection of ADR transports in tunnels can add an extra layer of security for risk management. Cameras can automatically detect which ADR vehicles are in the tunnel and which dangerous goods they are carrying. This information can be forwarded to the tunnel operators in near real-time. In case of an emergency, the operators can look up which ADR goods are present in the tunnel and take the necessary measures to mitigate the emergency situation, for example by shutting down pump systems or alerting the emergency services about the hazard codes of the goods.

The Agency for Roads and Traffic is currently testing and evaluating a proof of concept (POC) project about real-time registration of ADR transports. The purpose of this project is to gain some practical experience with this system and to evaluate the results:

- How accurately can the orange labels be detected and identified?
- What is the percentage of false positives and false negatives?
- Do external factors (weather, light, ...) have an impact?
- How fast can the algorithm detect ADR goods?
- How can the data be implemented in the current tunnel system?

In the spring/summer of 2021, the Beveren Tunnel was equipped with cameras that can detect and identify ADR transports in near real-time. The tested system consisted of a 12 megapixel front camera at the entrance and exit in the tunnel. One camera can scan four lanes. There is also a line-scan camera to scan the right-hand side of the vehicles that are showing an empty ADR shield at the front. Currently, if the data on both shields are in conflict, the conservative approach is used and the shield at the side of the vehicle is stored in the system, but with a small note that the one on the front is in conflict.

A first evaluation of the results of a testing campaign is listed here:

- 96% of the ADR vehicles was detected (4% false negatives).
- 100% of the GEVI and UN numbers of the detected vehicles was properly identified.
- The amount of false positives is currently in the range of 1-5%.
- The algorithm detects and identifies the ADR goods within a couple of seconds.

- The data is implemented in a dashboard that is currently presented to the operators in a separate system. At any time of day, an overview of the number of dangerous goods vehicles that are present in the tunnel can be consulted. The current dashboard can later be implemented in the existing operator's HMI (human machine interface).

One of the problems that led to false positives is the fact that the small shields used in front of school busses roughly have the same dimensions as the shields used for dangerous goods transport. The system has been recalibrated to avoid these false positives.

When an unforeseen incident/accident happens in the Beveren Tunnel, the operator now gets an immediate overview of dangerous goods trucks that are still within the tunnel (i.e. entered the tunnel and did not yet reach the exit). The pictures of the GEVI and UN codes are also presented, together with the interpretation made by the software. Apart from the number and amount of dangerous goods still being inside the tunnel, also the number of trucks, small vans, busses and passenger cars is determined and can be presented to the operator or emergency services. License plate recognition is used, together with image analysis of the type of vehicle (van, bus , HGV, …), to obtain a real-time overview of all traffic being present in the tunnel. At this moment, this data is used only for the handling of immediate safety issues by operators and emergency services. To prevent issues pertaining to the European GDPR (General Data Protection Regulation), data is not (yet) stored for law enforcement use.

Non-technical challenges

Since the proposed methodology has never been used in Flanders, it might not find enough support with the considerable amount of stakeholders with various interests.

Currently, the construction of many new tunnels is being planned in Flanders. These new (politically more interesting) projects often compete with renovation or upgrading projects for the available financial resources.

The emergency services and tunnel operators need to be properly trained to use the system and to effectively keep using the system when it is most needed (in case things are already getting nasty).

There is a vast infrastructure project (called the 'Oosterweel link') currently under construction that might have a tremendous influence on the intensity and nature of the traffic going through the Beveren Tunnel in the coming years. The R1 (ring of Antwerp), which is currently open on the northern side, will be closed and several new tunnels will be built on the existing and new parts of the R1. This means traffic flows around Antwerp will be redirected several times in the subsequent phases of the construction works. Although traffic flow models were already used to predict the effect of the Oosterweel link on the R2, the effect of subsequent redirecting of the traffic as a function of the different construction phases for the Beveren Tunnel is not yet fully evaluated. During its construction, the Oosterweel project might ask for additional intermediate measures in the Beveren Tunnel, apart from the ones used once the project is finished.

Evaluation
(effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)

The first results of the real-time ADR detection are promising. The reaction time of the system is definitely acceptable (a couple of seconds). The calibration of the system is still being studied: a further increase of false positives is acceptable to prevent false negatives, as long as the ratio does not become too skewed.

Lessons learned and recommendations
[-]
Further information
At this moment local 'tunnel metering' is already installed in the Beveren Tunnel. Tunnel metering is a dynamic traffic management measure that is applied in function of traffic safety. The Roads and Traffic Agency is applying this measure for the first time in the Beveren Tunnel of the R2, the outer ring road around Antwerp. It means that when there is a traffic jam in a tunnel, the number of lanes available is temporarily limited in order to remove the tail of the traffic jam from the tunnel. The traffic jam is then no longer formed in the tunnel, but in front of it, while the traffic can still flow smoothly through the tunnel. The aim of tunnel metering, therefore, is to ensure that the traffic jam does not occur in, but in front of the tunnel and that the traffic passes through the tunnel in a controlled manner. In this way, the road authority wants to improve traffic safety in the tunnel. The system works dynamically and will therefore only be activated when a traffic jam (risk) is detected in a tunnel. The detection is done by means of measuring loops in the road surface. When a traffic jam is detected, the number of lanes available for entering a tunnel is reduced. This is done by 'crossing off' one or more lanes on the dynamic road signs above the motorway. In addition, the speed limit is reduced on the available lanes.
References or interesting web links
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APPENDIX E: CASE STUDY: TO CONTINUE OPERATING AFTER DAMAGES CAUSED BY OVER-HEIGHT TRUCK, FOURVIÈRE TUNNEL, LYON, FRANCE

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	To continue operating after damages caused by over-height truck Fourvière tunnel, Lyon, France
Authors	Michael Potier, Eric Premat
Date of preparation	15/04/2021
Description of the case study	
On 28 September 2017, an oversized truck damaged severely the structure after entering the South tube of the Fourvière twin-tube tunnel, where it became stuck. The ventilation ducts located in the vault were damaged at the northern entrance of the tunnel[17]. Traffic was disrupted in the Lyon conurbation for several weeks. The South tube was initially closed and then reopened rapidly and partially in several degraded operating modes.	
Objectives	
The Fourvière tunnel is a strategic infrastructure for the Lyon urban area. It provides a national and international transit function. It also allows exchanges between the north and south of the conurbation. The objective of this case study is to show how the operator and the project owner were able to reopen the tunnel quickly: first with operating restrictions and then in near-normal mode. There are four operating phases: 1- Operation in mono-tube mode, with only one tube open; the other tube is closed. 2- Operation in twin-tube mode after emergency work 3- Operation in nominal mode as soon as possible 4- Operation in nominal mode with new measures to prevent this type of event from occurring The case study will focus on the specific characteristics of each of these 4 phases.	
Description of each phase and technical challenge of each one	

[17] The tunnel has a North West – South East orientation. Hence, both the tubes as the entrances are refered to with "North" and "South"

0- 28 September 2017 (8.07am): oversize vehicle in the south tube of the tunnel

Figure 1. The vehicle that caused the damage

A special convoy carrying a construction machine entered the tunnel. The construction machine, whose arm had not been folded, scraped the vault of the structure (roof slab) and carried away the boxes and beams housing the smoke extraction duct used in the event of a fire.

1- Operation in mono-tube mode, with only one tube open; the other tube is closed.

There is only one tube open: the north Tube. The south tube is closed. All south-bound traffic must use the diversion routes. This closure causes saturation of the Lyon urban area's main road network.

The damaged tube will be closed for five days in order to analyse the damage to the twenty or so elements (including supports) of the vault that were hit by the truck.

On the theme of resilience:

One of the advantages, in terms of availability, of a twin-tube tunnel is the ability to keep one tube open when an event in the other tube leads to closure of that tube.

Two options are possible:

- Operating the open tube in nominal mode and transferring the traffic from the other tube to another route, which requires an alternative route capable of absorbing the significant additional traffic.
- Operating the open tube in bi-directional mode, which requires an adapted ventilation system and/or additional operating measures (speed reduction, gauge limitation).

For a tunnel that is part of a road network with significant traffic, the twin-tube mode not only offers safe operation in nominal mode (longitudinal ventilation, elimination of head-on collisions, evacuation of users to the safe neighbouring tube in the event of a fire) but also, by its design, the tunnel is resilient in its operation when an event occurs in one of the two tubes.

2- Operation in twin-tube mode after emergency work

From 28 September 2017 to 04 October 2017, installation in the South tube of:

- shores and reinforcement beams
- reinforced concrete barrier for protection
- vertical signs (signs next to or above the road)
- horizontal signs (signs on the road surface)
- the physical gauge at the tunnel entrance

- the device, under the supervision of 2 agents at the tunnel portals

The tunnel is opened the 04 October (05.00 pm) with operating restrictions:

Prohibition to vehicles with a Gauge > 3.5 meters or a weight of > 3.5 tonnes

Reduction of the Speed limit : 50 km/h (normally 70 km/h)

Figure 2. Arrival of the reinforced concrete barriers to protect the shoring

This prohibition requires the mobilisation of the police to control vehicles that do not respect the prohibition and arrive at the head of the tunnel. These vehicles have to be evacuated via a road ramp not designed for this type of traffic. Approximately 100 vehicles must be evacuated each day. This situation generates traffic jams on the local network. This operating situation is not sustainable for the operator.

Technical challenge:

Additional sounding tests are necessary to check the quality and resistance of the materials and reinforcement of the vault. At the same time, shoring and metal beams are being installed to stabilise the vault.

Check the capabilities of the smoke extraction system with regard to :

- the degree to which the ventilation equipment is still available
- the traffic that will be allowed in the downgraded mode (light vehicles only)

Figure 3. Shoring and metal beams to stabilize the vault

On the theme of resilience:

Reopening the tunnel very quickly for “light” vehicles only is conditional for:

1. Carrying out emergency and safety work

The project owner must have at his disposal at any time the file relating to the actual technical condition of the structure, the associated plans and the results of the civil engineering inspections. The execution of emergency and safety works requires the support of specialised design offices that are familiar with the specific characteristics of the structure. Having a purchase order contract also simplifies administrative procedures and saves time. Similarly, the project owner must have a list of companies specialised in emergency and safety works and capable of intervening very quickly.

2. Implementation of specific operating and support measures

The operator must set up specific signs to direct unauthorised vehicles to alternative routes. Coordination with other road operators is essential, in particular the implementation of diversion routes well in advance of the tunnel in order to avoid congestion on the secondary road network near the structure.

To do this, it is necessary to have defined a traffic management plan in advance:

A traffic management plan is drawn up to deal with road traffic disruptions requiring coordinated action by those involved in road operations (authorities, coordination and information services, operators, law enforcement agencies) on a given route or network.

3- <u>Operating in nominal mode as soon as possible.</u>

From 04 october 2017 to 14 october 2017 :

Exceptional work is being carried out at night in order to reopen the tunnel to all vehicles. This work consists of :

- rerouting the cables running in the stale air duct
- removing the lighting in the affected area
- demolishing the slab in the affected area and removing the spoil
- modifying the ventilation duct ensuring the smoke extraction of the structure by building a partition of the stale air duct
- remove the device installed in phase 2 (shores and reinforcement beams; reinforced concrete barrier for protection; vertical signs)

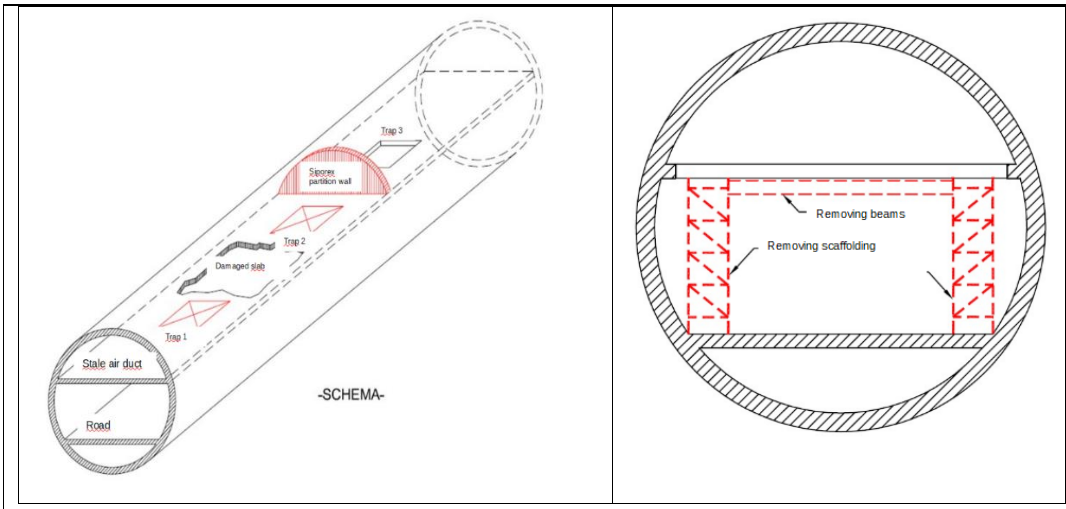


Figure 4. Modifications of the ventilation duct, indicated in red (left) and the schematic depiction of the stabilizing shoring and metal beams, also indicated in red (right)

Technical challenge:

Part of the ventilation duct has been removed (200 m at the northern entrance of the affected tube). Ventilation studies are necessary in order to verify that the smoke extraction system is still effective despite the removal of several extraction traps and the consignment of a ventilation plant. The CETU's ventilation division was asked to provide this expertise.

In order to guarantee good smoke extraction, the scenarios are modified:

opening of an additional trap door in compensation and increased control of the air flow.

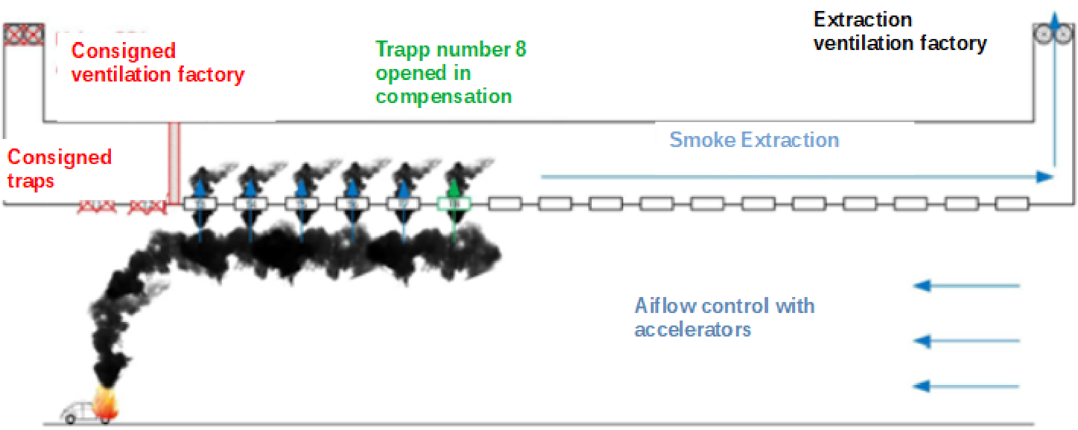


Figure 5. Principle of the smoke attraction after the modifications shown in figure 4

On the theme of resilience:

The Fourvière tunnel has two ventilation plants at each head, each equipped with 2 fans when only one is needed. Initially, the smoke extraction shaft was split in two. The partition has been removed in the past, so in nominal mode, the smoke is drawn in at both ends and the pressure drops are much lower. There is therefore a lot of margin on the operation of the ventilation in nominal mode.

In degraded mode (with one of the two factories unusable), the smoke extraction capacity remains very good, despite the reduction in size required for the civil engineering work, and remains redundant with two fans.

In a tunnel designed from the outset to be smoke-free from each head, which would be the case if it were built today, this type of event and the associated consequences would reduce the smoke removal capacity more significantly. Perhaps, the smoke extraction would become limiting for the remaining traffic allowed. Finally, the fans would certainly not be redundant with the risk of having to close the tunnel as soon as a fan is out of order.

For a tunnel structuring a road network with a very high traffic volume, the resilience of the system is partly based on the performance of the safety systems, including smoke control. In the case of the Fourvière tunnel, it was above 100% with major equipment redundancy so as to keep the infrastructure open at least for the transit of light vehicles.

The October 14th, the south tube is opened in nominal mode.

4- **Operating in nominal mode with new measures to prevent this type of event from occurring (and closing the night during the restoration of the structure)**

Phase 4-1: reconstruction of the damaged roof slab: work to be carried out during night and weekday closures.

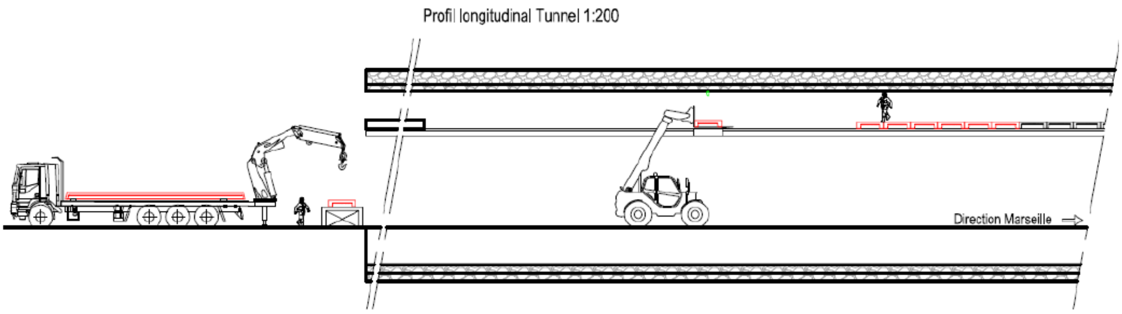


Figure 6. Laying prefabricated slabs of the exhaust air duct

Technical challenge:

The solutions for repairing the slab elements are relatively complex. They require several weeks of preparation and 3 to 5 weeks of night-time work, which entails closing the tunnel tube and implementing diversionary routes. The planning of the work must be very precise since the work can only be carried out at night with a maximum of one full weekend of closure.

One night's work corresponds to a closure from 10 p.m. to 5 a.m., i.e. an effective working time of around 5 hours per night. 4 nights of closure break are planned per week.

A working weekend corresponds to a closure from Friday at 10.30 p.m. to Monday at 5 a.m., i.e. 54.5 hours of closure time, which corresponds to 52.5 hours of actual work.

Phase 4-2 : modify the height of the current physical gauge at the entrance of the tunnel tube when it is reopened to heavy goods vehicles

Technical challenge: Installation of oversize detection equipment before the tunnel

Since 8 February 2019, the Lyon metropolitan authority has installed several sensors 300 metres from each entrance to the Fourvière tunnel. This height-detection system is capable of detecting vehicles that are over 4.30 metres high and are not allowed to pass through the tunnel.

As soon as an over-height truck is detected by the sensors, the barriers are automatically lowered at the tunnel entrance in the direction concerned (after the traffic has been warned through a variable message sign). The police can then take charge of the driver of the oversized truck. Once the area is secured, the barriers are raised and traffic can continue.

On the theme of resilience:

In order to avoid a recurrence of such an event, it is necessary to implement out-of-gauge detection equipment with automatic tunnel closure. In order to avoid too many closures, it is essential to communicate with local and regional road hauliers about the limitations in force on the road network. It is also necessary to reinforce the vertical road signs upstream of the tunnel well before the last point of choice of route. It should be noted that the management of oversize vehicles in road tunnels is the subject of a PIARC working group. It seems essential to share the feedback and the characteristic elements of the measures implemented within the tunnel community.

Non-technical challenges

- Management of traffic flows within the conurbation: setting up major diversion routes to avoid suffocating the Lyon road network.
- Communication on the new prohibition measures to users, particularly road haulage companies

Evaluation

(effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)

- Evaluate the performance of new detection systems.
- Evaluate the impact of implementing automatic closures in case of oversize.

Lessons learned and recommendations

- In terms of availability, a twin-tube tunnel permits to have one tube open when an event occurs in the other tube and generates its closure.
- The execution of emergency and safety works requires the support of specialised design offices that are familiar with the specific characteristics of the structure. Having a purchase contract for these works helps to shorten the recovery time.
- In case of event, It is necessary to have defined a traffic management plan in advance
- The resilience of the system tunnel is partly based on the performance of the safety systems, including smoke control;
- After the event, it is essential to share the feedback and the characteristic elements of the measures implemented within the tunnel community.

Further information

See webpage link below.

References or interesting web links

https://www.lyon.fr/actualite/deplacements/les-camions-hors-gabarit-sous-etroite-surveillance-en-amont-du-tunnel-sous

APPENDIX F: CASE STUDY: IMPLEMENTATION OF PHOTOVOLTAIC PANELS, L2 RING ROAD CROSSING THE CITY OF MARSEILLE, FRANCE

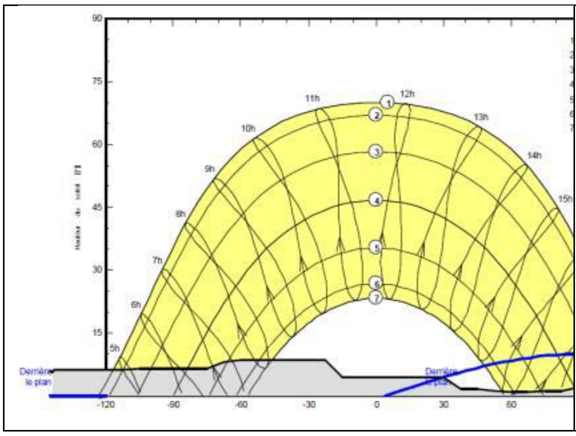
Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Implementation of photovoltaic panels L2 ring road crossing the city of Marseille
Authors	Gilles RAKOCZY, Olivier CRAGUE
Date of preparation	15/09/2021
Description of the case study	
The L2 ring road is a 12 km urban ring road crossing the city of Marseille, mainly in cut-and-cover tunnels. The main challenges of the infrastructure concern safety, availability and the environment (pollution, noise, energy). In this context, the company (SRL2) in charge of the maintenance is considering the implementation of photovoltaic panels on part of the derelict places in order to ensure greater availability of the infrastructure by self-powering part of the infrastructure and to limit the carbon footprint.	
Objectives	
This action contributes to the resilience of the infrastructure by promoting its social acceptability in an urban area, limiting energy consumption and improving its availability. The SRL2 company wishes to use on-site photovoltaic energy in its overall energy sourcing to: ➢ Enhance the value of unused land ➢ Secure the availability of the infrastructure through energy self-sufficiency ➢ Secure a fixed price in a context of high volatility of energy costs to the benefit of the State ➢ Contribute to its corporate social responsibility (CSR) objectives	
Technical challenges	
Integrate new equipment into the electrical architecture Integrate a new energy source without weakening the installation and maintaining 100% availability Robustness of the Equipment	
Non-technical challenges	
• Free up the land • Convince the customer • Guarantee the security of the installation (camera, fence to be raised)	

Evaluation

(effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)

Verify the performance of the system: 31% of the energy of the PEFT* concerned by the connection and 7% of the overall consumption of the rocade L2 (out of 5 GWh)

**PEFT: Poste Electrique Forte Tension (High Voltage Substation)*



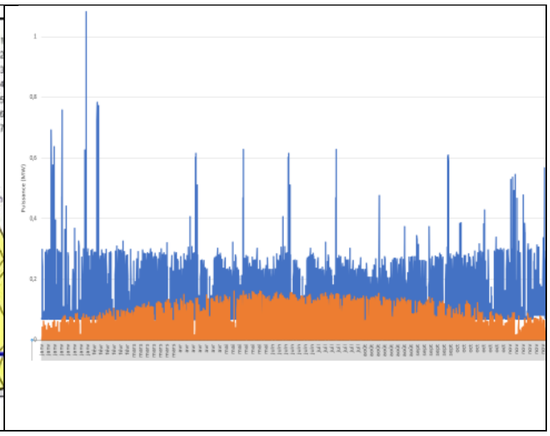


Figure 1. Sunlight profile *Figure 2. Annual load curve*

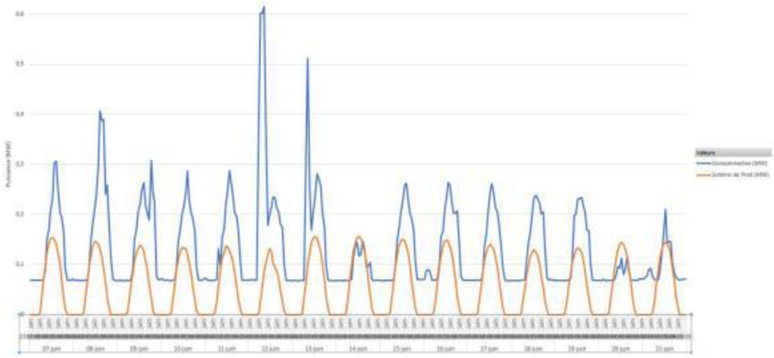


Figure 3. June load curve

Figure 4. Impression of the installed panels - (view from above)

Lessons learned and recommendations

- Search for additional land for optimal coverage of tunnel needs
- Implementation of electric charging points for operational staff.

Further information
Need to accompany the implementation of the system with an information plan for partners and users: ➢ Display consumption in real time ➢ Video communication ➢ Time lapse of work
References or interesting web links
http://www.cvegroup.com

APPENDIX G: CASE STUDY: RITUN – RESILIENT ROAD TUNNELS, GERMANY

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	RITUN – Resilient Road Tunnels
Author(s)	Bernhard Kohl, Bernhard Klampfer
Date of preparation	March 15th 2021

Description of the case study

The research project RITUN, funded by the German Federal Ministry of Education and Research (BMBF) as part of the “Research for Civil Security 2012 to 2017” framework programme, provides methods to increase the availability of road tunnels while complying with the minimum requirements of tunnel safety as a mandatory constraint.

Objectives

As a result of high expectations in terms of availability in conjunction with extreme events, climate change and increasing traffic operators and owners of road transport infrastructure are faced ever-growing and even new challenges. Since tunnels have a direct influence on the availability of whole road networks, they represent particularly critical elements. The research project RITUN therefore aims to improve the resilience of road tunnels to both familiar and emerging threats.

For this purpose the first step is an extensive hazard analysis by means of the all-hazard approach in order to identify a broad spectrum of relevant threats relating to road tunnels. They are grouped into natural and intentional/unintentional man-made hazards. Further, the identified threats may lead to various damage scenarios on the components of road tunnels. In this context their respective point of impact was distinguished between tunnel structure, tunnel equipment, road segment and centralized tunnel systems. As a solid basis of the methodology and to facilitate the applicability to a broad range of existing tunnels, an extensive statistical analysis of road tunnels in the German federal road network and their characteristics was performed.

In order to maintain the availability fully or partially and to ensure a safe operation despite damages occurred minimum operating requirements including temporary compensation measures have to be elaborated. Since restricted traffic could be the consequence, the effects on traffic are analysed on local as well as on regional level. With the superior goal of increasing the availability adequate resilience measures are identified, developed and assessed.

Technical challenges

Currently road tunnels in Germany and most parts of the world are designed and operated in strict accordance with applicable regulations and guidelines. However, in a large part the required facilities, actions and processes are targeted on preventing incidents as well as protecting the tunnel and its users in case of an event. In contrast, few guidelines provide ways how to react appropriately and to recover the availability of a road tunnel in the aftermath of an event.

Here a vital element of the RITUN methodology comes into play, the so called *Minimum Operating Requirements*. They define conditions, including temporary measures, under which a tunnel can still be operated - maybe in a degraded mode - at a tolerable safety level after an event. The methodology pursues a risk- and a measure-oriented approach. One of the challenges in their development is the clear definition of an acceptable level of safety. Basically, tunnels equipped according to national guidelines are considered as safe, the resulting risk is publically accepted and specifies the minimum safety level in normal operation (Figure1). With regard to a time-limited operation after an event a certain tolerance range is discussed – representing a kind of trade-off of contradicting safety and availability requirements

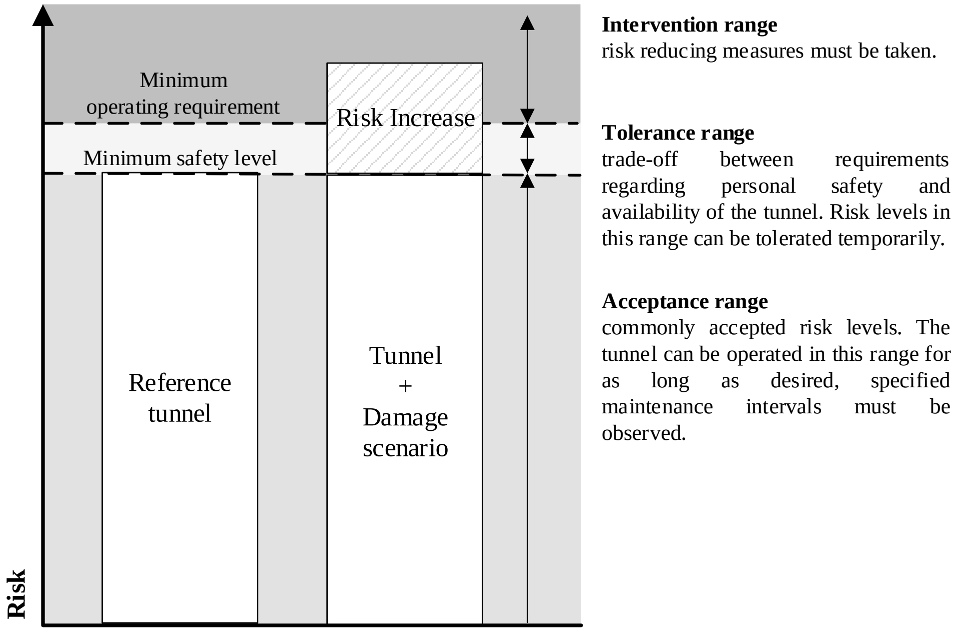


Figure 1: Thresholds of minimum safety level and minimum operating requirement

This concept takes into account that not all effects of damages caused by a disruptive event are safety relevant or influence safety in a significant manner. Further in this context it has to be acknowledged that there are limits with respect to a quantification of the related safety-relevant effects as well as the effects of measures. The following framework provides a concept to assess the effects of damage scenarios on tunnel operation based on tunnel safety as a mandatory constraint. For this purpose qualitative and quantitative risk analysis are performed following a certain procedure to evaluate whether specified risk criteria are met, possibly with the aid of additional compensation measures, which might result in traffic restrictions as a final step.

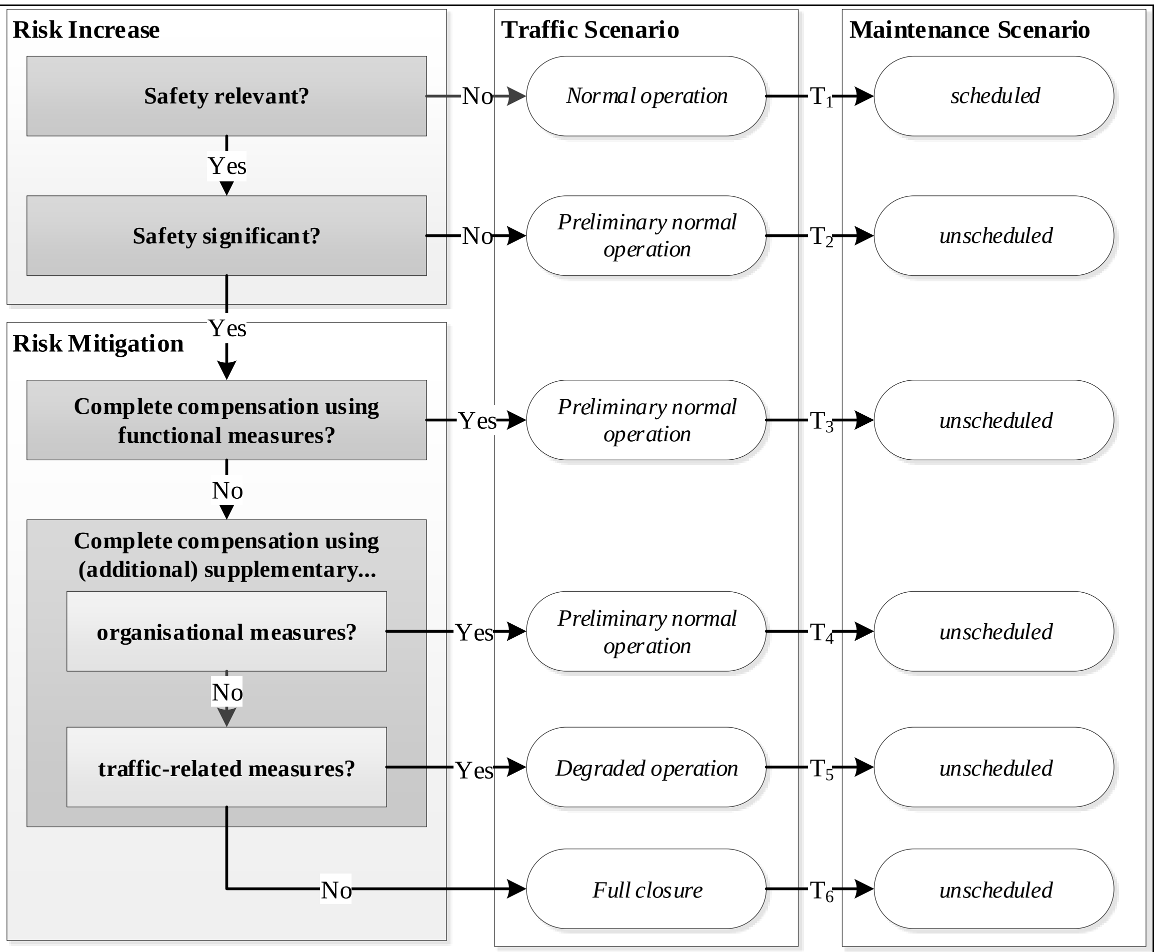


Figure 2: Framework for the development of minimum operating requirements

Risk mitigation measures after an incident aim to ensure a tolerable level of safety in order to allow the operation of the tunnel. Organizational and traffic-related measures can be combined, including for example:

- Speed limit
- Consistent control of the average speed
- Truck driving ban
- Driving ban for dangerous goods transport
- Fire brigade stand-by
- Ongoing control runs

Non-technical challenges

[-]

Evaluation
(effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)

One of the project outputs is a comprehensive list of potential resilience measures. In order to support the selection of appropriate measures according to tunnel-specific requirements, a simple and practical assessment of resilience measures was elaborated. Of course this general assessment is only preliminary and requires a careful and detailed review in any individual case.

The applied methodology is based upon a traffic light system considering various parameters regarding essential aspects of road tunnel resilience:

Availability		Interdependencies				Existing Tunnels			New Tunnels		
Prevention	Mitigation	Safety	Object	Tunnel	Threat	Feasibility	Costs	**recommended**	Feasibility	Costs	**recommende**
🟢🟡🔴	🟢🟡🔴	🟢🟡🔴	Y / N	Y / N	Y / N	🟢🟡🔴	🟢🟡🔴	**Y / N**	🟢🟡🔴	🟢🟡🔴	**Y / N**

Legend / Explanation:

🟢 positive / no problems

🟡 neutral or mildly positive / some points of attention

🔴 negative / problematic

- Availability
  As the main objective is to increase the availability of road tunnels this parameter is assessed considering effects of prevention as well as mitigation.
- Interdependencies
  - Safety: Measures increasing the availability may affect safety too, not only in a positive, but also a negative way.
  - Object: Improving the conditions in a tunnel may have positive effects on the surrounding road network or other objects (e.g. bridges) too.
  - Tunnel: Improving the conditions in a tunnel may have positive effects on other tunnels too.
  - Threat: A measure can show its effect to one specific threat only or act independently of threats.
- Feasibility
  Depending on the complexity of implementation the assessment of the feasibility reflects the required effort to implement a measure, differentiating between existing and new tunnels.
- Costs
  Completely independent of its effect this parameter gives an idea of the dimension of expected costs.

Note that the aim of the traffic light colours is rather to provide a quick overview of the effects on various aspects than to define a detailed acceptance criterion for the measures.

Lessons learned and recommendations

Discussions with various tunnel operators showed that in particular measures to maintain or increase a defined traffic flow immediately after an incident, but also during the repair work are missing and provide additional value in order to increase the availability and resilience respectively. The methodology to define minimum operating requirements including temporary compensation measures with a risk-based approach therefore meets the existing requirements.

Further information

Putting the developed approach into practice and to verify the applicability of results the methodology was tested by analysing two existing road tunnels in Bavaria, Tunnel Pfaffenstein and Bayreuth.

References or interesting web links

The webpage www.bast.de/ritun provides all relevant outputs relating to the research project, including a handbook, guidelines and tools in order to put the methods into practice as well as the detailed working package reports.

APPENDIX H: CASE STUDY: REHABILITATION OF THE A81 ENGELBERG TUNNEL, GERMANY

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Case study: Rehabilitation of the A 81 Engelberg Tunnel, Germany
Author(s)	Jens König
Date of preparation	October 12, 2021

Objective

The rehabilitation of heavily frequented motorway tunnels represents a special challenge. The planning and implementation of the measure must be guided by the requirement to keep traffic restrictions as low as possible.

Description of the case study

The Engelberg Tunnel is located on the motorway A 81 west of Stuttgart near Leonberg and was opened to traffic in 1998/99. The A 81 links to the motorway A 8 at the Leonberg interchange. The two motorways form a bypass around the Stuttgart metropolitan area and accommodates through traffic and destination traffic from and to Stuttgart and the surrounding area. The tunnel is located in the immediate vicinity of the Leonberg interchange and is therefore of central importance for the east-west and north-south connection in southern Germany.

The two tubes of the uni-directional traffic tunnel each have 3 lanes and a hard shoulder. The tunnel has a length of 2,520 metres and is used by 110,000 vehicles per day with a heavy traffic share of 17%.

The ground is geologically challenging and contains the swellable mineral anhydrite. Water percolating into the mountain transforms the anhydrite into gypsum, which presses on both tunnel tubes over a length of approx. 180 metres. Over the years, it became apparent that the reinforced concrete and the previous refurbishment measures were not sufficient to withstand the pressure of the swelling rock in the long term. Cracks and deformations of the tunnel wall were again detected, which is why the tunnel section in question must be fundamentally rehabilitated to ensure long-term availability.

With the main construction measure starting in 2019, a comprehensive structural and operational upgrade of the Engelberg Tunnel will take place, which is to be completed by 2025. The inner tunnel shells will be upgraded over a length of approx. 180 metres and other typical age-related damage in the tunnel will be repaired. In addition, the complete safety and operating technology will be renewed over the entire length of both tunnel tubes, which will then also meet the current safety standard of the regulations.

The structural rehabilitation and the operational modernisation will be carried out together. This minimises the number and duration of traffic interventions compared to a separate execution.

The work and the structural changes also require ventilation conversions and adjustments to the ventilation control. For the overall measure, it is helpful that the semi-transverse ventilation of the driving area can be omitted. The current supply air duct under the carriageway will then become a service duct for cables and the relocated extinguishing water pipe. Furthermore, the ventilation concept and the ventilation control will be adapted to the current guidelines.

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

Preparatory measures

In advance, measures have been implemented since 2016 to improve the escape and rescue situation and to ensure construction freedom and traffic routing. A shaft with a depth of 20 m for material transport was constructed in the north operations building between the two tunnel tubes, which incorporates a staircase, a crane and an elevator. This will allow the conversion and renovation works to be accelerated.

The concrete support floor of the carriageway was reinforced with 50 cm (see figure 1) in the 180 m long reconstruction area and adjacent longitudinal sections in order to be able to absorb the forces of the swelling rock, acting laterally on the tunnel´s inner linings. The work was mainly carried out under the carriageway, so that the tunnel could remain under traffic almost without restrictions.

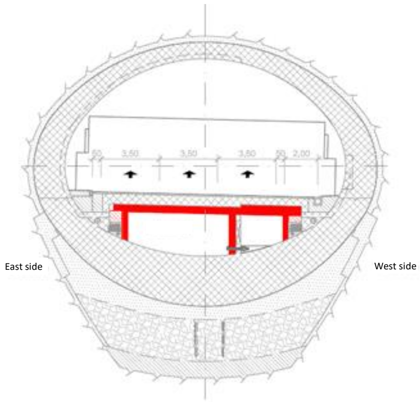


Figure 1: Roadway reinforcement in a tube [2]

The two central reservation crossings at the north and south portals were rebuilt to make it easier to swivel traffic. New tunnel traffic technology, including new traffic sign gantries, was installed and linked to new and existing route control systems on the A 8 and A 81. This makes it possible to react faster and better to different traffic situations.

In addition, a system for displaying the travel time on the A8 and A81 motorways and a federal highway was put into operation. This system provides road users with up-to-date and accurate information on the existing traffic situation with the aim of keeping traffic on the motorway, thus relieving surrounding communities from nuisance.

These traffic measures are intended to reduce the construction time and enable optimal traffic management during the construction period.

Rehabilitation of the tunnel´s inner lining

The large-area mining cross-section profile allows the installation of a steel skeleton embedded in concrete consisting of intermediate ceiling and wall reinforcements without falling below the minimum dimensions of the driving space. Concrete is used either as a prefabricated element or as in-situ concrete.

Traffic will continue to have a maximum of three lanes per direction, which can be realised with the help of swings, reduced lane widths without hard shoulders and the associated reduced speeds. No diversions into the subordinate road network are necessary.

In the rehabilitation tube, two lanes are used in one direction. The third lane and a peripheral area are permanently reserved for the construction site. The adjacent tube is operated in two-way traffic with four lanes, three of which serve the other direction. Temporary adaptation

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

lighting for two-way traffic is installed in the area of the exit portals. During low-traffic periods at weekends and at night, the rehabilitation tube can be completely closed to traffic.

Figure 2 below shows the sequence for the work in the west tube and the available lanes:

- Construction phase I: Reinforcement of wall area 1
- Construction phase II: Reinforcement of wall area 2
- Construction phase III: Insertion of the false ceiling

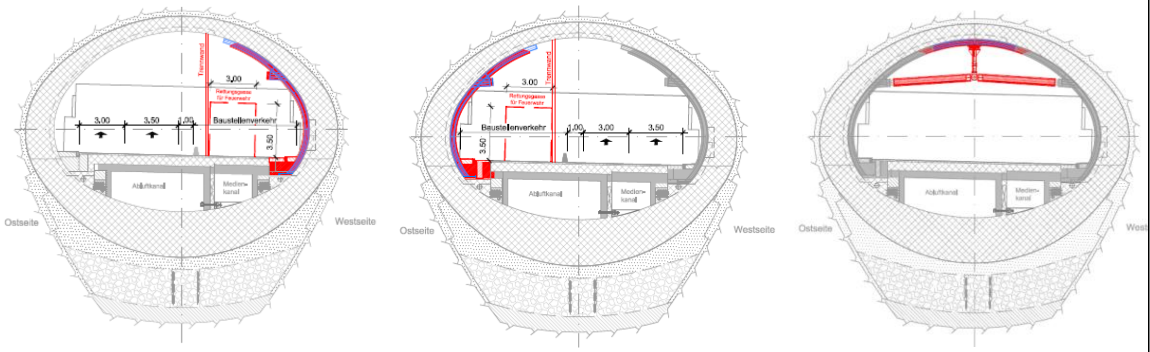


Figure 2: Construction phase I to III West tube [2]

The reconstruction area is enclosed and separately ventilated. Work will be carried out in this area 24 hours a day. Outside the reconstruction area, repair and operational work will take place as long as traffic and construction site safety are not impaired. In the complete construction site area, there is a continuous delivery lane along the length of the tunnel, which is used as an emergency lane if necessary.

The lane occupancy in the east tube during the rehabilitation of the west tube is shown in Figure 3.

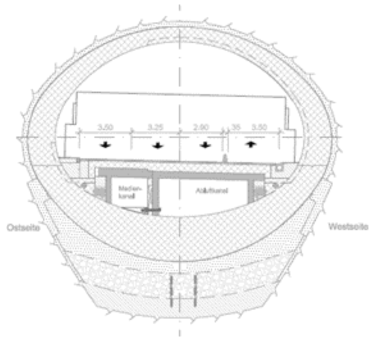


Figure 3: Traffic routing in the east tunnel during construction phases I to III [2]

The rehabilitation of the east tube is carried out in mirror image in construction phases IV to VI.

Technical challenges

A particular challenge is the strengthening of the tunnel lining in an area of swelling rock. Figure 4 below shows the design of the structure, which is intended to prevent deformation and failure of the tunnel lining in the affected area in the long term.

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

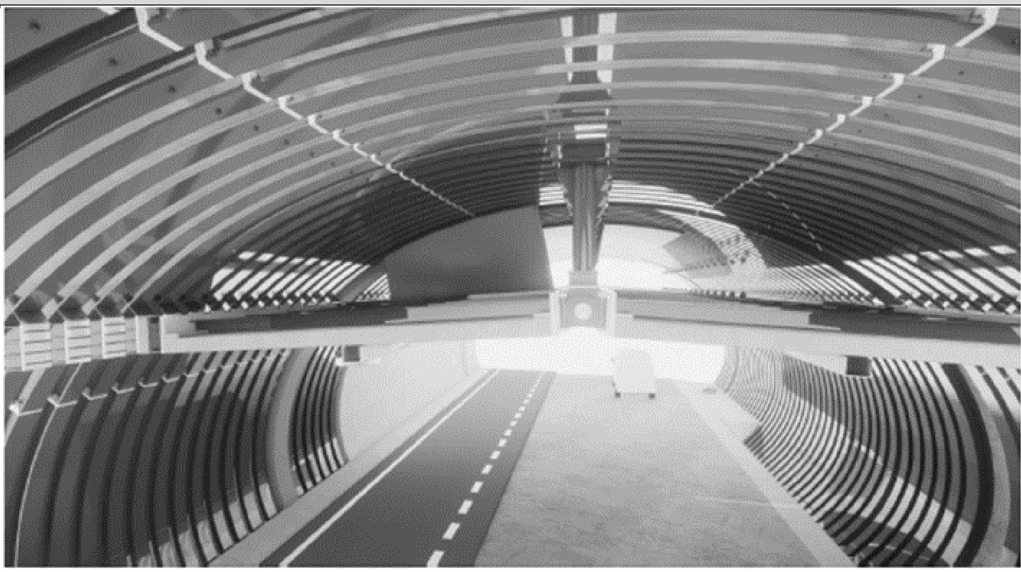


Figure 4: Steel construction skeleton for stabilising the tunnel inner shell [2]

The lateral steel girders set in concrete for reinforcing the tunnel walls also serve as a connection for the support of the intermediate ceiling. The intermediate ceiling consists of adjustable segments to absorb a horizontal load and to reduce deformations in the upper vault area of the tunnel. When the force effect gets too high, the intermediate ceiling is to be relieved. For this purpose, the intermediate ceiling elements were designed as a 3-joint construction. When the limit force is exceeded, the pressure support is shortened and the intermediate ceiling is relieved. The mobility of the suspended ceiling elements is ensured by linear tilting bearings and a central joint. [2]

Another special challenge is the conversion of the ventilation system. The Engelberg Tunnel is equipped with a smoke extraction system that is realised via stub ducts at intervals of approx. 20 m. The ducts lead into an exhaust duct under the carriageway. The smoke extraction openings previously located in the tunnel ridge must be connected to the new smoke extraction dampers in the intermediate ceiling via height-adjustable plenum boxes. Figure 5 below shows the situation schematically on the left.

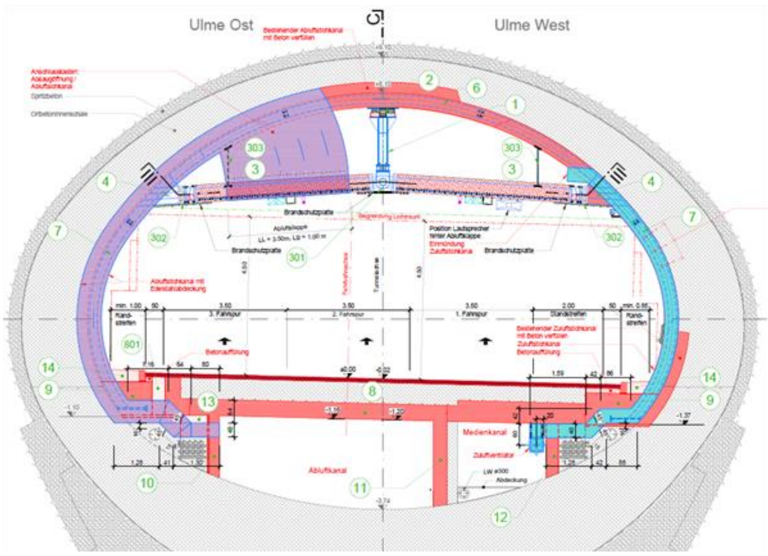


Figure 5: Cross-section smoke extraction and fresh air supply intermediate ceiling [2]

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The two ends of the intermediate ceiling are closed. The fresh air supply of the media duct is used to minimise the risk of corrosion for the exposed steel components around the joints and supports of the intermediate ceiling. For this purpose, air is conveyed into the space above the false ceiling via a stub duct with a separate fan, schematically shown on the right-hand side in Figure 5.

The other smoke extraction dampers outside the refurbishment area are to be replaced and installed in the extract air duct, see Figure 6. Due to changing installation situations, each of the 185 dampers to be constructed must be assessed regarding the free cross-sections and fastening options.

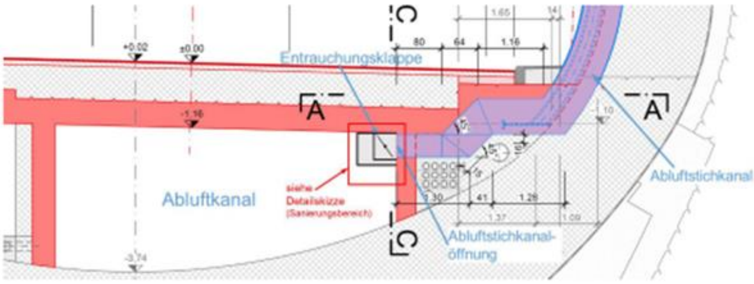

Figure 6: Installation situation smoke extraction damper in the exhaust air duct [2]

With the completion of each construction phase, the integration of new equipment groups is planned and changes are to be made to the tunnel control system. To accelerate the re-commissioning and at the same time achieve a safety gain through a larger number of test scenarios, the new tunnel control is largely pre-tested via simulation software.

In addition, safety-relevant switching sequences of the event-effect matrix are tested by the tunnel investigation body as an independent testing authority.

Non-technical challenges

The effort required to coordinate a large scale rehabilitation such as this is very high. For example, documents relating to safety issues must be prepared and interlinked. These include a safety concept for tunnel users during the construction period, the general health and safety concept for personnel, the fire protection concept, the tunnel's alarm and hazard prevention plan for the construction phase and the further contractor's documents based on these.

The cross passages between the tubes are generally available to tunnel users and construction site personnel as emergency exits during all construction phases. Only in very limited periods of time can an individual cross passage be exceptionally closed due to the construction process. The protective walls installed to separate the construction site area and the directions of travel are equipped with easy-to-operate manual opening elements at the level of the cross-passages. Tunnel users can cross the construction site area on marked paths. The entire marking of the escape and rescue routes will be adapted during the construction phase.

The event detection and automatic switching sequencies for the tunnel, except for the enclosed reconstruction area, remain in place and are adapted in detail depending on the construction phase.

The site personnel in the reconstruction area will be alerted to alarms from other areas of the tunnel via temporarily installed optical acoustic units. Fire alarms from the fire alarm control centres are automatically forwarded to the optical acoustic alarm system.

Case Study PIARC TC 4.4 WG2 on Safety and Resilience
The complete site personnel are also alerted via personal emergency call devices, with automatic fire alarms from the tunnel being switched directly to these devices. The reconstruction area does not have its own automatic fire alarm systems. Therefore, the site personnel can also send alarms themselves via the emergency call devices, which are connected to the construction site gate. The gate initiates further measures such as closing the tunnel and alerting the emergency services. The site gate also has the option of manually triggering alarms on the personal emergency devices and activating the temporary additional visual and acoustic alarm units. The site gate acts as a communication interface construction site – traffic area tunnel, 24 hours a day during the entire construction period and is in contact with the site, the emergency services, the tunnel operation and the tunnel control centre. Furthermore, the concerns of the population affected by the construction works must be considered. Originally, it was planned to close one tube completely to traffic. After protests from the surrounding communities, the concept was changed. A former mayor of Leonberg had compared the project to "open-heart surgery". Blocking a major artery around Stuttgart could easily have led to a “traffic infarct”. Therefore, a complete enclosure was planned for the rehabilitation area, so that work in the rehabilitation area can also take place under traffic. Three lanes are still available in each direction.
Evaluation, Lessons learned and recommendations
The main construction project has only just begun this year. Nevertheless, some experiences can already be derived: It has proven successful that, in addition to the factory inspections, construction site inspections are also carried out as part of the quality control. Innovative processes and techniques accelerate the construction process. Here are to be mentioned: • The rehabilitation procedure developed here is special, but transferable to similar cases in terms of construction and the associated assembly technology. • The use of a tunnel simulator (simulation tool) proved to be useful to accelerate complex automation-related commissioning in tunnels and subsequently to increase user safety. • The linked traffic engineering systems lead to a smoother traffic flow. A ThermoScan system was installed to minimise the risk of fire especially from hazardous good transports in the tunnel and to enable the tunnel to be operated in compliance with the guidelines during the refurbishment work. The involvement of the population has led to the successful optimisation of the planned measure in terms of construction progress and traffic flow. During the construction measures, the acceptance of the population can be maintained by appropriate traffic control technology and information.
Further information
See hyperlinks below.
References or interesting web links

Case Study PIARC TC 4.4 WG2 on Safety and Resilience
[1] https://rp.baden-wuerttemberg.de/rps/pr/pressemitteilungen/engelbergtunnel [2] Regierungspräsidium Stuttgart, A81 Engelbergtunnel, Baubeschreibung (project description) and related documents, 2019 [3] Leonberger Kreiszeitung, U. Otto, Engelbergtunnel, 3.1.2019

APPENDIX I: CASE STUDY: CONCEPT OF MEASURES AND DESIGN METHODOLOGY FOR RECOVERY FROM EARTHQUAKE DAMAGE TO A MOUNTAIN TUNNEL IN JAPAN

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Concept of measures and design methodology for recovery from earthquake damage to a mountain tunnel in Japan
Author(s)	Nobuharu ISAGO and Atsushi KUSAKA
Date of preparation	2021.8.31

Description of the case study

At 21:26 on April 14, 2016, there was an earthquake with a magnitude of 6.5 on the Richter scale at a depth of about 10km in the Kumamoto Prefecture, on the island of Kyushu, Japan. About 28 hours later, at 1:25 on April 16, there was an earthquake with a magnitude of 7.3, again at a depth of about 10km. In the municipalities where the maximum seismic intensity was measured (6- or higher on the Japanese seismic intensity scale where 7 is the maximum) there were 234 road tunnels with a total length of about 84 km. At the Tawarayama tunnel (2,057m in length), while no fatal collapse such as blockage of the tunnel space itself was observed, collapse of the lining, surging of the road surface, shear cracking over the permanent lining, etc. occurred in many sections.

The most severe damage cases are shown below.

Around 1,650m from the west-side portal, the half cross section (1/2 to 1/3) of a concrete-cast unit of the permanent lining (hereinafter referred to as 'span') collapsed. Photo 1 shows the situation. In this section, we encountered fragile Andesite rock at the original tunnel construction, and it was necessary to change the temporary support structure of the original design during excavation work. In addition, a weak layer that seemed to be a fault was confirmed. Silt-like cohesive soil occupies the edges, making it moist and prone to loosening.

Photo 1 Damage situation 1,650m from the west-side portal.

Photo 2 Damage situation in 115m from the west-side portal.

Photo 3 Damage situation 40m from the west-side portal.

In the vicinity of 115m from the west-side portal, as shown in Photo 2, compressive fracture with a width of 1m occurred over the entire circumference of the tunnel section, the lining collapsed and an uplift of road surface occurred. Furthermore, in the vicinity of 40m, cracks occurred in the diagonal direction of the lining as shown in Photo 3. Periodic (visual) inspection was carried out in this tunnel in 2012, but almost no deformation was observed then. We also compared the inspection results before and after the earthquake for the spans where bending compressive fracture and cracks occurred due to the influence of the earthquake. As a result, there were some spans where water leakage and cracks in the longitudinal direction up to a width of about 0.5mm could be confirmed. However, there were not many places where the deformation occurred as a whole. Leakage and longitudinal cracks are common deformations in tunnels. Similar deformations were seen in spans that were not significantly deformed by the earthquake. Therefore, it was confirmed that the relationship between the deformation before and after the earthquake could not be confirmed. With reference to the damage situation of the Tawarayama tunnel that caused such great damage, the restoration method was discussed at the local branch of national government. In addition, the central government and its affiliated research organizations such as the Public Works Research Institute examined the concept of the measures to control damage caused by earthquakes in road tunnels.
Objectives
In the past, when a relatively large-scale earthquake occurred in Japan, although the frequency was not so high, road tunnels were damaged to a degree that they had to be closed for traffic. However, it was generally thought that mountain tunnels were strong and resilient against earthquakes and the technical standards by the national government only showed a qualitative concept. And once a tunnel was damaged, road administrators such as local governments, etc. investigated the damage situation and decided the restoration method by themselves. Based on the analysis and knowledge of cases of earthquake damage in road tunnels in mountainous areas, including this tunnel, the purpose of the study is to show the development of damage control measures for road tunnels by the central government and related organizations.
Technical challenges
The Tawarayama tunnel was inspected after the earthquake to make a judgment (evaluation) regarding the structural health of the tunnel. The soundness index of each span dictated as a part of a concrete-cast unit of the permanent lining was determined. As a result, out of 209 spans, the section classified as index I (meaning a good structural health according to Japanese law) consisted of 54 spans; 66 spans were classified as Index II, 31 spans were classified as Index III and 58 spans were classified as Index IV, which means that these spans required urgent measures. In this tunnel, the repair and reinforcement design was aimed at taking measures for the spans with soundness index II to IV. As part of the design, the concept for selecting the repair / reinforcement method was described, taking into account that the tunnel where the deformation occurred is in service. However, there were no criteria to assess the external forces caused by earthquakes; neither were there guidelines or standards for reconstructing the lining and invert.

In this restoration work, no major deformation was observed after the seismic activity had converged. Therefore, based on the survey results, the local technical council, which was organized by the central government, discussed the basic policy while referring to the past knowledge and restoration work for tunnels damaged by volcanic activity. Based on the results, we decided the details in a way that suits the site and proceeded with the examination.

This time, the places where the concrete lining fell on a large scale were all sections without reinforcing bars ("rebars") in permanent lining. For example, the damage shown in Photo 3 was in the section where the rebars were placed because of various mechanical uncertainties in the portal area, and despite the fact that it was thought to have been subjected to a large earthquake motion, no large-scale fall of concrete lining was observed. Therefore, in order to prevent the concrete lining from dropping on a large scale, even when deformation occurs in the event of a similar earthquake in the future, it was decided to place reinforcing bars in the cross section where (parts of) the lining had fallen.

Photo 4 Damage situation of the temporary support, 1,650m from the west-side portal

For places where the concrete lining fell on a large scale, or where there was a risk of falling due to large shear cracks or compressive destruction of the lining, the lining was removed to check the structural health of the temporary support measures, such as spray concrete, steel arch supports and rock bolts. Photo 4 shows the example around 1,650m from west-side portal. As shown here, when deformation was confirmed in the temporary support, the cross section was re-excavated and the temporary support and permanent lining were reconstructed. Also, the pavement was demolished, the inverted concrete was inspected and was repaired and reinforced, when necessary. When there was no damage in the temporary support, only the permanent lining was reconstructed.

Figure 1 shows the selection flow diagram for selecting the restoration method, which was examined by the local council. According to this flow diagram, each span of lining was classified into one of the following categories: Rebuild 1, 2 and 3, Repair 1 and 2, and Inspection. For the 15 spans that were classified as "Rebuild 1, 2, or 3" excluding the west-side portal (that is, near Kumamoto side), the concrete lining was removed. Visual inspections and observation were carried out, and a restoration method was planned. For 11 spans with inverts (parts below the pavement), the pavement was removed and a visual inspection was carried out

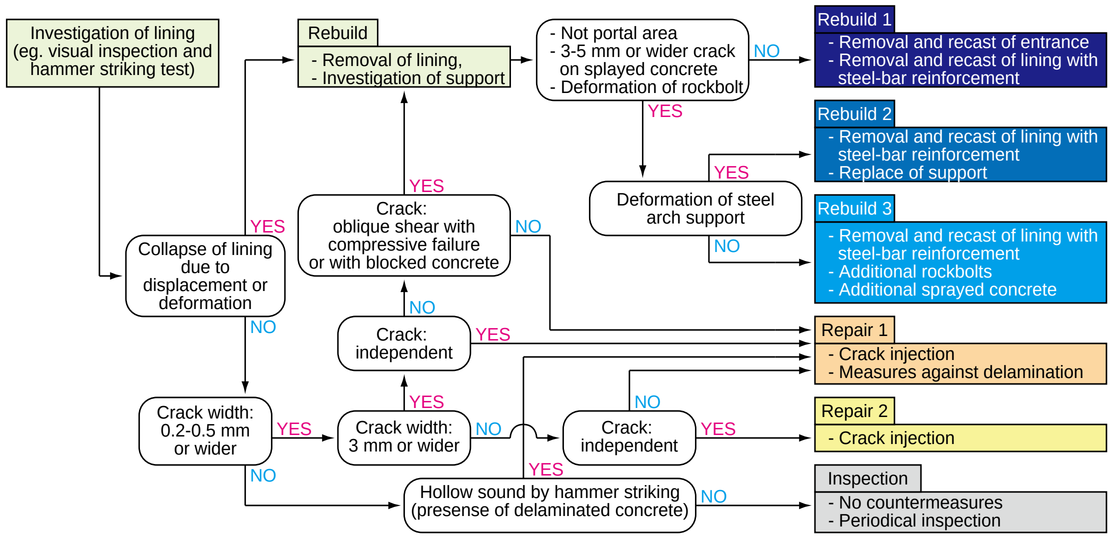

Figure 1 Selection flow diagram for restoration method in the Tawarayama tunnel.

For example, the vicinity of 1,650m in Photo 1, which was the most damaged in this earthquake, was judged as "Rebuild 2", and the rigidity of the support was equal to that of the portal, and the cross section was re-excavated. In addition, as shown in Photo 4, the steel arch support was severely buckled and there was a concern that the ground would fall off during excavation. The forepoling method was performed before detaching the steel arched support.

For the other spans, 13 spans in which deformation of the steel arch support was not confirmed were designated as "Rebuild 3", and the steel arched support was left as it was, sprayed concrete was removed once and resprayed with increased thickness and rock bolts were added.

Further technical challenges

In the Kumamoto earthquake, although various damages occurred in the Tawarayama tunnel, there was no fatal collapse such as blockage of the tunnel space itself. In addition, it was confirmed from past records that the collapse occurred in an extremely defective part of the soft rock. It was also confirmed from past records in the Minami-aso tunnel, next to Tawarayama tunnel, that there were signs of fault zones (zones with fractures or discontinuities in the rock soil) although the damage was minor.

Based on the above, it was judged that it is necessary to reduce the possibility of damage for users by reinforcing the lining, to avoid the collapse of large blocks of damaged concrete lining in road tunnels. Therefore, the following concepts were conducted as a countermeasure.

(1) Considerations, related to restriction measures to control large block collapses caused by earthquakes (hereinafter referred to ‘restriction measures’) should be clarified, so that they can be taken into account in mountain tunnel planning, survey, design, construction, and maintenance.

(2) Special conditions, like ground conditions, should be considered when selecting / implementing these restriction measures.

The following points should be noted as specific measures for the concepts above.

1) At the planning and survey stage, we need to locate the position of active faults and take as much distance as possible when determining the tunnel alignment.

2) At the design stage and construction stage, sufficient support structures, including invert concrete and lining with rebars, should be installed in sections with special conditions such as extremely poor soft rock and soil or unbalanced ground pressure, caused by a fault or a sudden change of ground stiffness.

3) At the maintenance stage, when special conditions exist as mentioned above and a deformation of the lining (possibly due to external forces) is found during periodical inspections, the cause and the progress of the deformation should be examined. At the same time, measures should be considered, including reinforcement such as backfilling of the back cavity of permanent lining, installation of inverts, placement of rock bolts, and the implementation of reinforcement inside permanent lining.

In consideration of these measures, the draft concept of the examination, as shown in the flow diagram in Figure 2, was proposed as a reference for selecting the adequate reinforcement, when required.

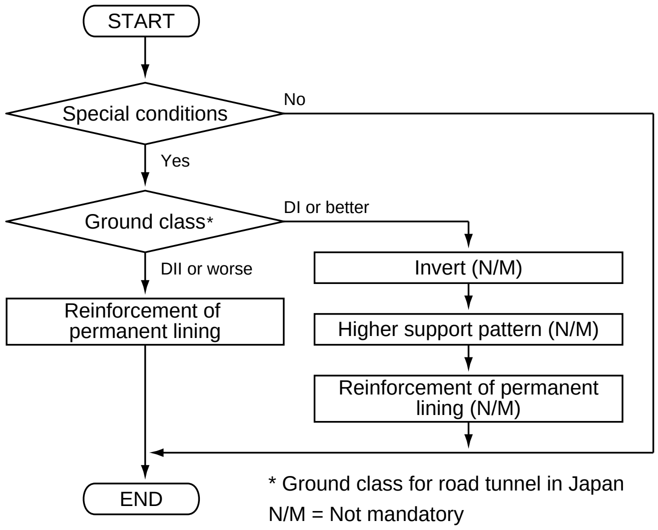

Figure 2 Flow diagram for selection of reinforcement.

When applying this flow diagram, it is necessary to take the concept of the tunnel support structure into account in the step 'special conditions'. Therefore, it is important to pay attention to the following items:

(a) Installing an invert concrete structure to make a complete tunnel a ring structure, thus making it more mechanically stable.

(b) Sufficient room should be provided for sprayed concrete, steel arch support, and rock bolts.

(c) Placing rebars in the permanent lining, so that the concrete will not fall on a large scale when the lining collapses, not even in case of an earthquake.

From the viewpoint of damage control measures, and based on the current knowledge, it is difficult to accurately calculate the mode and magnitude of the external force acting on the lining in case of an earthquake. Even if the external force can be calculated, it is even more difficult to estimate how it will change / develop in case of subsequent future earthquakes. In addition, even if the magnitude of the external force is evaluated based on some assumptions, for example, assuming a deformation that accompanies a large-scale fall of lining concrete, we need to set quite large force which cannot be used in ordinary tunnel design. It may occur that we cannot perform a rational design for tunnel.

In addition, after the earthquake, we conducted a model experiment in which reinforcing bars were placed and fiber sheets were attached to members simulating permanent lining concrete. As a result, it is difficult to prevent the compressive fracture of the lining by both materials. Especially, it may be difficult to expect the effect of suppressing the large-scale fall of concrete lining when the fiber sheet is attached. Furthermore, even if fiber reinforced concrete is used for the lining, it can only be expected to be effective in suppressing the fall of small concrete debris; however, the fibers cannot follow the behavior of the lining when it collapses and large deformation occurs. It also shows that it may be difficult to expect the effect of suppressing the large-scale fall of concrete lining. Therefore, further studies are required for adoption other than the placement of rebars in permanent lining as restriction measures against the impact of earthquakes on the tunnel.

Considering the above, referring to the design and construction examples of ordinary mountain tunnels so far, it is rational to judge that it is desirable to place single rebars in permanent lining and inverts in the specific soil grade where the special conditions can be in force.

In addition, it is necessary to think about restriction measures even at the maintenance stage. However, tunnels with an old construction age often do not have sufficient records of the design and construction stages. Therefore, it may be difficult to judge whether or not the special conditions of the tunnel, which are considered to be easily affected by the earthquake, are met. Based on these facts, it is important to enhance maintenance when implementing restriction measures in existing tunnels. In other words, It was concluded that it was effective to take priority measures (damage control measures) at locations where it could be identified through maintenance that the special conditions of the soil that are considered to be easily affected by earthquakes were manifest, as well as in the sections where deformation had already occurred.

Evaluation
(effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)

In Japan, the heavy earthquake to induce fatal collapse of tunnel happens roughly every decade or so. However, it is impossible from a budgetary point of view to carry out reinforcement uniformly to all road tunnels, since the number of tunnels is quite huge in Japan. Although the qualitative concept of countermeasures for tunnels damaged by earthquakes has been established, it is basically assumed that the rock around the tunnel has not collapsed due to the earthquake. Therefore, it is desirable to take measures based on the conditions that are considered to include factors that may lead to collapse, and it is thought that economic rationality can be guaranteed by this.

If the damage caused by an earthquake in a mountain tunnel is accompanied by deformation of the surrounding rock and soil, it is assumed necessary not only to re-excavate the tunnel support and permanent lining, but also to implement large-scale measures to ensure the stability of the surrounding rock and soil. In this case, it may be necessary to take individual measures according to the situation at the actual site.

On the other hand, when it is judged that the stability of the surrounding rock and soil is not significantly impaired even if the tunnel is deformed by the earthquake, it is considered that measures from inside the tunnel will be the main measures. When the tunnel is deformed on a relatively large scale, it is necessary to take emergency measures such as road closure and then consider countermeasures.

Most fatal damage for tunnel users is the falling of permanent lining by collapse. Except for portal areas and poor ground areas in the tunnel, the permanent lining is made by plain concrete in Japan. However it was experimentally confirmed that the permanent lining with rebar could avoid the fall of concrete mass, not small debris, and a reinforcement method using rebar is one method to mitigate the damage and maintain the minimum function in terms of allowing traffic in tunnel. In the case of the Tawarayama tunnel as described above, it took eight months to reopen the tunnel. Discussion about cost-effectiveness, side-effects and so on should be continued because this also depends on the social conditions. However, such reinforcement method may be needed for specific tunnels.

Lessons learned and recommendations

Based on the viewpoints above, Figure 2 shows the draft of the concept for selection of countermeasures against earthquake disaster for newly-build road tunnels by conventional tunnelling method, as well as Figure 3 for recovery of damaged road tunnels. When applying this flow diagram, it is necessary to gain new knowledge and review the procedures because it can be said that the accumulation of knowledge for examination is still limited.

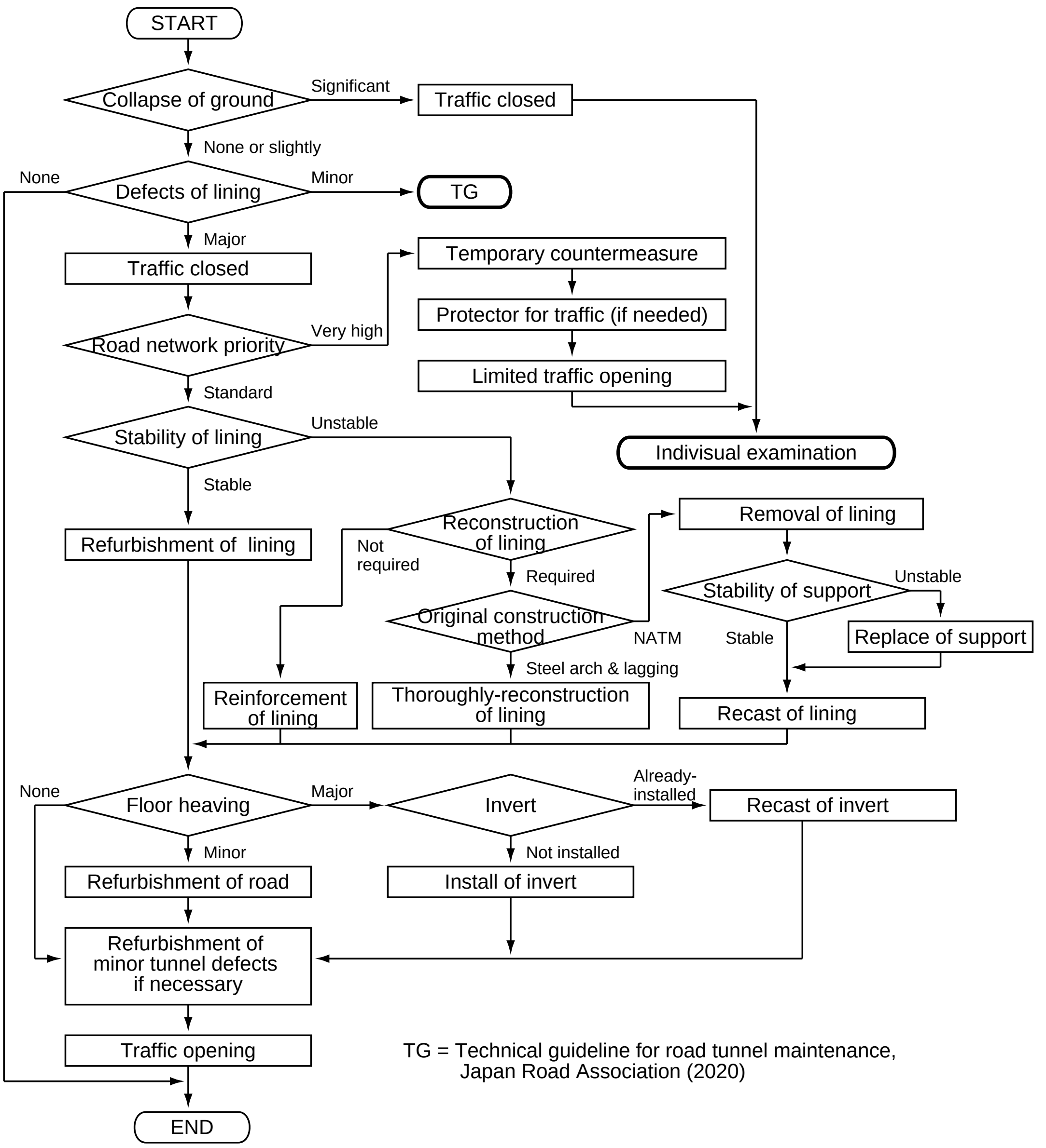

Figure 3 Draft of the concept for selection of countermeasures by earthquake disaster recovery of mountain tunnels.

Further information

See documents below.

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APPENDIX J: CASE STUDY: SOCIETAL COST-BENEFIT ANALYSIS FOR A WATER MIST SYSTEM, TO ENHANCE THE AVAILABILITY OF THE LEIDSCHE RIJN TUNNEL IN UTRECHT, THE NETHERLANDS

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Societal cost-benefit analysis for a water mist system, to enhance the availability of the Leidsche Rijn Tunnel in Utrecht, The Netherlands
Author(s)	Ronald Mante
Date of preparation	September 6, 2021
Description of the case study	

The Leidsche Rijn Tunnel in the A2 in Utrecht (see figure 1) was fully opened for traffic in 2012. It is a state-owned road tunnel, managed by Rijkswaterstaat (RWS), part of the Ministry of Infrastructure and Water Management. It is a so called "land tunnel": a roofed (covered) road, to shelter the vicinity from traffic noise and pollution, and to make multiple uses of space possible, including the area above the tunnel. The Leidsche Rijn Tunnel consists of 4 tubes with a length of 1,650m; 2 tubes per driving direction, with a total of 2 x (4+2) = 12 lanes. Moreover, there is an emergency lane in every tube, as well as a spare lane (not yet in use) to process a future traffic load increase. The total traffic load (the sum of the load in the 4 tubes) is about 200,000 vehicles per day (in 2020).

Figure 1: The south portal of the Leidsche Rijn Tunnel in 2018

(photo by Marion Golsteijn, https://creativecommons.org/licenses/by-sa/4.0)

Due to the largely decentralized administration in The Netherlands, the local authority (the College of Mayor and Aldermen of the city of Utrecht) are responsible for issuing the building permit and the opening permit for the tunnel. During the design and construction phase of the tunnel, the implementation of the European directive 2004/54/EC in the first version of the Dutch Tunnel Safety Act (2006) left room for discussion about the required safety systems in the tunnel, because the legally required safety level was not clearly defined. In this discussion, the local authority required a water mist system (WMS) to control large tunnel fires, as a condition for the opening permit. RWS argued that the common safety measures, not including

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

WMS, were sufficient. In the end, the discussion was settled by independent experts that were accepted by both parties. The experts concluded that the safety level was sufficient without WMS. The opening permit could therefore be issued without such an additional safety system.

However, subsequently another concern was expressed by the city of Utrecht. One feared that a large fire could cause the tunnel to be heavily damaged, resulting in a long closure for repair, thus compromising the accessibility of the city, resulting in severe economic damage. After ongoing debates, the Minister of Infrastructure and the Mayor of Utrecht made an administrative agreement to investigate if it would be cost-effective on a societal level to install WMS after all, after the opening of the tunnel for traffic. Thus, the discussion moved from safety to availability. The agreement implicated that WMS would be installed when it proved to be cost-effective and that the life span costs would be covered by RWS. To solve the dispute, RWS performed a societal cost-benefit analysis (SCBA), that was validated by an independent party (Ecorys, an international economic research and consulting company). The SCBA compared the life span cost of WMS (purchase installation, additional works, operation and maintenance) with the expected value of the benefits during this life span, being the prevented damage to the tunnel, as well as the prevented economic damage that results from the required closing of the tunnel to carry out repairs. On the other hand, installation and maintenance of WMS also require tunnel closures that cause economic damage; this was also taken into account. And, although safety wasn't part of the discussion anymore, the expected value of the monetized societal benefits of saved lives by WMS (and reduced medical care for injured people) were also considered.

The results of the analysis showed that installing WMS would NOT be cost-effective, not even if the system had been built in already during the construction of the tunnel. The main reasons for this conclusion are as follows:

1) The common safety measures in the tunnel, like longitudinal ventilation in combination with emergency exit doors every 100m, already provide a high safety level, thus reducing the added value of WMS;

2) The life cycle cost (LCC) of WMS is considerable, because of the required maintenance and periodic replacement of components;

3) The probability of a large fire causing significant damage is very low and has decreased even more over the years, as was shown through a study by TNO;

4) The expected damage to the structure in case of fire is limited, because polypropylene-fibre concrete was applied; even if the structure would be damaged significantly, the repair would be relatively easy, because it concerns a land tunnel, no risk of flooding as with a tunnel under open water;

5) Because there are two tubes available per driving direction, and a large fire is expected to only affect one tube, the economic damage of the closure of that tube is relatively limited; the traffic can be processed through the remaining tube, albeit with a reduced speed limit and more congestion; detour routes are also available.

Based on these results, it was mutually agreed upon by the Ministry and the City of Utrecht that WMS should <u>not</u> be installed in the tunnel.

This case study aims to focus on the applied methodology for the SCBA, rather than the outcome of the analysis. The methodology is considered to be generally applicable worldwide, but the outcome would be country or even tunnel specific.

Case Study PIARC TC 4.4 WG2 on Safety and Resilience
Objectives
The objective of the societal cost-benefit analysis was to gain integral insight into the effects of a fixed firefighting system such as WMS on the availability for traffic of the Leidsche Rijn Tunnel. In other words, the goal was to see if WMS would be a cost-effective measure to enhance the resilience of the tunnel against fire incidents.
Technical challenges
The main technical challenge was to select and apply a fitting methodology for the assessment of the costs and benefits of a fixed firefighting system in a road tunnel. Since such a system would be part of state-owned infrastructure and since it is the policy to perform a societal cost-benefit analysis in the planning phase (because the infrastructure is funded with taxpayers money) the standard method for such an analysis was also chosen in this case. This method, developed by the Ministry of Economic Affairs and the Ministry of Infrastructure and Water Management, is called “OEI” (Overview Effects Infrastructure[18]). The first basic principle is that the effects of the realisation and exploitation of infrastructure, in terms of costs and benefits, should be considered on a societal level, because society as a whole should benefit from the investments. The second basic principle is that all the effects, both costs and benefits, should be quantified (monetized) as much as possible, to enable an objective evaluation. While many effects can indeed be quantified (including, for instance, the effects of noise, pollution and environmental damage) not every aspect can be expressed in money yet (like the public image of a ministry that can be effected by a decision (not) to build a certain road). The method therefore allows the effects that cannot be quantified to be described qualitatively. These qualitative effects are taken into account alongside the quantitative cost-benefit balance. Although this might be considered a limitation of the method, it illustrates that the analysis is meant to <u>support</u> the decision whether or not to realize the infrastructure, not to <u>dictate</u> it; the decision remains the responsibility of the Minister and the Parliament. The effects that are normally taken into account in an OEI analysis include: 1. Accessibility (travel time, travel distance, reliability); 2. Road safety (material damage, fatalities and injuries); 3. Quality of life (air quality, noise, vibrations, stench, climate, quality of public space); 4. Social quality (social participation, social trust, social contact); 5. Cultural quality (diversity cultural offer); 6. Nature (biodiversity, recreational attractiveness, etc.); 7. Cultural history (archaeology, landscape, etc.); 8. Soil (pollution, stability, fertility); 9. Water (water quality, water quantity); 10. Indirect effects: image, identity, appearance, etc. Taking into account the relevance for the decision whether or not to install WMS in the tunnel, the effects were structured as follows, see figure 2.

[18] In Dutch: Overzicht Effecten Infrastructuur

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

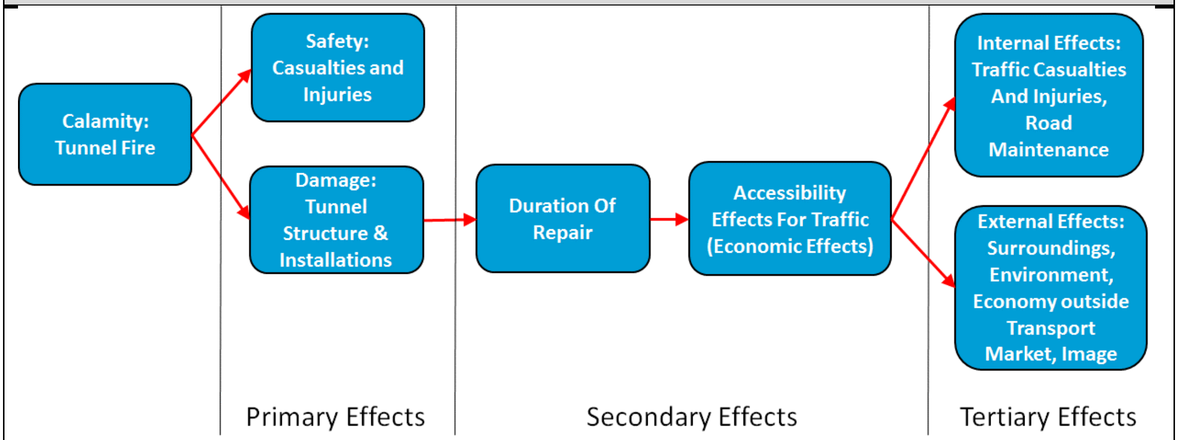

Figure 2: The effects of a calamity in the Leidsche Rijn Tunnel, taken into account in the SCB analysis for installing WMS

Based on an expert judgement (and the pilot calculations performed by RWS, for the effects on traffic casualties and injuries on the detour route and traffic incidents caused by a faulty activation of WMS in a normal traffic situation), it was concluded that (in this case) the tertiary effects were not relevant and/or not decisive for the decision whether to install WMS in the tunnel. Therefore, it was decided to leave the tertiary effects outside the scope of the SCBA.

As such, the summarized costs and benefits of installing WMS, as compared to the option <u>not</u> to install WMS, are as follows:

<u>Costs</u>

a. Required investment for the installation of the system in all 4 tunnel tubes, including civil works, traffic measures, etc.;
b. Reduced availability of the tunnel for traffic during the installation, leading to extra travel time for the traffic participants (detour and/or congestion) and/or less travel time reliability;
c. Yearly operation: extra tasks for operating staff (including education and training), energy consumption and maintenance of the system, including periodic replacement of components that are end of life: inspections, tests, cleaning, storage of spare parts, etc.;.
d. Reduced availability of the tunnel, as a result of the yearly maintenance and periodic replacement (for the part that these works require extra closure of lanes or entire tubes, because they cannot be done parallel to other maintenance works already scheduled in the current situation without WMS).

<u>Benefits</u>

e. In case of a tunnel fire: less casualties and injuries (provided that the system was successfully activated);
f. In case of a tunnel fire: less damage to the structure, the road and the installations; less repair cost (provided that the system was successfully activated);
g. In case of a tunnel fire: less reduced availability of tunnel for traffic, because of a shorter repair time (provided that the system was successfully activated).

Following the structure presented in figure 2, the costs (a) and (c) are the primary costs of WMS; (b) and (d) are the secondary costs. As for the benefits, (e) and (f) are the primary benefits of WMS; (g) are the secondary benefits.

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

All these costs and benefits were taken into account for the complete life span of WMS. Based on experience and expert judgement, this life span is was set at 25 years, meaning that after 25 years the entire system should be replaced because it is end of life.

Not all costs and benefits appear in the same year during the life span:

- The investment cost (a) and the cost of reduced availability during installation (b) appear in the year that the system is installed (year 0);
- The yearly cost of operation (c) and the reduced availability during maintenance (d) appear during the years of the life span of the system after installation (year 1 to year 25).
- The benefits of the system (e), (f), (g) appear at uncertain moments, that is, only in case of a tunnel fire. For the analysis this was solved by introducing a yearly expected value for the benefits, based on the probabilities of incidents with a certain fire power and the impact of the system on damage reduction (reduction of casualties, injuries and damage to the tunnel and the reduction of non-availability of the tunnel); thus, the resulting yearly reduction of societal cost by WMS equals the yearly benefits of the system. These reductions / benefits were assessed by comparing the damage in the situation without WMS with the situation in which WMS is installed in the tunnel. A critical point of attention in this comparison is the reliability of the system. When WMS is not successfully activated in case of fire, there is no damage mitigation and the damage will be exactly the same as if WMS is not installed. In the analysis, a reliability of 95% was chosen, based on expert judgement and experience. This means that, for every 100 fire incidents, there are 5 incidents in which the system is not effective at reducing damage, because the system is either not activated at all, or activated too late, or the wrong sections are activated (not the sections where the fire is).

  <u>Example (derived from the actual analysis / SCBA):</u>

  Suppose the damage to the tunnel structure and installations in a 100MW fire without WMS is € 5,000,000 (repair cost, excluding VAT) and that WMS could reduce this damage by 80% to € 1,000,000. Furthermore, suppose that the probability of a 100MW fire is 0.05 per year and that the reliability of WMS is 95%. Then the expected value for the damage is:

- Without WMS: 0.05 * 5,000,000 = € 250,000 per year;
- With WMS: 0.05 * (0.95 * 1,000,000 + 0.05 * 5,000,000) = 0.05 * 1,200,000 = 60,000 per year;
- Reduction of damage to tunnel by WMS: 250,000 – 60,000 = € 190,000 per year.

In the analysis, all above mentioned costs and benefits in the subsequent years of the life span were converted into a base year (in this case 2016 = year 0) using a so-called discount rate (interest rate). The role of this discount rate is to properly value future costs and benefits. It serves to express the difference in value between a euro now and a euro in the future. The discount can also be understood as the return requirement that must be imposed on a public investment or project from a social point of view. Such discounting means that effects (cost and benefits) that occur later in time are less weighted than effects that occur earlier. The effects in the first years after realization therefore have a larger share in the results of the analysis than the effects in subsequent years.

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

The weighted sum of costs and benefits over the years, that is thus created, is called the Net Present Value (NPV). In accordance with the then applicable agreements in this regard, an interest rate of 4.5% (0.045) was used in this SCBA for both costs and benefits.

In formula:

$$NPV = -\text{Investment} + \sum_{n=1}^{n=25} \frac{(\text{Total benefits} - \text{Total Costs}) \text{ in year } n}{(1 + 0.045)^{n}}$$

For the application of OEI method (SCBA), key figures have been derived to express the different effects in monetary value. Some examples are given below, in the detailed outline of the costs and benefits. The price level year of all costs and benefits is 2016.

<u>Costs of WMS</u>

The cost of installing WMS in the tunnel (4 tubes) was estimated between € 15 million and € 25 million, excluding VAT (Value Added Tax), or between € 16.6 million and € 27.7 million including VAT. These values were taken into account as lower and upper limit in the SCBA (the analysis was done for both values).

The additional cost of traffic measures and traffic management during the installation period were estimated at € 1.1 million, including VAT.

RWS estimated that each tunnel tube would have to be closed for about 3 weeks to realize the installation (1 tube at the time to limit traffic nuisance). RWS quantified the societal cost of reduced availability for traffic during this period. However, by lack of suitable references, Ecorys decided not to quantify the costs, but to include them qualitatively as "negative" in the analysis.

The yearly costs of operation of WMS (extra tasks operators, education and training, energy consumption and maintenance, including periodic replacement of components that are end of life) was estimated at € 0.44 million per year, or a present value of € 6.6 million for the entire life span of 25 years (including VAT). The maintenance costs were based on the maintenance specifications by the SOLIT-2 project [1], and subsequently validated by comparison to the experiences with the Roer Tunnel and the Swalmen Tunnel in the A73, the only tunnels in The Netherlands with WMS.

From the experiences with the A73 tunnels, it was also established that the yearly maintenance works could be combined with other scheduled maintenance works, so that no extra tunnel closures would be required. Thus, the yearly costs of non-availability due to maintenance of WMS were estimated at “0”.

<u>Scenarios</u>

To calculate the yearly expected benefits of WMS, several fire scenarios were defined, including the probabilities that these scenarios will occur. These probability values (frequencies) are the product of the yearly traffic load, the probability of a fire per vehicle kilometre, the tunnel length and the probability this fire will grow to a certain fire size / power. It was decided to use the same scenarios and probabilities as in QRA-tunnels [2], the quantitative risk assessment model that is legally required in The Netherlands for the evaluation of the safety of a certain tunnel. The scenarios are summarized in table 1.

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

Table 1: scenarios, taken into account in the SCBA

Scenario	Probability (frequency) per year
Fire 25 MW	13E-02 (about once every 8 years)
Fire 50 MW	8E-02 (about once every 13 years)
Fire 100 MW	5E-02 (about once every 20 years)
Fire 200 MW	1E-03 (about once every 1,000 years)
Pool Fire (dangerous goods)	2E-05 (about once every 50,000 years)
Warm BLEVE (dangerous goods)	5E-08 (about once every 20,000,000 years)

The probabilities were validated through by a study by TNO, a Bayesian analysis / update, based on large fire incidents that occurred in The Netherlands during the past decades (and worldwide) [3]. The TNO study showed that the probabilities of 25 MW, 50 MW and 100 MW are about a factor 10 lower then the probability taken into account in QRA-tunnels. However, the probability of a 200 MW fire was estimated higher by TNO (about a factor 8). Therefore, a sensitivity analysis was carried out to estimate the impact on the benefits of WMS if the probabilities derived by TNO were used instead of the probabilities according to QRA-tunnels. The impact on the result of the SCBA proved to be marginal.

Benefits WMS: reduction casualties and injuries in case of fire

To calculate the yearly expected value of the reduction by WMS of casualties and injuries, the afore mentioned model QRA-tunnels was used. QRA-tunnels calculates both the societal risk (presented in a graph) and the expected value per year of the number of casualties in the tunnel. Both results are based on a vast event tree, covering thousands of scenarios, involving (among other things) the fire scenarios mentioned above. Various sub-scenarios are taken into account in the calculation, like the location and the development speed of the fire, possible congestion in the tunnel when the fire occurs, possible failure of certain tunnel installations, etc.

The effect of WMS was modelled by increasing the value of the probability parameter in QRA-tunnels that an occurring fire will be extinguished in an early stage, thus preventing lethal circumstances (the policy in The Netherlands is to activate WMS as quickly as possible after a fire detection). The default values for this probability [0 to 0.25] are based on people using fire extinguishers from their vehicle or from an emergency aid cabinet. For the situation in which WMS is installed, the value is increased to 0.95 (corresponding with the reliability of the system, as mentioned earlier), except for pool fire and jet flame scenarios. The rationale is, that the lethal effects of these fires develop so quickly [4] that casualties will occur almost instantly, before WMS is activated (detection of the fire before activation may take 1 to 2 minutes). Thus, the probability of early extinguishing is kept “0” for pool fires and jet flames, in the calculations of the casualties.

The results of the calculations show:

- Expected value of casualties without WMS: 0.429 per year;
- Expected value of casualties with WMS: 0.403 per year;
- Reduction of number of casualties by WMS: 0.026 per year.

According the key figure used in the OEI method, the cost of a casualty is valued at € 2.7 million excluding VAT. Thus, the benefits of WMS concerning the reduction of casualties caused by fire are 0.026 * 2,700,000 = € 70,200 per year, or a present value of € 1.0 million (including VAT) for the entire life span of 25 years.

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

In addition to the cost of casualties, the cost of injuries (requiring first aid or hospitalisation) could be taken into account. However, since these costs are lower, and QRA-tunnels is a "conservative" model, the cost of injuries is thought to be included in the cost of casualties.

Benefits WMS: reduction of damage to the tunnel in case of fire

The estimated reduction by WMS of damage to the tunnel (expected value per year) was based on the results of full-scale fire tests in assignment of RWS in the Runehamar tunnel in Norway [4] and the results of CFD-analyses performed by the UPTUN project [5]. Thermocouple measurements during various fire scenario test gave insight in the temperature developments without and with activation of WMS. As such, the damage to the structure and the installations, as a function of the distance to the fire, could be assessed. For example, tunnel lighting will be lost when the temperature gets above 60 °C and ventilation units will be lost in temperatures above 250 °C. Next, the repair cost was estimated, based on the extent of the damage, for each fire scenario (see the previous example for a 100 MW fire). In this context, it is worth mentioning that polypropylene fibre concrete was used for the tunnel structure, thus limiting fire damage.

For all the fire scenarios combined, this leads to the following results:

- Expected value of damage to the tunnel without WMS: € 336,017 per year;
- Expected value of damage to the tunnel with WMS: € 70,083 per year;
- Reduction by WMS of damage to tunnel: € 265,933 per year (incl. VAT)

This results in a present value of € 3.4 million of damage reduction for the entire life span of 25 years (incl. VAT).

Benefits WMS: reduction of repair time (and thus reduction of non-availability during repair)

The repair time for each fire scenario (without and with WMS) was estimated based on the extent of the damage. For example: in case of a 100 MW fire, the repair time without WMS is 63 days (tunnel tube closed). With WMS (and a successful activation) the repair time is reduced to 20 days.

Most scenarios lead to damage of just one tube. Only in case of a warm BLEVE two tubes will be damaged and closed for repair; however, the probability of a warm BLEVE is very low, so not dominant in the non-availability effects.

When a tube is closed for repair, this leads to accessibility effects for the traffic:

- Extra travel time, caused by congestion and/or a detour route; the resulting cost is related to the Value Of Time (VOT). The VOT values to be used in an OEI SCBA are (excluding VAT):
  - Passenger transport: € 10.67 per person per hour (average for personal and business travel goals);
  - Freight transport: € 45.78 per vehicle (freight) per hour;
- Increased unpredictability of travel time; this additional cost is believed to be 25% of the calculated cost of extra travel time;
- Decreased variable journey costs and excise duties; since the detour route (through the city) is often shorter (although the travel time is longer), the variable journey cost of the vehicle decreases, which is a benefit for the owner/driver; on the other hand, less fuel consumption means less income though excise duties, which is a cost for the government (note that environmental effects are not within the scope of the accessibility effects).

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

Traffic model simulations and economic calculations showed that, in case WMS is implemented, the effects on the predictability of travel time are positive and the effects on variable journey costs and excise duties are negative and that the effects cancel each other out when expressed in monetised values. This leaves the benefits of a reduction by WMS of extra travel time to be considered. The value of this benefit could be calculated based on the reduction of the duration, the traffic load (of passenger cars, trucks and buses), the average number of passengers per vehicle and the cost per person per hour or vehicle per hour as mentioned above.

Example: the cost of 1 day closure of one of the main tubes, causing 15 minutes (0.25 hour) extra travel for a total of 55,040 passenger cars (with 1.2 occupants in average), 7,680 trucks and 640 buses (with 22 occupants in average) would be: 0,25 * 55,040 * 1.2 * 10.67 + 0.25 * 7,680 * 45.78 + 0.25 * 640 * 22 * 10.67 = € 301,639 (excl. VAT).

Since the cost of non-availability is considerable, as the example shows, RWS developed traffic management scenarios, as a resilience measure for calamity situations (like a big fire) that would cause a tunnel tube to be closed for a long period of time (say, more than 3 weeks). In such a case, the traffic of the closed tube would be led through the remaining tube in the same driving direction (together with the regular traffic in that tube). To make this possible, traffic measures will be implemented, like more (narrower) lanes in the tube in question (including the use of the emergency lane as regular lane) and a connection between the roadways (asphalt and safety barriers) to enable the traffic to switch from one roadway / tube to the other. This implementation will take about 1 to 2 weeks, spread out over traffic-calmed moments, to avoid nuisance for the traffic in the still-available tubes . During this period, traffic has to take a detour route. After this period, traffic through the tunnel is possible again for all roadways leading to the tunnel, but with a short delay of about 1.5 minutes (more congestion, reduced speed limit because of smaller lanes, etc.). It is important to mention that these scenarios will be implemented after a big fire that caused considerable damage, with and without WMS. This means that the detour period occurs anyway, and that the reduction of repair time by WMS will translate in a shorter period in which all the traffic in the same direction makes use of just 1 tube. In other words, only the duration of the period with an extra travel time of 1.5 minutes will be reduced by WMS. This limits the benefits of WMS related to accessibility. Thus, based on traffic simulations with Tool+ , it was estimated that the total cost of a 1-day closure of just 1 tube would be € 22,800 (excl. VAT) and a 1-day closure of 2 tubes (after a warm BLEVE) would be € 33,900 (excl. VAT).

This results in a present value of € 0.7 million of travel time cost reduction for the entire life span of 25 years (incl. VAT).

Conclusion of the analysis / SCBA

As a result of the SCBA, the following values for the Net Present Value (NPV) were derived:

- Lower limit of the investment: NPV = €- 19.1 million (incl. VAT); benefit/cost ratio = 0.2;
- Upper limit of the investment: NPV = € - 30.2 million (incl. VAT); benefit/cost ratio = 0.1.

These negative values mean that installing WMS in the tunnel is not cost-effective (the costs are higher than the benefits). A cost-effective business case would require a positive NPV (or a benefit/cost ratio > 1).

Case Study PIARC TC 4.4 WG2 on Safety and Resilience
Non-technical challenges
The main non-technical challenge was that the involved parties had to agree on the procedure and method to settle the dispute over WMS, which took several years. This was ultimately achieved by decoupling the decision on WMS from the opening permit for the tunnel and by involving an independent expert party in the analysis to substantiate the decision.
Evaluation **(effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)**
In the end, a societal cost-benefit analysis proved to work well to gain insight in the effects of WMS and to support the administrative decision making on a complex matter. This was the first time that such an analysis was performed for a tunnel installation / system.
Lessons learned and recommendations
The dispute over WMS was one in a long series of discussions with local authorities about permit requirements, which took place in many construction projects for new state-owned road tunnels. It was therefore decided to evaluate and adjust the Dutch Tunnel Safety Act, in a way that: • A legal safety criterion (societal risk criterion) was introduced (QRA-tunnels model to be used for evaluation whether or not a tunnel complies); • A standardized tunnel equipment for new to be built state-owned road tunnels was introduced; In the updated Tunnel Safety Act (2013), the principle is that when the safety of the tunnel complies with the legal safety criterion with the standardized equipment (and the tunnel complies with all other legal requirements) the local authority is not allowed to refuse the building permit and/or the opening permit. Moreover, the choice for the (standardized) equipment is to be coordinated with the local authority in the planning phase of the project; this means that the decision to build a tunnel coincides with the decision for the equipment to apply. Furthermore, based on this case study, it was decided not to include WMS in the standardized equipment for state-owned road tunnels.
Further information
Implementation of a fixed firefighting system (FFFS) like WMS in Dutch state-owned road tunnels is still possible, namely when a tunnel does not comply with the legal safety criterion with the standardized equipment alone. In that case, additional measures have to be taken to comply. Then, of course, a cost-benefit analysis will be performed to choose the optimal additional measure, but in the end, complying with the legal safety criterion is mandatory, even if it takes measures that are normally not cost-effective. An illustrative situation (not occurring in The Netherlands) would be that a FFFS has to be installed in a long, heavy trafficked, one-tube tunnel without emergency exits, to comply with the legal safety criterion. For a general impression of an activated WMS: see figure 3. Since WMS was **not** installed in the Leidsche Rijn Tunnel, these pictures represent a general situation in which a high pressure WMS is activated.

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

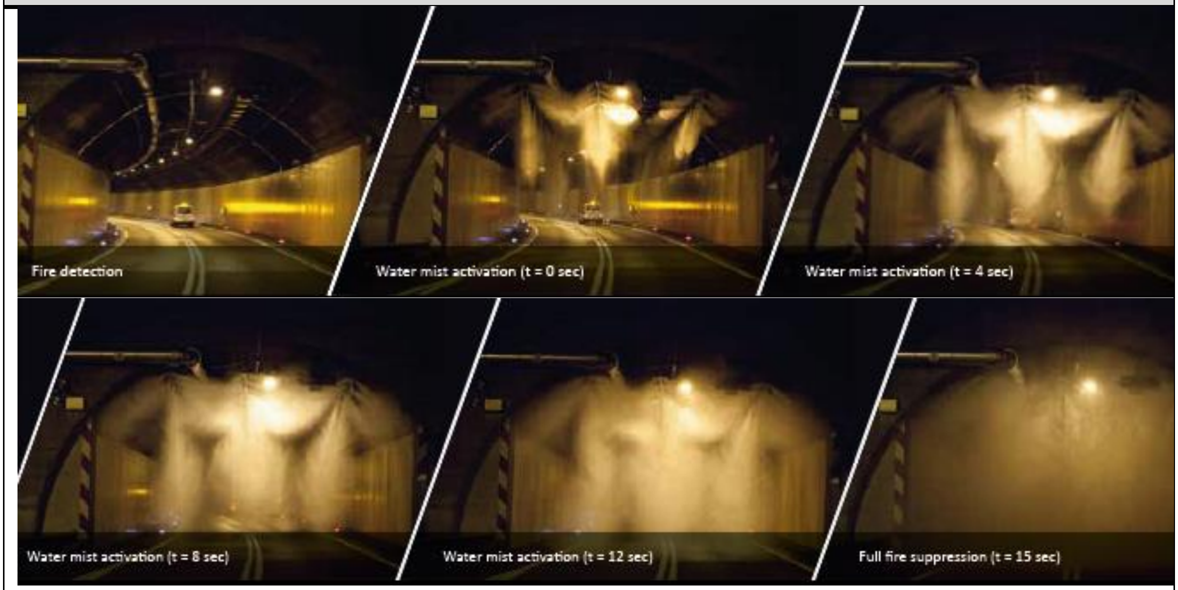

Figure 3: Activation of a high pressure WMS (source: Aquasys)

References or interesting web links

References, mentioned in the previous sections:

1. SOLIT-2, *'Engineering Guidance for a Comprehensive Evaluation of Tunnels with Fixed Fire Fighting Systems, Annex 3: Engineering Guidance for Fixed Fire Fighting Systems in Tunnels'*, version 1, Cologne (Germany), June 2012.
2. RIJKSWATERSTAAT, STEUNPUNT TUNNELVEILIGHEID (CENTRE FOR TUNNEL SAFETY), '*Gebruikershandleiding QRA-tunnels 2.0' ("User Manual QRA-tunnels 2.0"*), document number 4818-2012-0004, and '*Achtergronddocument QRA-tunnels 2.0' ("Background Document QRA-tunnels 2.0"*), document number 4818-2012-0005, Utrecht (The Netherlands), February 2, 2012. See https://puc.overheid.nl/rijkswaterstaat/doc/PUC_159718_31/ .
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4. EFECTIS, *'Effects of water mist on real large tunnel fires: Experimental determination of BLEVE-risk and tenability during growth and suppression'*, doc.nr. 2008-Efectis-R0425, Rijswijk (The Netherlands), June 2008. See https://puc.overheid.nl/rijkswaterstaat/doc/PUC_159817_31/
5. UPTUN PROJECT, *'CFD-modelling of tunnel fires'*, UPTUN WP2 D214, July 2006. See www.uptun.net

Interesting web links:

- OEI Method for SCBA (in Dutch): https://www.rwseconomie.nl/
- Document (in Dutch) 'Grote vrachtwagenbrand tunnel A2 Leidsche Rijn' (Large truck fire in A2 Leidsche Rijn Tunnel') by Ronald Mante (Centre for Tunnel Safety, RWS): https://puc.overheid.nl/rijkswaterstaat/doc/PUC_146957_31/ ;
  Note: this is an early version (2012) of the SCBA that was later updated according to this case study sheet in 2013 (Mante/RWS) and 2016 (Ecorys). Please be aware that the content is partially outdated by advancing insight (mainly regarding the required closures for maintenance and the societal cost of tunnel closures) but generally this document gives some more background information and details.

APPENDIX K: CASE STUDY: APPROACH TO MAXIMIZE AVAILABILITY DURING THE REFURBISHMENT OF THE HEINENOORD TUNNEL NEAR ROTTERDAM, THE NETHERLANDS

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Approach To Maximize Availability During The Refurbishment Of The Heinenoord Tunnel near Rotterdam, The Netherlands
Author(s)	Ronald Mante
Date of preparation	July 28, 2021

Description of the case study

The Heinenoord Tunnel, part of highway A29, connects the Hoeksche Waard Island, surrounded by rivers, with the city of Rotterdam. The tunnel crosses the Oude Maas river, is 614m long, consists of two unidirectional tubes (each with 3 lanes) and has an average daily traffic load of 92,100 vehicles.

It is a state-owned tunnel, managed by Rijkswaterstaat (RWS), part of the Ministry of Infrastructure and Water Management.

Currently, the tubes are separated by a single wall, whereas most tunnels in The Netherlands have a central gallery between the tubes, containing a separated emergency escape gallery and service gallery, for tunnel installations and cables. In the case of the Heinenoord Tunnel, the escape route in case of emergency currently leads through the neighbouring tube, that is accessible through emergency exit doors in the wall between the tubes. Moreover, the installations and cables that are normally in the service gallery, are currently located in the tunnel tubes, not accessible for maintenance without closing (at least two lanes of) the tunnel tube.

The Heinenoord Tunnel was opened for traffic in 1969. The structure is still sound (apart from some relatively minor issues) but a full refurbishment of the installations and systems is required, because they are end of life. The refurbishment allows the tunnel system to be upgraded according to the RWS Tunnel Standard. However, even the current tunnel system works well in terms of availability for traffic. Moreover, the capability to deal with disruptive (traffic) events is on par with the requirements. Therefore, no specific objectives were set to improve resilience, beside the main goal to organize the refurbishment itself (as well as future maintenance works) in a resilient way, to limit the nuisance for traffic as much as possible.

A long closure of the tunnel (or even one tube) to carry out the refurbishment is not possible, because alternative routes are scarce and require significant extra travel time, not suitable for the high traffic load. Thus, various scenarios were considered to assure the accessibility of the Hoeksche Waard during the refurbishment works, scheduled for 2023-2024. Multi-criteria analyses were performed for each scenario, mainly taking into account the total project costs, total societal costs (due to extra travel time during the refurbishment) and the total required time span for the works (calendar time).

In the end, **refurbishment through** "**parallel assembly**" proved to be optimal. This concept means that the new installations and systems are installed next to the current ones, that will remain in service until the end phase of the refurbishment. The existing installations and systems are only dismantled after integral testing has shown that the completed new installations and systems work properly. This approach allows most of the works to be carried out during a series of night and weekend closures of just one tube. This limits nuisance, because each time one driving direction is left undisturbed, while the nuisance for the other driving direction (extra travel time connected due to the alternative route) is limited because

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

the closures take place in low-traffic periods. Before reopening the tunnel tube after a night or weekend closure, a series of simple regression tests are performed, to demonstrate the current installations and safety systems were not compromised by the refurbishment works and still function properly.

To facilitate the parallel assembly, and to create better evacuation facilities for the future, a **central gallery** (consisting of an escape gallery and a service gallery) will be constructed in the west tube, during one of the first phases of the refurbishment. The width of the cross section allows for this, because in the current situation there is an evacuation path behind the safety barrier on the left side of the roadway in both tubes (see figure 1).

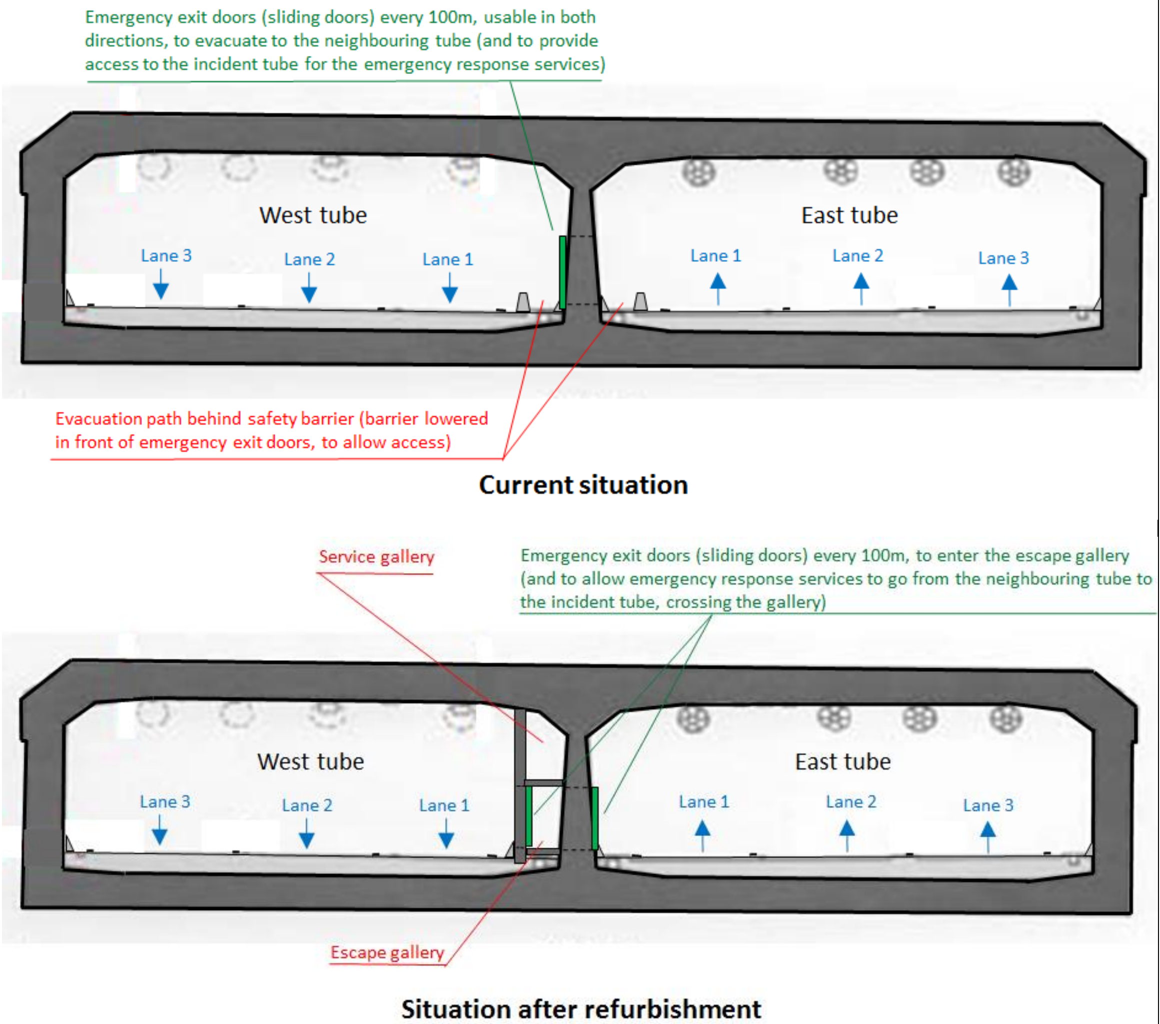


Figure 1. Construction of a central gallery (escape gallery and service gallery) as part of the refurbishment (source: Rijkswaterstaat)

The rationale for this approach is that, as research shows, normally **50%** of the tunnel systems is located in the service buildings, **40%** in the service gallery and only **10%** in the tunnel tubes. This means that, when a central gallery is present, most of the parallel assembly works can take place outside the night and weekend closures, while the tunnel tubes are still in service for traffic (provided the escape gallery remains available for possible evacuation situations, which is normally the case, since the service gallery is in a different compartment).

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

Moreover, a central gallery will enhance the possibilities for future maintenance and refurbishments without the necessity to close a tunnel tube, thus enhancing the **resilience** of the tunnel system.

The disadvantage of constructing a central gallery is that the tunnel has to be fully closed for a certain period, because both tubes are needed as a site to facilitate the works and the accompanied logistics. However, using prefab components and an "industrial" construction process, the main structure of the gallery can be finished in two calendar weeks, scheduled in the summer holiday period of 2023. In this period, the traffic load is somewhat lower compared to normal working days (and maybe the habit of working at home more often, introduced by the COVID 19 pandemic, will also help in this case). This two-week closure will therefore produce less hindrance than the total hindrance that would follow from additional night and weekend closures that would be required without constructing a central gallery.

A second two-week full closure of the tunnel will be required in the end phase of the refurbishment, for integral testing of the new installations and systems and for training of the tunnel staff (including operators) and emergency response services. This second full closure is also scheduled in a summer holiday period (in 2024).

To summarize, the total number of closures to facilitate the refurbishment is as follows:

- 30 Weekend closures and 40 night closures of one tube;
- Two periods of two weeks (and one extra weekend) in which the tunnel is fully closed (both tubes) in the summer of 2023 and 2024 respectively.

To mitigate hindrance for the traffic, public transport is promoted by running extra bus services during closures. In combination with this, the detour route for busses is shortened by temporarily allowing them to go through a tube of the neighbouring Second Heinenoord Tunnel, normally only in use for agricultural traffic (tractors) and motor cyclists. To make this possible, temporary extra safety measures have to be implemented. Since the detour route for other traffic is significantly longer (40 kilometres, through the Kil Tunnel) it is expected that, during refurbishment closures, many people will choose to travel by bus rather than by car.

Objectives

The main objective ("mission") was to find an approach for the refurbishment works that balances safety, hindrance for traffic (accessibility of regional destinations), technical feasibility and project costs, see figure 2.

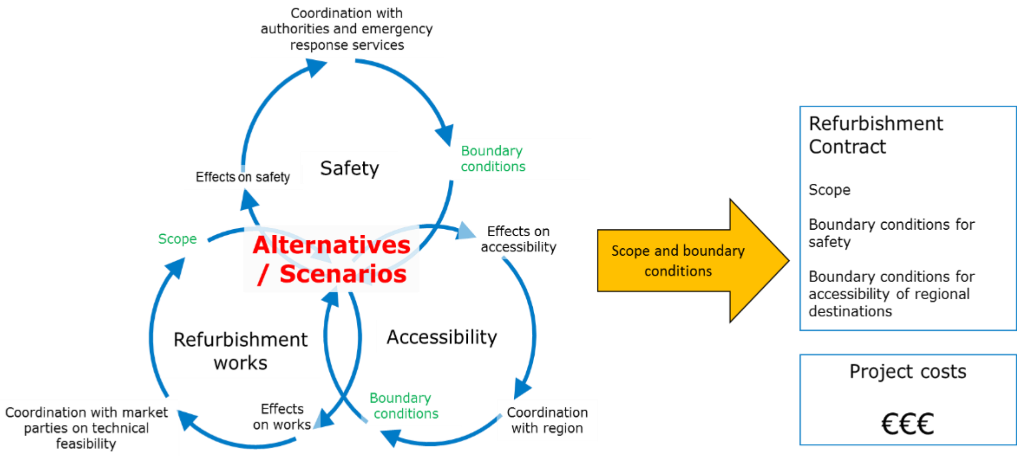


Figure 2. Balancing possibilities for refurbishment works, safety, accessibility and project costs (source: Rijkswaterstaat)

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

Various scenarios for the execution of the refurbishment works were considered and evaluated in order to select the optimal solution to be implemented in the contract. This approach was "holistic", and could be tackled from various angles, but basically, the starting point was to consider a certain scenario, like closing one tube for refurbishment while temporarily allowing bidirectional traffic in the other tube. Then, for that concept, the required measures to assure traffic safety, tunnel safety and the occupational safety for the construction workers were defined. Subsequently, the consequences for the accessibility (traffic flow) were determined, as well as the possibilities to execute the works effectively and efficiently within these boundary conditions. Based on these analyses, the total project costs, total hindrance for the traffic and the required time schedule / lead time for the scenario could be determined.
 	
By analysing all relevant scenarios along this way, the optimal solution, as mentioned above, could be selected, by applying a multi-criteria analysis. The following criteria, related to the aspects presented in figure 1, were taken into account:
 	
• Technical impact:
  ○ Scope of the works that can be included in the refurbishment (given the scenario)
  ○ Possible technical issues, uncertainties or risks
  ○ Expected life span of the results, before a next refurbishment would be required (goal: structure 30 years and installations/systems 15 years)
• Accessibility / hindrance for traffic:
  ○ Total travel time delay (per trip during rush hour) due to detour and/or congestion
  ○ Total duration of the hindrance during the period of refurbishment
  ○ Required measures (infrastructure, mobility, communication) to assure or improve accessibility
  ○ Direct societal / economic damage (monetized in euro) caused by loss of time / travel time delay during the total period of refurbishment; the monetized damage is based on validated cost of loss of time, taking into account the shares of business traffic, freight traffic and private / social traffic; the loss of time is determined on the basis of traffic flow models
  ○ Expected cost of compensation for freight transporters (to be paid by the ministry); this cost obviously is related to the calculated economic damage mentioned above
  ○ Effects on image (public opinion)
  ○ Possible effects on motivation of traffic participants to travel outside peak hours
  ○ Required communication to the public
• Project costs:
  ○ Total expected costs (in millions of euro's)
  ○ Possible additional costs, due to risks
• Safety and sustainability:
  ○ Main points of attention to assure safety (cost of required safety measures already included in total project costs as mentioned above)
  ○ Main points of attention to assure sustainability
• Summary of opportunities and threats
  ○ Opportunities
  ○ Threats
  ○ Further required studies

Case Study PIARC TC 4.4 WG2 on Safety and Resilience
In the above list, accessibility was a very important criterion, more so than project costs, although the required budget had to be feasible within a certain acceptable range.
Technical challenges
The main challenge was to find or create possibilities to perform the refurbishment works, while maintaining an acceptable travel time for the traffic, under acceptable safety conditions. In general, more (safe) availability for traffic means fewer possibilities to perform the work, resulting in a longer period in which the refurbishment takes place. Thus, balancing the degree of hindrance and the duration of hindrance, two important resilience aspects, was also important. That is why the total monetized economic damage, based on the total loss of time (travel time delay) during the refurbishment period, was chosen as a fitting criterion. The following scenarios were considered: 1. Limit the refurbishment scope to the most urgent installations and systems: no civil works and some installations not yet completely end of life remain in service, resulting in an additional refurbishment later on; 2. Parallel assembly during weekend and night closures (the chosen alternative); 3. Same as 2, but only night closures (resulting in a longer time span for the refurbishment, because the performance of the works is less efficient); 4. Closure of one tube at the time for refurbishment and allowing bi-directional traffic in the other tube (without allowing trucks and dangerous goods that could cause a large fire, because the longitudinal ventilation is not fit for bi-directional traffic); 5. Same as 4, but not a full closure of a tube, leaving one lane available for traffic (requiring safety measures for the construction workers and severely limiting the efficiency of the works, resulting in a long required time span for the refurbishment and hindrance); 6. Construction of temporary bridge to cross the river (in one or two directions) and then close a tunnel tube or the entire tunnel for refurbishment; 7. Same as 6, but construction of new tunnel (one or two tubes) instead of temporary bridge. The multi-criteria analysis showed that scenario 1 would not meet the goals for the life span of the tunnel system. Scenario 3 would be less effective than scenario 2 and scenario's 4 and 5 would cause heavy congestions on weekdays that are not acceptable. Scenario 6 proved to be technically difficult, because of the required height of the bridge and/or required bridge openings during peak hours (to let tall sea-going vessels pass). Scenario 7 would be (too) expensive and the required time span to finish the refurbishment would be too long (also considering the risks connected to the fact that the tunnel systems are end of life). Scenario 2 proved to be best for accessibility / availability, and also positive for the total project costs.
Non-technical challenges
Intensive coordination was required with the local authority (municipality) that is responsible for issuing the building permit and the permit for the re-opening of the tunnel after refurbishment, to align the phases of the works with legal decision-making process and the required measures to assure safety. The chosen concept of parallel assembly helped in this context, because it is transparent that current safety systems remain in service until the very end of the refurbishment. Moreover, intensive coordination was required with the local authority on the temporary safety measures in the Second Heinenoord Tunnel to facilitate temporary public transport by busses through the tube normally used by agricultural traffic (tractors). This has to do with the fact that there are no emergency exit doors present in the Second Heinenoord Tunnel. This is

Case Study PIARC TC 4.4 WG2 on Safety and Resilience
acceptable for occasional tractors with one driver, but for busses with lots of people on board a safety concept had to be developed to compensate for the lack of emergency exits. The solution was found by installing temporary longitudinal ventilation, with enough capacity to control bus fires (20-50MW). When busses go through the tube (during refurbishment closures of the Heinenoord Tunnel) the ventilation is permanently fully activated. In addition, on site traffic managers control the arriving busses (traffic metering) in a way that only one bus at the time is present in the tunnel; the next bus is only allowed to enter when the previous bus has left the tunnel. That way, in case of fire, people from the bus can evacuate smoke free by walking out of the tunnel in the direction opposite of the direction of ventilation. The bus drivers are instructed to guide this evacuation, supported by a steward on the bus. Lastly, a quick response fire fighting team is present on site. This concept allows a bus to pass every two minutes. The timetable for the bus service is organised on this basis. Lastly, the communication to inform the public about the works and the measures / recommendations to avoid hindrance will be crucial. The communication plan is still being developed.
Evaluation **(effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)**
The described approach takes into account all these aspects, resulting in the chosen option that is most cost-effective on a societal level and feasible for the tunnel manager.
Lessons learned and recommendations
The approach works well and proves to give a good basis for the planning of future refurbishment programs. From a resilience point of view, two aspects prove to be relevant: • The inventory of the resilience of the current tunnel system, of which the tunnel manager may not be (fully) aware in advance: what possibilities does the current tunnel system offer to reduce hindrance in case of maintenance or refurbishment? The findings of this inventory ought to be documented in the maintenance plan for the tunnel; • Possibilities / provisions, to be included in the refurbishment scope, to enhance the resilience for future maintenance and refurbishment works. Lastly, we became even more aware that standardized modules for tunnel installations and systems are very beneficial for reducing the required time to replace existing end-of-life installations during a refurbishment. Thus, standardized modules support the reduction of nuisance for the traffic.
Further information
[-]
References or interesting web links

Case Study PIARC TC 4.4 WG2 on Safety and Resilience

Link to Infographic (in Dutch): [Infographic Renovatie Heinenoordtunnel : wat betekent de renovatie op hoofdlijnen? - Rijkswaterstaat Rapportendatabank (overheid.nl)]

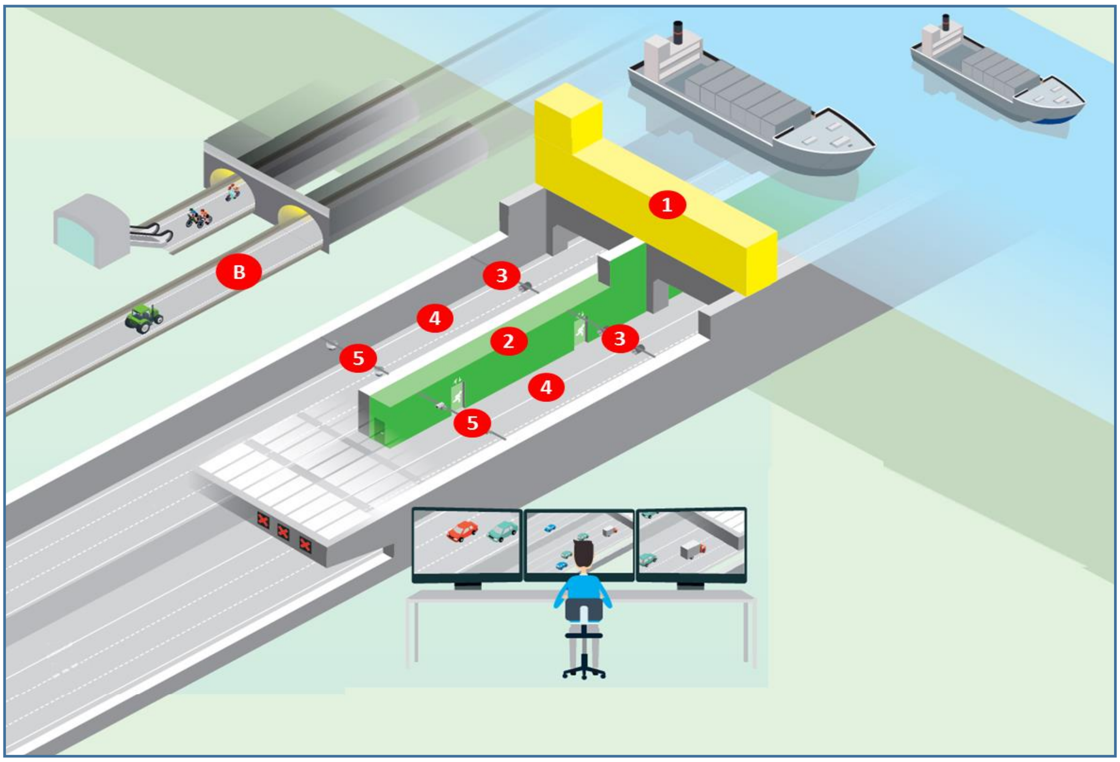


Figure 3. Part of Infographic refurbishment Heinenoord Tunnel (source: Rijkswaterstaat)

B = temporary bus transport through tube of Second Heinenoord Tunnel (normally used by agricultural traffic / tractors)

<u>Refurbishment phases:</u>

1 = Refurbishment service building; civil works: 10 weekend closures and 10 night closures of 1 tube

2 = Construction of central gallery (escape gallery and service gallery): full closure both tubes during 2 weeks + 1 weekend

3 = Installation works in tunnel and service gallery: 15 weekend closures and 30 night closures of 1 tube

4 = Switching from old to new installations (including testing and training): full closure both tubes during 2 weeks

5 = Removing old installations: 5 weekend closures of 1 tube

APPENDIX L: CASE STUDY: EXTREME WIND CONDITIONS AT THE HUGUENOT TUNNEL NEAR CAPE TOWN, SOUTH AFRICA

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Extreme wind conditions at the Huguenot Tunnel near Cape Town, South Africa
Author(s)	Tiago Massingue (South Africa), Kate Hunt (United Kingdom)
Date of preparation	June 23, 2021

Objective

The Huguenot Tunnel, north of Cape Town, is accessed via the 530m long, high-altitude Hugo River Viaduct. Keeping the tunnel available for traffic use is a priority for the South African National Roads Agency (SANRAL) and the extreme wind conditions blowing over empty trucks and small delivery vehicles needs to be mitigated. This Case Study investigates how the prevailing wind in the area adversely affects tunnel operation and how to provide safe measures for road/tunnel users during the crossing to the tunnel. The main objectives of the study can be summarized as follows:

- To evaluate and analyse the available data from the installed weather station;
- To determine the correlation between wind speeds and vehicle incidents on the viaduct;
- To recommend a solution to pre-warn road and tunnel users of the weather conditions.

Description of the case study

The high-altitude Hugo River Viaduct forms part of the National Route 1 and is an integral part of the Huguenot Tunnel in South Africa with the total length of approximately 4 km. The viaduct sits in a funnel formed by the mountains that cause a Venturi effect along the valley causing even higher winds speeds on the viaduct. During high wind seasons as shown in *Figure 1*, the 'black South Easter' wind causes a lot of disruption on the viaduct bridge by blowing over empty trucks and small delivery vehicles resulting in the tunnel being closed for trucks until it's safe to travel again.

Figure 1 - Wind accidents at the Hugo River Viaduct

Engineers at SANRAL have embarked on establishing how this unsafe situation can be mitigated to promote safety for road and tunnel users. An 03002-L Wind Sentry Set Weather was the first step towards mitigating the dreadful impact of horizontal wind loads. The task attributed to the Tunnel Operators was to determine pre warning measures about the prevailing gale force winds in the area to prevent incidents on the viaduct from impacting tunnel operations.

Weather monitoring procedure

A weather station installed on the viaduct (shown in figure 2) captures wind data to guide and provide information to Tunnel Operators.

Figure 2 - Weather station on the Hugo River Viaduct

The data output consists of the following:

- Average wind velocity
- Maximum wind velocity
- Average wind direction
- Maximum wind direction
- Average N/S direction
- Maximum N/S direction
- Average E/W direction
- Maximum E/W direction

Figure 3 – Setting of the Hugo River Viaduct

<u>Average wind speed:</u> The wind speed is logged at 4 second intervals at the PLC and then the average is calculated over a 10-minute interval and saved in a SQL database. Thus, the average wind speed is taken from 150 samples in the 10-minute interval.

<u>Maximum wind speed:</u> A new maximum wind speed is only logged if the wind speed logged in the 4 second interval is greater than that day's previous maximum wind speed. Therefore, it is not possible to see the maximum wind speed which occurred in each 10-minute interval.

Analysis of wind forces on trucks

A sensitivity analysis for different type of trucks and trailers was done on the impact of the wind force. The calculated wind force is unique for each truck since the calculation is based on the mass and dimensions of the truck. Mathematical functions together with a general understanding of the summation of momentum was used to determine the expected wind force. It is noted that the camber angle is the angle between a vehicle's axis and the horizontal road. Three calculations were done on small, medium and large trucks with no load in their trailers/containers to calculate the wind speed at which the truck would blow over.

<u>Scenario 1: Small Truck</u>

Figure 4 below shows the calculations done on a small truck which indicated that the wind will blow the truck over at 84 km/h.

At what wind speed will a stationary truck of the following dimensions and weight overturn on the Viaduct:

Variables	Value	Units
Camber Angle	6	Degrees
Truck & Trailer Mass	1500	kg
Load Length	8	m
Load Height	2	m
Truck Width	2.5	m
Truck Height	2.5	m
Calculated Force on Truck	5	kN
Calculated Wind Speed	84	km/h

Radians to Degrees	0.01745329
Gravitational Acceleration	9.81

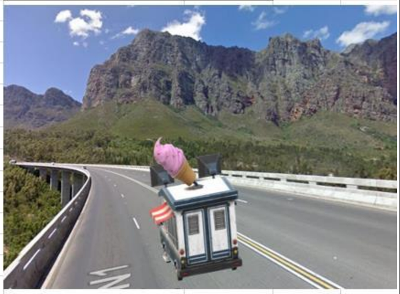


Figure 4 - Analysis for a small truck

<u>Scenario 2: Medium Truck</u>

Figure 5 below shows the calculations done on a medium truck which indicated that the wind will blow the truck over at 94 km/h.

At what wind speed will a stationary truck of the following dimensions and weight overturn on the Viaduct:

Variables	Value	Units
Camber Angle	6	Degrees
Truck & Trailer Mass	12000	kg
Load Length	18.75	m
Load Height	3	m
Truck Width	2.5	m
Truck Height	4	m
Calculated Force on Truck	23	kN
Calculated Wind Speed	94	km/h

Radians to Degrees	0.01745
Gravitational Acceleration	9.81

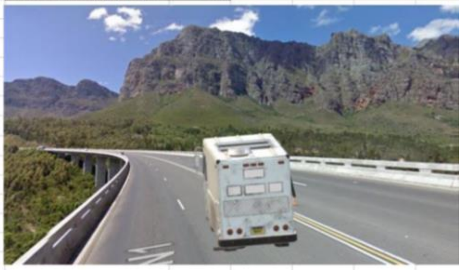


Figure 5 - Analysis for a medium truck

<u>Scenario 3: Large Truck</u>

Figure 6 below shows the calculations done on a large truck which indicated that the wind will blow the truck over at 171 km/h.

At what wind speed will a stationary truck of the following dimensions and weight overturn on the Viaduct:		
Variables	Value	Units
Camber Angle	6	Degrees
Truck & Trailer Mass	40000	kg
Load Length	18.75	m
Load Height	3	m
Truck Width	2.5	m
Truck Height	4	m
Calculated Force on Truck	76	kN
Calculated Wind Speed	171	km/h

Radians to Degrees	0.017453
Gravitational Acceleration	9.81

Figure 6 - Analysis of a large truck

Evaluation
(effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)

<u>a) Evaluation of weather data</u>
High wind loads can and do have devastating effects on the viaduct: a small, empty truck is estimated to be overturned from a calculated force of 5 kN – corresponding to a wind speed of 84 km/h.

This is in line with the incident that occurred on 21 July 2015 when the famous “Black South-Easter” hit the Viaduct and surrounding areas. Two trucks were blown over by the gale force winds and another two trucks were involved in a collision as was shown in *Figure 1*1.

The raw data captured by the Weather Station was exported to an Excel file to be interpreted and analysed, and is shown in Figure 7 below. According to the personnel at the Huguenot Tunnel, the incident happened between 18:00 and 18:10. The average wind speed at this specific 10-minute time interval was calculated and logged as 25,03 m/s (90,09 km/h) and the maximum wind speed on that day was logged at 11:10 in the morning, as 42,43 m/s (152,76 km/h). The average wind speed at the time of the incident did not have a peak value significantly higher than the average wind speeds around the time of the incident. It is important to note, however that the wind speed in the 10-minute time interval of the incident could have had very short duration gusts close to 152,76 km/h.

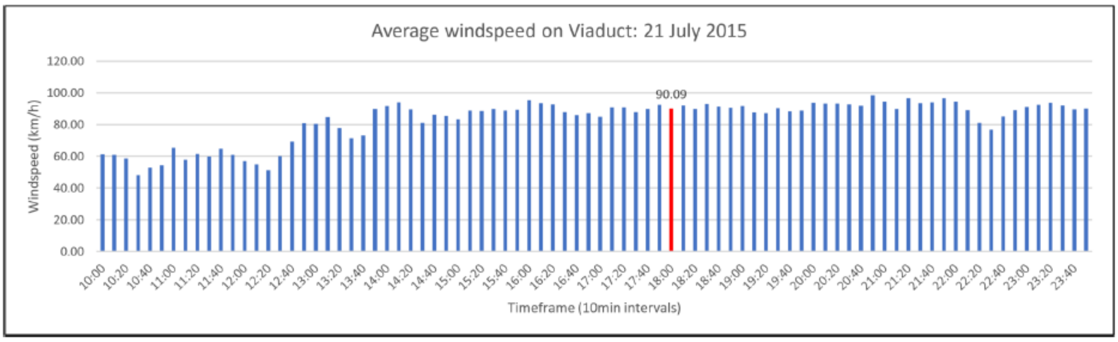


Figure 7 - Average wind speeds recorded on the viaduct – 21 July 2015

<u>b) Correlation wind speeds and incidents on the viaduct</u>
Information delay from the time of an incident to tunnel operators was the main challenge in the process. While the Tunnel operator could read the information and establish the

seriousness of wind impact on the viaduct in real time (i.e. as it happened), he could not have predicted the wind speeds in advance, to plan for this event and prevent accidents happening.

The study has shown as a result that the current weather station does not proactively feed into any prevention of incidents. An alternative was therefore assessed to mitigate the inefficiency of the correlation process.

c) Solution to pre-warn road users

SANRAL established a partnership agreement with the South African Weather Service (SAWS). This agreement was put in place so that the SAWS could provide advance hazardous weather alert services to SANRAL in respect of certain portions of the N1 at the Huguenot Tunnel. In terms of advanced forecasting, the SAWS, through its extensive network of surface and atmospheric weather observation stations and remote weather observation network (satellite, radar, lightning detection network and CCTV cameras) is able to monitor weather conditions and issue alerts of adverse weather conditions. The current SAWS network includes:

- Positioning and extension of surface and atmospheric weather observation stations, including the addition of CCTV cameras in some areas;
- S Band radars installed in 2010 which are fully operational and have been positioned to ensure maximum coverage across the country,
- Meteofactory, an integrated state-of-the-art Forecast Product Generator (FPG) system that allows for the expert management by forecasters of meteorological events in the case of forecasted hazardous weather conditions,
- Alert triggered monitoring software to alert forecasters of the probability of high impact weather.

Lessons learned and recommendations to tunnel managers

Safety Recommendations

In order to promote safety at the Huguenot Tunnel and adjacent Viaduct, the following recommendations were made:

1) Close the viaduct at a Calculated Maximum Wind Speed

- The viaduct must be closed to trucks if the wind speed exceeds 84 km/h. This maximum wind speed could be lowered to include an additional safety factor in the calculations. It is important to act pro-actively and close the viaduct at a defined maximum wind speed using the live data from the existing Weather Station. The Tunnel Operators therefore must act quickly if an alert is received on the SCADA network in the Control Room if the wind speed is close to 84 km/h.

2) Construct a Framed Mesh on the Viaduct

- Construct a framed mesh on the viaduct to disrupt the flow of the wind and thus reduce the lateral load applied to vehicles on the roadway. The scope of the work may include the following:
  - Studying further the specific wind conditions on the viaduct to determine the maximum wind speeds, durations, frequency, direction and others.
  - Analysing the data from the Weather Station on the viaduct and site visits.
  - Preparing a brief report to summarise the basic wind conditions on site.
  - Identifying potential solutions to decrease wind effects on vehicles without unduly adding additional loads to the bridge structure and its foundations.

- Carrying out full or partial scale wind tunnel testing of the designed mesh wind screen system(s).

3) Maintain formal Agreement with South African Weather Service

- Use the SAWS technology to prewarn operators of the tunnel when to close the roadway to trucks to prevent incidents on the viaduct. The SAWS may provide a 4x4km forecast model covering the viaduct and the Huguenot Tunnel. Similarly, the SAWS can supply SANRAL Engineers & Tunnel Operators with site specific wind prediction forecasts for the Viaduct for the next 36 to 48 hours and issue alerts by File Transfer Protocol (FTP), SMS or email to assist the tunnel operators in implementing measures for the safety of road users using the viaduct leading to and from the Huguenot Tunnel.
- A summary of the hazardous weather conditions to be tracked and verified by the SAWS and alerted to the Tunnel Operators are outlined below.

Hazardous weather conditions to be tracked and verified by the SAWS		
Ref	**Alert level**	**Criteria**
A	**Severe storm/s with large hail**	Storms that reach a specified National criterion which quantifies them being classed as severe, thus resulting in expected damage to property and/or loss of life
B	**Severe storm/s with abundance of small hail**	
C	**Severe storm/s with strong gusty conditions**	
D	**Severe storm/s with heavy rain**	
E	**Severe storm/s with gusty winds, hail, heavy rain and reduced visibility**	
F	**Severe storm/s with gusty winds, heavy rain and reduced visibility**	
G	**Strong winds resulting in hazardous driving conditions**	Average wind speed of more than 62km/h or gusts in excess of 81 km/h for land-based regions
H	**Heavy rain**	50mm or more within 24 hours
I	**Flooded roads**	Any report of or expectation of flooding based on meteorological experience and guided by input from the South African Regional Flash Flood Guidance system and the SA Flash Flood system, Satellite, Radar, CCTV cameras and/or reports
J	**Strong winds and flooded roads resulting in hazardous driving conditions**	Combination of (G) and (H)
K	**Significantly reduced visibility**	When the visibility is expected to drop below 500m due to the obscuring phenomena
L	**Significantly reduced visibility and flooding**	Combination of (I) and (J)
M	**Slippery roads due to wet or icy conditions**	Only when **first** rains are expected over an area at the commencement of the wet season and rain is expected; **Slippery roads due to icy road conditions**; Only when rain is expected when overnight temperatures expected to drop below freezing resulting in slippery roads or when snow is expected to cause hazardous driving conditions
N	**Snow creating hazardous driving conditions**	When snowfalls are expected to impact negatively on driving conditions to such an extent that passes/roads may be closed during the event

Further information
[-]
References or interesting web links
- News24, 2015. News24. [Online] Available at: https://www.news24.com/news24/southafrica/news/Huguenot-Tunnel-closed-after-winds-overturn-trucks-20150721 [Accessed 21 July 2015].   [“Resilience for safety at Huguenot Tunnel”] JC van der Walt and R Baxter undertook a study in 2020 to determine the wind speeds prevailing at the tunnel. This Study was used as the reference for the case study.

APPENDIX M: CASE STUDY: IMPROVING FIRE SAFETY OF MID-LENGTH EXPRESSWAY TUNNELS IN SOUTH KOREA

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Improving fire safety of mid-length expressway tunnels in South Korea
Author(s)	Nam-Goo Kim, Yoon-Ho Lee
Date of preparation	28/6/2021

Description of the case study

KEC (Korea Expressway Corporation) is the main organization of the expressways in South Korea, and manages 1,092 tunnel tubes as of 2021.

Classification	Total	>3km	1~3km	0.5~1km	0.5km>
Tubes	1092	35	241	355	461

Table: The existing expressway tunnels

According to the data from 2004, 188 cases of fire occurred in expressway tunnels in South Korea. Especially in 2020, the Sa-me 2 tunnel fire accident, including a chain collision of 32-vehicles, caused 48 people to be injured from smoke inhalation in absence of a ventilation system in the tunnel. Consequently, one of the countermeasures by the national government is to update the standards of emergency ventilation in a more strict way, targeting mid-length tunnels (500m to 1 km) to improve the fire safety.

KEC, as a main expressway organization in South Korea, already installed smoke ventilation systems in 44 of the existing mid-length expressway tunnels from 2009 on, and newly added 55 tunnels to the list in 2021 to improve fire safety due to the newly strengthened national standard.

This case study mainly focuses on the:

- Installation of smoke ventilation system (Jet Fans) for the existing tunnels to improve fire safety;
- Background, financial and technical issues as well as traffic safety management.

Objectives

One of the major issues regarding tunnel resilience is fire safety since fire accident may threaten human life as well as traffic continuity when the measures are not enough to mitigate damage to people inside and tunnel structure. Suppression of fire or the initiation of ventilation system at the early stage of fire is essential to secure fire safety of tunnels, and resilience can be improved by an early finish of the fire situation, which results in a fast recovery of the normal traffic situation, by support of fast evacuation, rescue and debris cleaning. In this context, the authors present a recent case of the measures for tunnel fire safety in South Korea

Technical challenges

Prevention of traffic accidents is highly required when installing jet fans in tunnels in operation. Structural safety is also essential at the spot where jet fans are installed because the structure has to endure full load of a jet fan including hanging parts that weigh approximately 2 ton per fan.

Non-technical challenges

Traffic congestion during the installing period should be minimized to deal with civil complaints, especially in the case of heavily trafficked tunnels in urban areas. Cost reduction and budget allocation are also important issues, since the total budget for the 99 tunnels is estimated about 120 million USD to install jet fans, power supply systems, remote control systems and wind speed sensors.

Evaluation
(effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)

Traffic management

To minimize traffic congestion and to prevent traffic accidents in the tunnels under operation,

long range tapering lanes with VMS and well-recognizable warning signs sufficiently in advance are properly deployed.

For tunnels with a heavy traffic volume, all the installation works are done during the late night and dawn, which entails increasing cost, and several projects are done in conjunction with LED light replacement or other essential maintenance works. Strict technical supervision and the traffic management resulted in zero accidents during the works.

Structural safety

To secure the structural safety at the spot where jet fans are installed, reinforced steel structures are applied, if necessary, after a thorough GPR (Ground Penetrating Radar) test and numerical analysis.

GPR Test

Reinforced Structure

Remote control

Real-time data from the wind velocity sensors inside the tunnel are sent to RTU (Remote Terminal Unit) and retransmitted to a branch office to effectively control the wind speed in the tunnel, using MMI (Man Machine Interface) software in case of fire accident.

Budget allocation

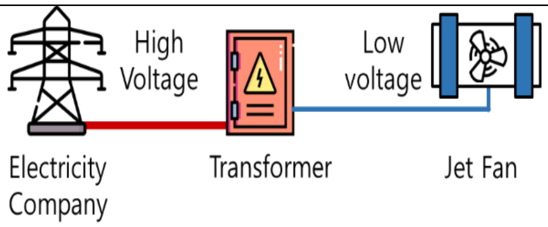
The priority order for the 99 tunnels (early stage 44+ the recently added 55) is determined by using a domestic QRA model to allocate financial resources to each year since 2009. The cost per tunnel (usually 2 tubes) are approximately 1.2 million, allowing 3 to 5 tunnels to be selected each year.

(Expected) effects on resilience / enhanced availability for traffic

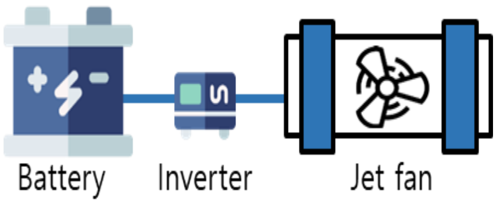
As previously mentioned in the "Objectives" section, resilience can be improved both from the fire situation and fast recovery of normal traffic condition.

Lessons learned and recommendations

Cost reduction is one of the key issues since the number of the tunnel is huge. So KEC is developing a battery-powered jet fan, named "Cable-Free Fan", which will be first implemented in this year. This will significantly reduce the installation cost and time (compared to conventional power supply systems) and will help to put forward the termination of the whole project.



Usual electric power supply



Battery-powered Jet fan

Further information

Please contact authors, unolee@ex.co.kr, ng1217@ex.co.kr

References or interesting web links

www.ex.co.kr

APPENDIX N: CASE STUDY: MADRID CALLE 30 RING ROAD RESILIENCE APPROACH, SPAIN

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Madrid Calle 30 Ring Road Resilience Approach
Author(s)	David Zamora Martínez
Date of preparation	12/10/2021
Description of the case study	

Madrid Calle 30 Ring Road is the most important and the busiest road infrastructure in Spain. 1.5 million vehicles per day use (part of) the Calle 30, of which 200,000 vehicles per day make a "full" journey that covers the use of all tunnels (48 km in total).

Figure 1: Cross Section - North tube from South By PassTunnel.

Tunnel sections mostly have two or more lanes. Heavy vehicles are not allowed, with the exception of buses, and, likewise, dangerous goods traffic is prohibited. During peak hours, the traffic load can exceed 200,000 vehicles per hour.

Figure 2: Location of the Madrid Calle 30 Ring Road.

There is a main Control Centre, as well as the possibility of managing the infrastructure from a secondary Traffic Control Centre, in case of emergency. This secondary centre does not have the operational management capacity of the main Control Centre, among other reasons because it has only one permanent operator, until the Emergency Plan is activated.

Figure 3: Main Control Centre.

There is also a First Intervention Team, with similar equipment as the public fire brigade, that is mobilised in the first part of the event. The team will control the event until the arrival of the external public emergency response services, to whom they will report and continue their intervention as auxiliaries, since the responsibility for emergency management falls on the Fire Services of the Madrid City Council. The First Intervention Team received dedicated education and training, adapted to their tasks.

The Main Control Centre is managed by a team, consisting of at least three operators, one supervisor, and one operation manager.

The rest of the organisation is related to the Maintenance and Conservation services, which are under the responsibility of an Operation Manager, who reports to the Authorities, in this case the Madrid City Council.

Figures 4 & 5: Maintenance operations.

The availability for traffic of Calle 30 is critical, since closure of the road would have a major impact. Not only on Madrid, the capital of Spain, but also on a national level. Such a closure could paralyze and at least collapse road communications “transports of people and goods”, and could generate great economic and social damage. So it is adequate to qualify the road as strategic and of vital importance.

The applied tunnel regulations are related to the European regulations for tunnel safety, and included in the Spanish Standard R.D. 635/2006. Although not all requirements are mandatory, there is a commitment to fully comply with this standard, since it represents the highest safety level.

Another standard that is applied, R.D. 393/2007, aims to assure Civil Protection, and includes requirements for self-protection measures, provisions in relation to critical infrastructures, as well as regulations applicable to Traffic and Road Safety.

Both standards cover the legal requirements, as well as specific technical requirements for equipment and systems, such as fire protection installations, evacuation systems and critical installations, as listed below.

Objectives

The safety control system of a tunnel monitors, a series of installations, equipment and elements that are pivotal to assure, that the minimum level of safety remains in service. These are the critical elements or systems.

We consider the following systems to be critical:

- Tunnel closing system
- External and internal power supply.
- Ventilation System.
- Equipment for fire control.
- Lighting system.
- Signalling system.
- Video Automatic Incident Detection (VAID)
- SOS system.
- Systems for analysis and control of environmental factors.
- Evacuation management systems.
- Communications equipment.

Figure 6: Emergency Exit along South By PassTunnel.

Figure 7: Emergency Gallery under road level from South By PassTunnel.

Technical challenges

Effective monitoring of the correct operation of each system by the Control Centre is very important. In case of degraded service, generated by a systems failure, a systematic response and decision making is triggered to ensure safety operations.

Non-technical challenges

Since this concerns the management of a public service through a concession to a company with public and private capital, there is a Concession Contract, which establishes the maintenance criteria and the quality requirements for the service, all focused on the safety of users and operators, and ensuring the integrity of the infrastructure itself.

Based on the requirements contemplated in R.D.635/2006, R.D. 393/2007 and the Concession Contract, the organization of the Operation, the emergency response and safety procedures, and the monitoring of the required quality standards, are structured and described in a Quality Plan. In the following section, we will explain how this relates to, the resilience of the infrastructure, according to our criteria.

Evaluation
(effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)

As described above, the applicable Spanish regulations for communication infrastructures, and especially for tunnels, taking into account safety in the broadest sense, the response in the event of incidents and management of the operation, as well as the attribution of responsibilities, are clearly defined, for the planning phase of the project, as well as for the construction phase and finally to the operations phase.

We therefore believe that it is appropriate to indicate how we continuously monitor compliance with the regulations.

The Operating Manual, a document required by R.D.635/2006, includes, among other aspects, procedures, instructions and actions related to the maintenance and conservation of the infrastructure, installations and equipment, in order to ensure their capacity for use during operation.

R.D. 393/2007 defines the equipment and organization for the response to incidents and accidents, as well as prevention.

Although the Operating Manual already defines the essential and required measures to maintain the infrastructure in service, in the case of Madrid Calle 30 there is a Maintenance Contract, which sets the parameters to be met in each and every one of the facilities and equipment that we have categorised as CRITICAL, to keep the infrastructure operational, and

even the minimum requirements in case of failures, to maintain the service in a degraded situation. These parameters refer, for example, to environmental quality, lighting levels, signalling management and others, and are permanently verified by the Control Centre, with a reliable record of their values. These parameters form part of the Quality Plan, that is aimed to comply with the requirements in the Operating Contract, and are regularly reviewed with both internal and external audits, which accredit their constant monitoring, and indicate the opportunities for improvement that should be implemented. The improvement actions are based on, experience and results of simulations, taking into account technological developments and advancements that can be applied to effectively support the improvement goal.
Lessons learned and recommendations
The existing regulations for safety in road communication infrastructures, specifically tunnels, include the different aspects that guarantee the safety of users, workers and emergency equipment, as well as the integrity of the infrastructure itself. The monitoring of the parameters established in the Operating Contract, which in turn form part of the quality standards set out in the Quality Plan, guarantees the availability of the road under the best operating conditions, and their review by independent bodies in audits assures the suitability of the contents of the Operating Manual and the Self-Protection Plan. Consequently, the resilience of the infrastructure to events of different causes will be guaranteed as long as the Quality Plans are complied with.
Further information
[-]
References or interesting web links
https://www.mc30.es/ Especially the page “Indicadores” (Indicators) is interesting in the context of resilience. Here you see the performance of the road in terms of traffic load, availability, incident management, etc. https://www.emesa-m30.com/

APPENDIX O: CASE STUDY: ADDITIONAL TUNNEL TUBE TO SUPPORT REFURBISHMENT, SWITZERLAND

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Additional tunnel tube to support refurbishment, Switzerland
Author(s)	Ingo Riess, Niels Peter Høj
Date of preparation	February 22, 2021

Objective

After operation for several decades, a road tunnel faces significant refurbishment works on the tunnel structure. This will require tunnel closures for several months or years. In order to maintain availability during construction, an additional tunnel tube is built (a “Refurbishment Tunnel”).

For the cases described here, the additional tube is not allowed to increase the tunnel's traffic capacity, as this would require an additional environmental approval. For these tunnels, the approval may be very difficult to obtain.

Description of the case study

In Switzerland, there are currently three projects underway:

Belchen Tunnel 3rd tube

The Belchen Tunnel along the highway A2 crosses the Jura Mountains. The mountain range is interspersed with large amounts of gypsum keuper, which has caused damage to the tunnel structure through swelling. Rehabilitation of the two uni-directional double-track tubes dating from 1970 is urgently needed. In order to keep the associated traffic restrictions to a minimum, the Belchen Refurbishment Tunnel is being constructed.

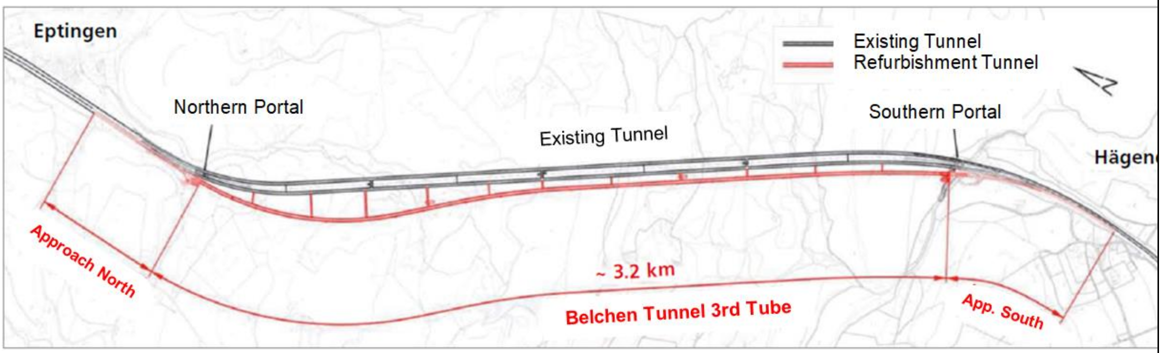


Figure 1: Situation of the Belchen Refurbishment Tunnel (red) parallel to the existing twin tube tunnel [image: ASTRA]

The Refurbishment Tunnel will be completed in 2021. Once the refurbishment of the existing tubes is completed, the central tunnel tube will be closed to traffic. It will serve as egress tunnel and as an alternative route during future refurbishment or maintenance work as well as following a collision or fire in one of the traffic tubes.

Gotthard Tunnel, 2nd tube

The 16.9 km long bi-directional Gotthard road tunnel was opened in 1980. It needs to be renovated due to its age. This will require a tunnel closure of several years. In order to maintain a road connection on the Gotthard axis all year round, the Federal Council and parliament have decided to build a second tube and then refurbish the existing tunnel. This procedure was approved by the electorate in a federal referendum on 28 February 2016. Thanks to the second tube through the Gotthard, traffic can be directed in a single lane with a hard shoulder after the renovation of the existing tunnel. This improves tunnel safety without increasing the existing traffic capacity.

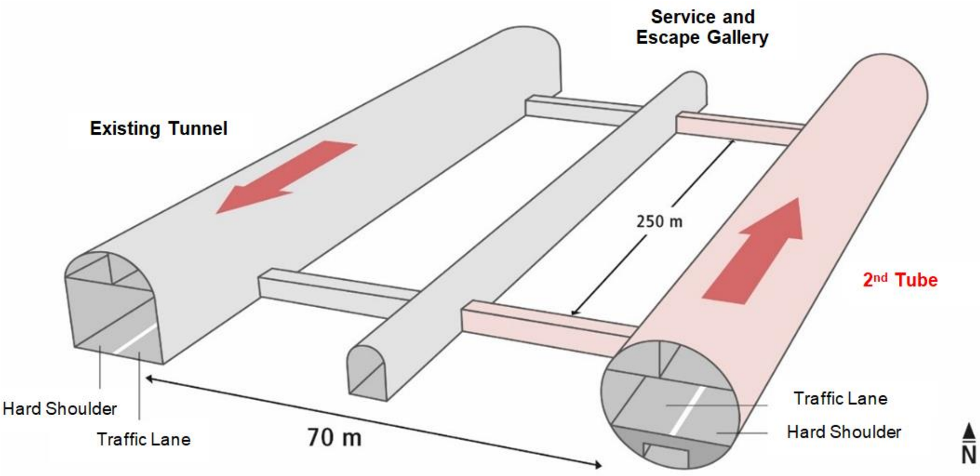


Figure 2: Schematic of the future twin-tube Gotthard Road Tunnel [image: ASTRA]

The project is currently in detailed design stage. Both tunnel tubes will be equipped for temporary bi-directional traffic in order to maintain an alternative operation scheme during future refurbishment or maintenance work as well as following a collision or fire in one of the traffic tubes.

<u>Rosenberg Tunnel, 3rd tube</u>

The A1 Rosenberg Tunnel was built in 1987. Starting in 2037, the two tunnel tubes must be refurbished completely. During construction work, the affected tube must be closed to traffic. A single remaining tube does not provide sufficient capacity for today's daily traffic. With the construction of a third tube, the refurbishment can be carried out in stages: While the existing tunnels are being rehabilitated one after the other, the traffic in the direction of St.Margrethen will flow through the Refurbishment Tunnel.

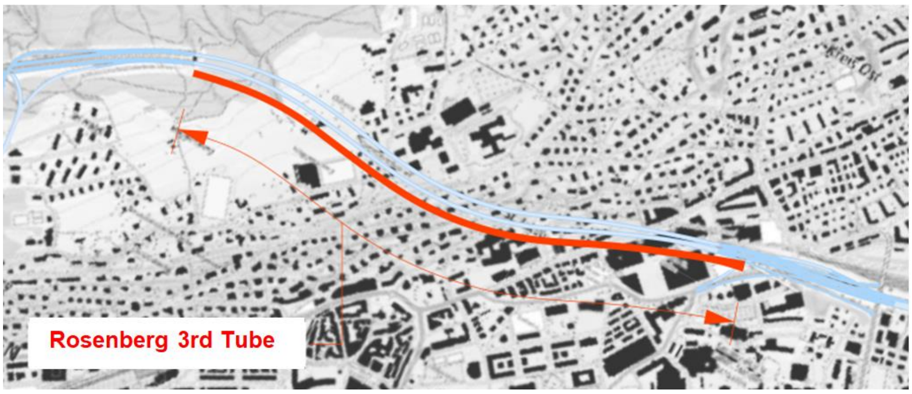


Figure 3: Situation of the Rosenberg Refurbishment Tunnel (red) parallel to the existing twin tube tunnel [image: ASTRA]

The project is currently in concept design stage. After completion of the refurbishment measures, the three tunnel tubes may be used for an increase of the traffic capacity subject to a future project approval.

Procedure

The maintenance of the Swiss national roads takes place in several phases:

- Observation, inspection and assessment;
- Maintenance planning and long-term planning;
- Project generation;
- Project planning; and
- Realisation.

In the phase of long-term planning, the requirement and the duration of refurbishment works are estimated along with potential impact on strategic goals, e.g. traffic flow and traffic management and/or tunnel safety. This assessment serves as a basis for the project generation phase. In case an additional tunnel tube is envisaged in order to meet the strategic goals, this is included in the assessment.

In the concept design stage ("Generelles Projekt"), a cost-benefit analysis is performed in order to justify the construction of the new tunnel tube. In the analysis, two scenarios are compared, with and without the realisation of the project. The analysis includes direct costs as well as external costs:

- Construction costs
- Replacement investments
- Land costs
- Accidents
- Travel times
- Vehicle operating costs
- Net benefit from additional traffic

The inclusion of accidents in the cost-benefit analysis may require a quantitative risk analysis. This was the case for the Gotthard Tunnel 2nd tube. However, if the risk is not expected to change significantly, accident rates from previous operation could also be used. If the expected benefits outweigh the costs, the project may proceed to the following design stages.

Technical challenges

The construction sites are in immediate vicinity of the existing road. Interference with the traffic must be minimised at all times, as this would have an impact on the benefits of the Refurbishment Tunnel.

A project involving a Refurbishment Tunnel goes through several project phases with different operation. Especially traffic management and safety critical installations have to operate for the active tunnel system in an integrated manner. This requires the new installations to be integrated and tested with the existing systems. Then, after refurbishment, the replaced safety installations also have to be integrated with the running system.

Non-technical challenges

Project approval is given for a Refurbishment Tunnel without an increase of traffic capacity. If there is a possibility that a future increase of traffic capacity might be desired, the construction shall not prohibit an appropriate adaptation. The design shall be sufficiently flexible without requiring excessive additional investment at the time of construction. The probability of a future extension has to be taken into account. For example, the 3rd tube of the Rosenberg Tunnel is designed for two traffic lanes and a hard shoulder that would allow future operation on three lanes. However, safety installations and traffic management are designed for two traffic lanes only.

Evaluation
(effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)

The necessity to construct a new tube in the three examples illustrates that the existing tunnels (with one or two tubes) are not resilient towards the effect of the rehabilitation work. After completion of the new tube, the tunnel will be significantly more resilient for both renewal and maintenance works as well as for accidents and other events in the tunnel tubes. The increased resilience is only available if the original tube or tubes are sufficient for the traffic load.

The expected effectiveness of the measure of an additional tunnel tube is evaluated in terms of resilience and safety for the three cases.

Legend: 🟢 = Positive / No problems 🟡 = Neutral or mildly positive / Some points of attention 🔴 = Poor / Problematic	Resilience for				
	Refurbishment	Maintenance	Accident	Fire	Safety
Tunnel Belchen 3rd tube	🟢	🟢	🟢	🟢	🟡
Tunnel Gotthard 2nd tube	🟢	🟢	🟢	🟢	🟢
Tunnel Rosenberg 3rd tube	🟢	🟢	🟢	🟢	🟡

Table 1: Evaluation of the expected effectiveness

As mentioned before, the cost-effectiveness of the measure was demonstrated through a (societal) cost-benefit analysis, as a boundary condition to get approval for the realisation / construction. This positive outcome was determined by aspects like a high traffic load (of heavy goods vehicles), the increase of travel time and/or congestion and/or accident rate without the measure, as well as the duration of the works and therefore the duration of the nuisance without the measure.

Lessons learned and recommendations

It is recommended to evaluate the cost-effectiveness of the Refurbishment Tunnel carefully. Depending on the weight given to the various aspects by the decision makers, the benefits could be calculated differently, giving different recommendations. A private tunnel operator might not include socio-economic benefits such as travel times and vehicle operation costs if not required by his contractual obligations.

Further information

See links below.

References or interesting web links

The following web-links have been evaluated as per 22 February 2021. The content of these links may change according to the project progress.

Tunnel Belchen:

https://belchentunnel.ch (German)

https://en.wikipedia.org/wiki/Belchen_Tunnel

Tunnel Gotthard:

https://www.astra.admin.ch/astra/de/home/dokumentation/medienmitteilungen/anzeige-meldungen.msg-id-45155.html (German)

https://www.astra.admin.ch/astra/de/home/themen/nationalstrassen/zweite-gotthard-strassenroehre.html (German)

https://en.wikipedia.org/wiki/Gotthard_Road_Tunnel

Tunnel Rosenberg:

https://www.astra.admin.ch/astra/de/home/themen/nationalstrassen/baustellen/nordostschweiz/a1_engpassbeseitigung_sg/projektuebersicht.html (German)

https://de.wikipedia.org/wiki/Rosenbergtunnel_(A1) (German)

APPENDIX P: CASE STUDY: REOPENING OF THE GOTTHARD ROAD TUNNEL AFTER FIRE DAMAGE, SWITZERLAND

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Reopening of a the Gotthard Road Tunnel after Fire Damage
Author(s)	Niels Peter Høj, Ingo Riess
Date of preparation	May 5, 2021

Objective

After a tunnel fire the resilience objective is to re-open the tunnel for traffic a soon as possible. Especially for bi-directional tunnels this implies that the safety of the tunnel will have to be reinstated in a fast-track procedure.

Description of the case study

The 16.9 km long bi-directional Gotthard Road Tunnel was opened in 1980. The tunnel is a crucial part of the national infrastructure providing the most important part of the road network across the Alps from the Central to the Southern part of Switzerland and an important part of the European road network as well. The description of the case study of the fire in 2001 is based on [1].

<u>Previous repair work</u>

Fires in the Gotthard Road Tunnel had occurred also before 2001. The lessons learned after the fires in 1991, 1994 and 1997 were stated in the report [2]. It was concluded that the intermediate ceiling had suffered serious damage in previous fires and before being able to reopen the tunnel it had always been necessary to install safety measures to support the slab itself. Hence, it was concluded in 1999 to prepare standard measures for the support and / or suspension of the intermediate ceiling in preparation for future events. The purpose of these measures is to have suitable material available to guarantee structural safety to the damaged parts and to reopen the tunnel in the shortest possible time.

<u>Gotthard Tunnel, Fire event on October 24, 2001</u>

On October 24, 2001, a devastating fire occurred which severely damaged the tunnel ceiling and secondary lining.

The rehabilitation of the section of the Gotthard road tunnel that was destroyed by the fire had to be planned and carried out under the greatest time pressure. Thanks to the readiness of everyone involved and the experience gained from previous repair work, it was possible to prepare the tunnel for reopening in less than two months with the same level of safety as before the fire.

The most important element that led to success is the appropriate choice of logistics, in which suitable and short-term available installations and human resources could be used in a targeted manner.

Figure 1: Support of the suspended ceiling at risk of collapse.

The assessment of the existing damage situation and the available funds included the following elements for an efficient solution:

- Appropriate use of the time during the surveys and investigations by the scientific police services (search for possible further victims, securing evidence, registering damage on vehicles, etc.). The actual clearance and reconstruction could only be started after the public prosecutor had cleared the tunnel.
- A solution had to be found that required the shortest possible mobilization time: Those involved with precise knowledge of the tunnel; Entrepreneurs who are already on the pitch; Use of material that is already available.
- As expected, a solution based on prefabrication proved particularly advantageous in this case. The tunnel was not allowed to be entered for the work during an initial period, which lasted more than three weeks. During this time, however, all planning and preparatory work could be carried out, including the start of the production of the prefabricated parts (concrete and suspension fittings).
- Certain finishing work that was of no relevance to safety (e.g. installing the side cladding walls) could be scheduled for the night of closure after the reopening. This was possible and reasonable because only a small volume of traffic is recorded during the winter nights.

Figure 2: Situation before assembly of the ceiling elements.

Coping with the time factor and the risks

The building program had to be made binding just a few days after the event, not least with a view to providing the public with the most reliable information possible about the date of the reopening. Since not all activities could initially be assessed precisely with their real time expenditure, compliance with this demanding program was associated with considerable risks. The deviations of the actual construction progress from the detailed planning program were recorded during daily reviews, discussed with all those involved and, where necessary, corrected using additional measures. Thus, the remaining uncertainty regarding the opening date could be gradually reduced.

The use of simultaneity proved to be an essential and decisive element, in all phases, in particular:

- First backup / completion of extinguishing work / work of the detection services
- Condition assessment / material removal / clearance / dismantling
- Cleaning / construction preparation
- Construction work / equipment / road surface / assembly of electromechanical systems
- Remaining work / controls / functional tests of the systems

It should be considered that the tunnel is a linear construction site and in this short time a considerable number of activities had to be performed simultaneously. Hence, it was a challenge to organise the processes for the workforce of approximately 80 people.

In summary, the work could be carried out in the following phases:

24.10.2001	-	Day of the fire
24.10.2001-26.10.2001	2 days	Immediate measures (securing access to the entire "red zone" for fire brigade and police):
27.10.2001-19.11.2001	23 days	Accompanying and securing the police identification services, additional support, recovery of vehicle debris, cleaning of the air ducts and the driving area
20.11.2001-26.11.2001	7 days	Demolition of the false ceiling (230 m), removal of the road surface (300 m), dismantling of the side cladding walls (600 m) and the electromechanical systems in the driving area to 750 m
27.11.2001-20.12.2001	24 days	Restoration of the false ceiling, the auxiliary structures, the sidewalks and the road surface, the metal parts, and electromechanical systems
20.12.2001	1 day	Test of all systems / Reopening

The fact that it was possible to repair the tunnel in an extremely short time for the circumstances is due to the combination of various favourable conditions and boundary conditions.

The good cooperation within the small but competent project team was also important, where everyone involved, representatives of the company, the project authors and the specialist contractors could contribute their experience from ongoing work in the tunnel.

Thus, from the very first hour, even while the tunnel was burning, work could be carried out efficiently, with a minimum of friction loss and with extraordinary motivation.

At the event, it was of great importance to have available information and documentation for the analysis of the situation and for the repair. In addition to the data, it was also important to have available staff and consultants with the necessary know-how and background and an organisation ready to cope with the situation. In the development of the preparedness in the time after the re-opening of the tunnel this organisational aspect and the available know-how have been maintained, and developed and have been part of the training and testing.

<u>Development since 2001</u>

Since 2001, no similar fires have occurred in the Gotthard Tunnel or anywhere else in Switzerland. The probability of a severe fire of this magnitude is extremely low, and additional preventive measures have further reduced the likelihood of damages comparable to the event in 2001 [3]. The preventive measures include among others:

- The previous ventilation system was replaced with a smoke extraction system, which can limit the area which is influenced by the fire. Therefore, a shorter part of the tunnel will be influenced by heating and the consequential damages. In addition, fewer electrical, mechanical, and structural parts will be polluted by smoke and soot, and hence the ventilation system can have a beneficial effect on the duration of tunnel closure.
- Furthermore, the smoke extraction system makes it possible for the fire fighters to come closer to the seat of the fire in shorter time, whereby the duration of the fire can be reduced.
- The procedures of fire fighting have been further developed part of the education of the fire fighters and have been regularly tested in the training facilities. As result of the improved tactics, procedures and use of water, less damage on the structure and the equipment can be achieved.
- The operation of the tunnels in the region has been unified and made more efficient with respect to detection of incidents and automatized reaction. Hereby the duration of the response has become shorter, and it is less likely that incidents develop to serious events.

Evaluation, Lessons learned and recommendations

The case study illustrates that it is important to be prepared for the possible damages resulting from a fire. The preparedness includes:

- The analyses of typical damages of fires in a road tunnel.
- Organisational preparedness with available know-how for the analyses of the actual damages (to the structure and the technical system) as well as know-how for the repair and construction process.
- Prepared procedures for the securing and stabilising the damaged structure.
- Available typical “spare-parts” for the structure and the technical system or prepared procedures for producing these parts (for example prefabricated structural elements for the wall lining).
- Preventive measures, including a ventilation system, fire fighting procedures and tunnel operation procedures.

Legend 🟢 = Positive / No problems 🟡 = Neutral or mildly positive / Some points of attention 🔴 = Poor / Problematic	Resilience against			
	Refurbishment	Maintenance	Accident	Fire
Gotthard Road Tunnel	-	-	-	🟡🟢

Further information
See links below.
References or interesting web links
[1] INSTANDSETZUNG VON TUNNELABSCHNITTEN IM HOCHTEMPERATURBEREICH AM BEISPIEL DES GOTTHARD-STRASSENTUNNELS, Andreas Henke, Lombardi AG, Beratende Ingenieure, Minusio, 102.1-R-143 Schulungszentrum TFB. [2] Mordasini Andrea: "Risanamento della galleria a seguito dell'incendio del 31.10.1997" Rivista tecnica, marzo 1999 [3] Meeting on 7. April 2021 with Willi Gnos, Head of Section Operation National Roads and Fabian Tresch, Head of Operational Control Centre, Office for Operation of National Roads / Canton Uri

APPENDIX Q: CASE STUDY: SECOND TUBE FOR TYNE TUNNELS, NEWCASTLE, UK

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Second Tube for Tyne Tunnels, Newcastle, UK
Authors	Hanson Pottinger, Fathi Tarada
Date of preparation	15/04/2021
Description of the case study	
Construction of second Tyne Tunnel to meet capacity demands and improve resilience of A19 corridor through North East of England.	
Objectives	
• Provide additional capacity to meet the demands of the A19 corridor which was regularly processing 33,000 vehicles per day through the existing tunnel which had a design capacity of 28,000 vehicles per day. • Construct a new tunnel and refurbish the existing tunnel to modern safety standards including emergency escape corridors.	
Technical challenges	
<u>Prior to the construction of the second tube:</u> An on-site fire-fighting presence had to be provided, since the Tyne and Wear Fire & Rescue service require 12 – 15 minutes to reach the tunnel, plus deployment time, whereas the require response time is 2-3 minutes. In practice, all fires were dealt with by operational staff, who acted as on-site fire fighters. Due to the nature of traffic flow in the bidirectional tunnel, any incident caused blockage on both sides of the tunnel, and recovery of stricken vehicles was difficult. <u>During construction:</u> Five different construction methods were utilised to accommodate interface with existing tunnel and underground facilities – gas/sewers: Cut & Cover, Contiguous Pile, Submerged Tube, Sprayed Concrete Lining and Box Section. A single 200 m^3 fixed fire-fighting system (FFFS) holding tank was built on the south side of Tyne river, as part of the new south extract ventilation building.	

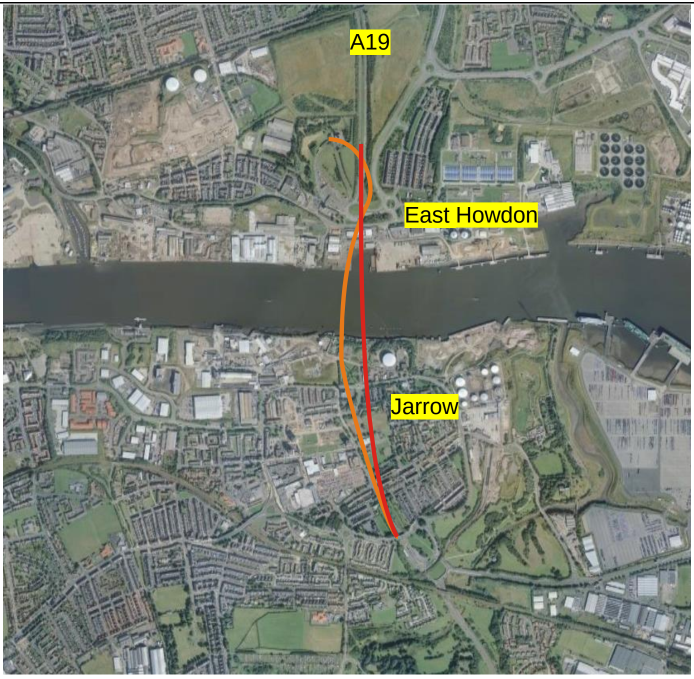


Figure 1. Tyne Tunnels Horizontal Alignment (orange=northbound, red=southbound)

Non-technical challenges

- Construction needed to be undertaken with no interruption of the existing facility. Migration of the new facility during refurbishment of existing tunnel was required with no impact on the existing capacity of the A19 corridor throughout the construction period.
- Better automation of toll plaza and the presence of FFFS led to a reduction in operational staff requirements. These reductions were negotiated and agreed with the trade union at the transition from local government (Newcastle City Council) control to TT2.
- Training of staff in new arrangements while still operating the existing tunnel was required. This was delivered using in-house training in collaboration with the equipment suppliers, integrators and consultants.
- A Tunnel Design and Safety Consultation Group was formed with all relevant stakeholders to discuss safety issues in relation to the tunnel design and operation.

Evaluation (effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)

- Capacity was increased to allow additional traffic along A19 corridor without any delays to travel. The peak vehicle throughput was measured at 63,445 in May 2016.
- Uni-directional travel of traffic greatly reduces the opportunity and potential outcome of an incident in the tunnels.
- Second lane in each direction allows natural clearance of vehicles around an incident without requirement of local traffic control around stricken vehicles.
- M&E facilities installed within both tunnels, with the option of operating bi-directionally in order to overcome any major incident in one tunnel.
- Fully enclosed, independently ventilated, escape corridors in both tunnels providing a safer means of escape from any incident.
- Implementation of resilient CCTV with Video Automatic Incident Detection (VAID) capabilities for real time system notification to control room of incidents within the tunnels.
- Introduction of High-Pressure FFFS to protect infrastructure and equipment in fire incidents, greatly reducing the potential impact of heat damage to structure and services and allowing the return of the tunnel to normal operations within a reduced time.

- FFFS installation removed the requirement for water and foam tanks on tunnel vehicles to fight fires and removed the requirement for operational staff to be trained up for firefighting techniques.
- Additional lifecycle costs in maintaining FFFS are expected to be outweighed by avoidance of traffic delays in the aftermath of a severe incident, followed by a reduction in injuries, fatalities and emergency service attendance costs and a reduction in damage to the tunnel structure and its installations (see Ref. 1 below).

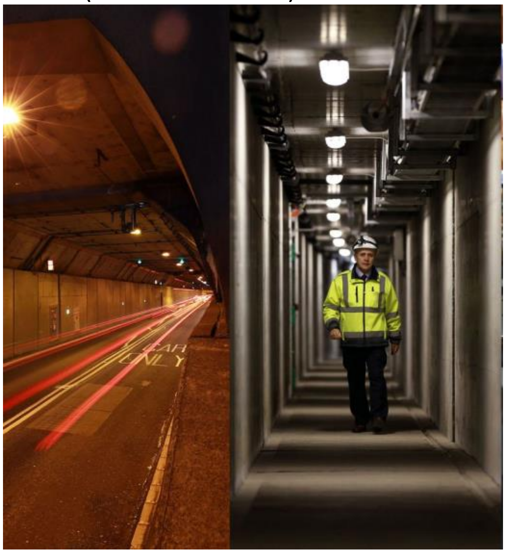


Figure 2. Evacuation passageway in the northbound Tyne Tunnel

Lessons learned and recommendations

Capacity requirements drove the project, with over-use of the existing tunnel resulting in significant delay in journeys around peak periods. These physical capacity limitations were mitigated with the construction of the new tunnel and refurbishment of the existing tunnel, removing all delays to normal travel along the A19 travel corridor. In particular, the availability requirements imposed by the North East Combined Authority on TT2 have been met. The travel through the tunnels is significantly safer through the reduction in the risk and consequences of an incident in the tunnel as well as the additional facilities protecting the tunnels, the facilities and the tunnels users. The presence of FFFS gives an additional layer of protection, also for unforeseen risks.

Further information

Tyne Tunnels website: https://www.tt2.co.uk/

References or interesting web links

Ref. 1: “Crossing points”, Fire Risk Management Journal, March 2009 (available from https://mosen.global/wp-content/uploads/2011/01/New-Tyne-Crossing-Fire-Suppression.pdf).

APPENDIX R: CASE STUDY: SALTASH TUNNEL, UK

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Saltash tunnel
Author(s)	Christian Perez, Gary Clark, Julian Mitchell
Date of preparation	April 19th 2021

Description of the case study

The Saltash Tunnel is a 410 m long, three-lane bi-directional road tunnel provided with a longitudinal ventilation system (jet-fans). Two lanes operate in one direction, one lane in the other direction. The central lane operates in the direction with the most traffic, and this can change between morning and evening peak. Due to this configuration, it is expected to have traffic at both sides of any disturbing event within the tunnel, potentially impacting the tunnel user safety and availability of the tunnel significantly. In addition to this, potential vehicle fires need special consideration as they are complex scenarios to manage safely as smoke may reach the tunnel users depending on atmospheric conditions and ventilation strategy.

This case study is about how Saltash Tunnel has sought to increase resilience by defining, implementing and validating operational procedures and minimum operating requirements that are focused on maintaining safety levels in the tunnel for all traffic scenarios and under degraded operating conditions.

Objectives

Saltash Tunnel defined target resilience levels and implemented a series of measures and strategies to maximise the availability of the tunnel through operational systems that provide for transparent decision making on elements such as operating procedures, maintenance intervention strategies, and building redundancy into design for refurbished systems:

For this purpose, a set of interrelated objectives were defined:

- Definition of the current and target levels of safety in the tunnel;
- Risk-based definition of minimum operating requirements;
- Identify and implement upgrade strategies for tunnel M&E and technology systems with cognisance of MORs and tunnel resilience requirements;
- Develop appropriate strategies for fire response that maintain the required risk-based safety levels (including the exploration in realistic environment with hot smoke experimentation).

Technical challenges

<u>Assessing the tunnel Safety Level (risk assessment)</u>

The focus of the stage is on understanding the overall safety levels in the existing tunnel for the existing safety system provision, with tunnel systems and procedures assumed to be operating effectively. Risk assessment is conducted to estimate the level of risk in the existing Saltash Tunnel and identify the risk reduction potential for various improvement measures to demonstrate that risk can be reduced to that of a target ‘reference’ condition where risk is judged to be ALARP. Risk results for key tunnel upgrade options are presented in terms of ‘Expected Values’, F(N) Risk Graphs and Risk Matrices, suitable for relative risk comparison between different cases.

Risk-based definition of MORs

A resilience tool based on MOR principles able to provide real time information on the tunnel safety level based on systems health was developed and implemented. Both degraded system and a sudden system failure scenarios were considered and a set of practical mitigation and compensatory measures were defined enabling a continued safe operation of a tunnel in case of degraded systems or sudden system failures (e.g. lane closure, speed limit, traffic management…).

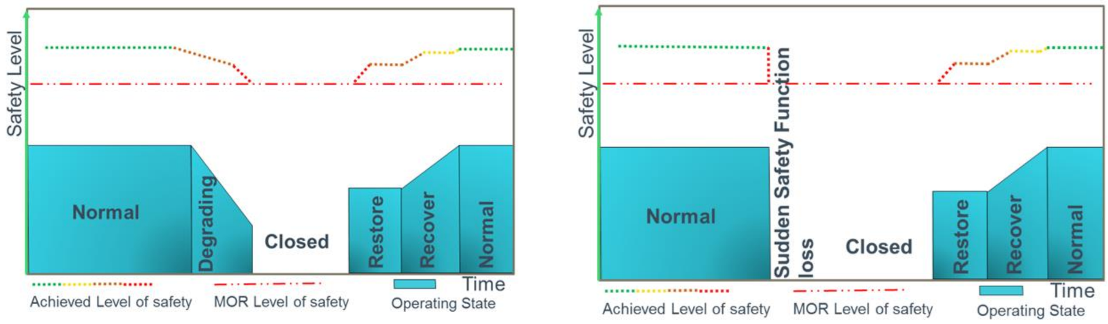


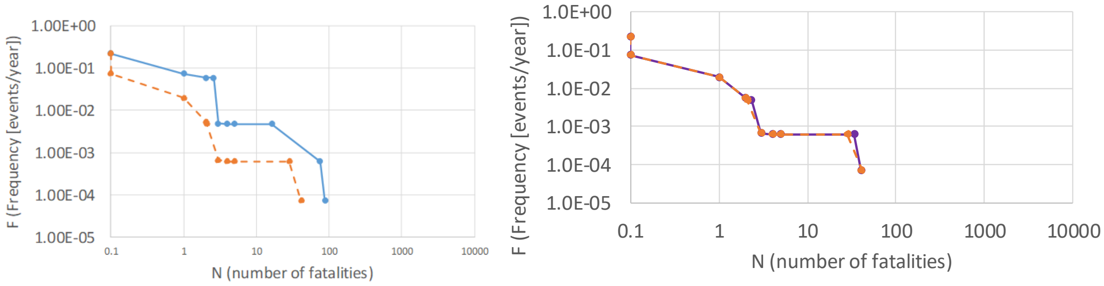
Figure 1: Illustration of MOR principles for degraded system and sudden failure system

This MOR system improves resilience by increasing the availability of the tunnel by providing real-time tunnel safety assessment and quick deployable measures under pre-defined and agreed strategies that reduce both the restoring and recovering periods.

Implementation of upgrade measures

A set of upgrade measures were considered, including automatic fire & incident detection system, PAVA systems, radio break-in, mobile telephone rebroadcast, wayfinding, ventilation system strategies, fixed fighting system, among others.

Risk results showed that upgrading systems like the incident detection and evacuation management systems can bring the estimated risk level down to that which is considered comparable to the reference, ALARP level of risk. Also results showed that additional risk reduction can be achieved with aditional provision like a fixed firefighting system (FFFS), Public Address – Voice Alarm (PAVA) systems or a ventilation extraction system for smoke control. The implementation of these provisions was assessed in the context of cost-benefit considerations (ALARP level of risk).



a) Tunnel without upgrades b) Tunnel with upgrades

Figure 2: Example of FN curve for different scenarios. Orange dotted line represents target safety level defined based on ALARP concepts– Blue solid line represents tunnel safety level based on existing/upgraded provisions and strategies.

With this approach it is possible to challenge and assess the benefit of the implementation of non-standard systems in UK as for example the installation of smoke detectors (first time in UK road tunnel) for which international standards and guidance were used.

Understanding the emergency response in case of fire

After the upgrade of the tunnel, the fire safety emergency strategy was challenged by performing a set of hot smoke demonstrations able to reproduce realistic effects in terms of smoke flow and temperature (similar to a vehicle fire).

Scenarios were defined, based on MOR and pre-defined emergency strategies. The response and coordination of tunnel operator and emergency response services as well as the contribution of the upgraded fire related systems (PAVA, wayfinding system, smoke detectors, ventilation strategies) on the tunnel of safety were assessed. Results provided evidence for the improvement of the safety and resilience level of Saltash Tunnel, and validating MOR mitigation strategies.

Figure 3: High performance hot smoke demonstration in Saltash

Non-technical challenges

N/A

Evaluation
(effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)

The project outputs were:

- A detailed ALARP risk profile for the tunnel, defining safety risk levels and requirements;
- A comprehensive set of minimum operating requirements linked to resilience level requirements and strategy for monitoring the level of safety of the tunnel as well as to provide a set of mitigation and compensatory measures that may be deployed to ensure the tunnel remains open, available and safe;
- A comprehensive methodology to upgrade Saltash tunnel considering the target safety level, changing conditions, and contribution of measures and provisions to the tunnel safety level;
- An implementation plan to upgrade the tunnel;
- A validation of the fire safety response improvement of the upgraded tunnel in case of emergency via the performance of a hot smoke demonstrations.

Lessons learned and recommendations
• It is recommended that road tunnels develop a comprehensive, validated set of minimum operating requirements at an early stage in the development of upgrade requirements in order to ‘drive’ the design towards maximising availability and resilience whilst maintaining safety levels. Such MORs should be presented in a transparent and simple way (ideally programmed into the tunnel SCADA system for ease of alerts and actions for operators) to enable effective implementation through the various stages in a tunnel life cycle. • It is recommended to consider overall safety in a performance-based approach. Alternative safety systems and procedures have potential to provide for greater resilience, but such approaches require significant effort in validation and stakeholder buy-in and approvals. • Hot smoke tests can provide an effective means to explore the interaction between the tunnel systems, the environment, and the products of a vehicle fire. This may be used to educate and inform both tunnel staff, emergency services and other stakeholders, providing input to the development and approval of a resilience-focused approach to the design for tunnel systems upgrade.
Further information
N/A
References or interesting web links
N/A

APPENDIX S: CASE STUDY: SCADRA SYSTEM, ITALY

Case Study PIARC TC 4.4 WG2 on Safety and Resilience	
Title of the case study	Improving Road Tunnel Resilience by SCADRA (Supervisory Control Acquisition Dynamic Risk Analysis)
Author(s)	Alessandro Focaracci, Italy
Date of preparation	12/10/2021
Description of the case study	

A SCADRA system is a new layout of the SCADA system, able to perform a Dynamic Risk Analysis, that has been developed to achieve immediate and effective benefits through the implementation of operational measures in Road Tunnels in which advanced systems and sensors are installed. Through the elaboration and analysis of all parameters acquired from sensors, a continuous monitoring of the safety level of the tunnel is carried out, performing the Dynamic Risk Analysis at regular pre-established intervals. Dynamic Risk Analysis is carried out under standard operating conditions and for an immediate re-evaluation of security conditions in case of sudden changes in traffic or environmental conditions or if some system performances decrease.

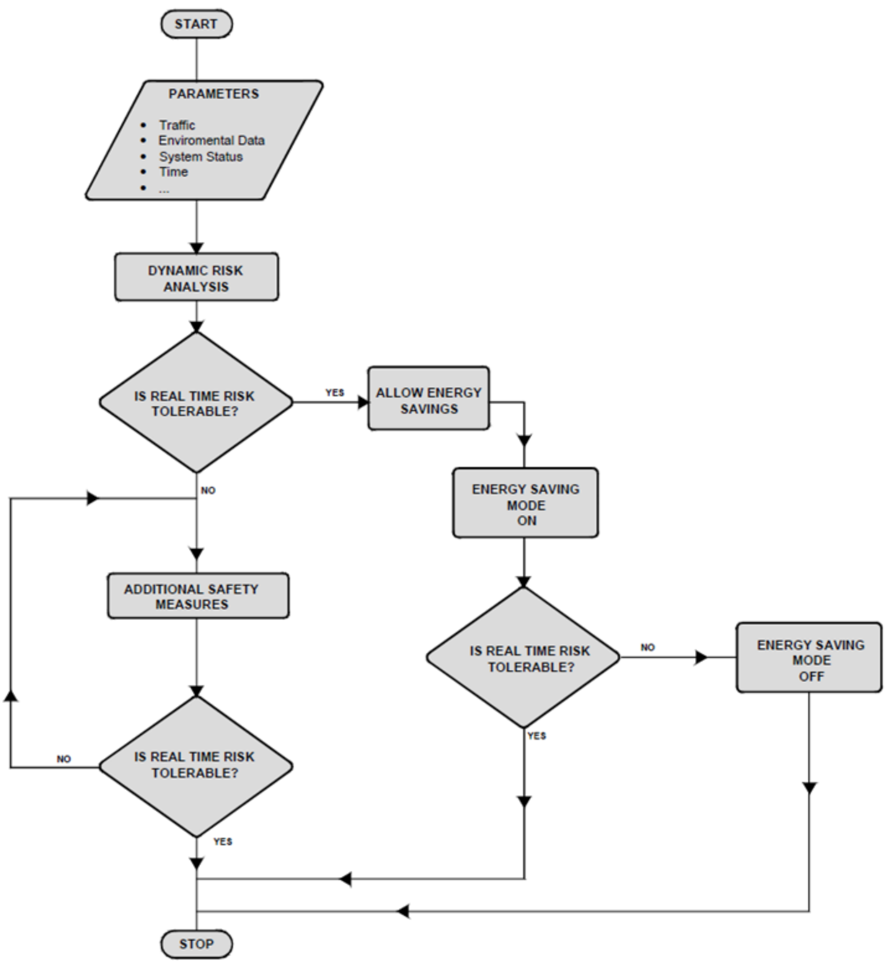


Figure 1 – SCADRA Flow Diagram

As shown in figure1, the innovative system of Supervisory Control and Acquisition oriented towards safety through a Dynamic Risk Analysis, also called SCADRA (Supervisory Control Acquisition Dynamic Risk Analysis) enriches the traditional system with an acquisition system of all parameters that may influence the managing of a tunnel (i.e. system failures, type of traffic, Heavy Good Vehicles, environmental conditions, …) that allow to do a quantitative dynamic risk analysis.

The following figures 2 and 3 show how a smart tunnel with a SCADRA system works. There is a status monitoring on safety equipment: an environmental parameters and traffic data acquisition, a traffic monitoring (for example reading plates of dangerous goods), a monitoring of the route through the use of fire patrols, etc.) All these inputs are used to perform a dynamic risk analysis with the SCADRA system that allows to have fast rescue in case of an emergency.

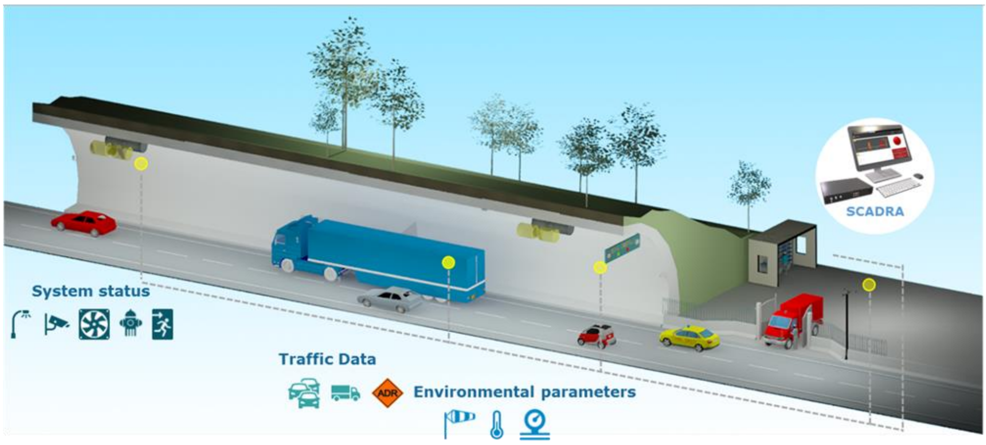


Figure 2 - Smart Tunnel and SCADRA

The information provided by the sensors and the historical data recorded are processed by the SCADRA through a specific software to have a real time risk evaluation in order to determine if the risk is tolerable or if it is necessary to implement additional planned measures.

The Dynamic Risk Analysis is performed at fixed time intervals (normally every 10 to 15 minutes) or when sudden changes in traffic, environmental or systems conditions occur.

The risk value is obtained through the quantitative probabilistic analysis according to the method defined by the Italian Law (IRAM) and the results of the analysis are the Expected Value of Damage (VAD) and the FN Curve of the tunnel that must be below the accepted Social Risk. The tolerability and acceptability criteria will be set evaluating risk in real time in comparison with the expected risk valuated during the design of the tunnel and approved by the Administrative Authority.

Also, the dynamic management of the tunnel installations, aimed at an energy efficiency, can be implemented respecting the safety of the users. The SCADRA allows to manage the systems in order to have energy savings only under optimal safety conditions so that this operation doesn’t determine an increasing of risk outside the tolerable values.

If the real time risk becomes relevant, the SCADRA start to manage the systems and to introduce some possible safety operational measures that could reduce it. In Figure 3 and 4 some examples of possible measures are shown.

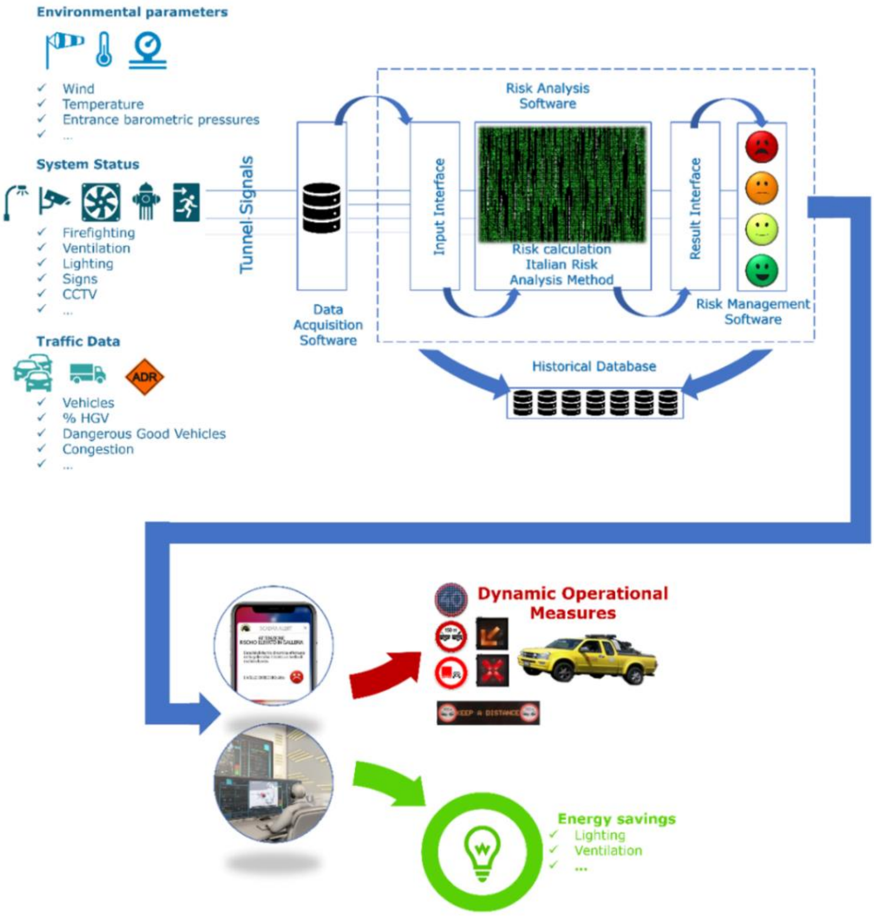


Figure 3 – System Layout

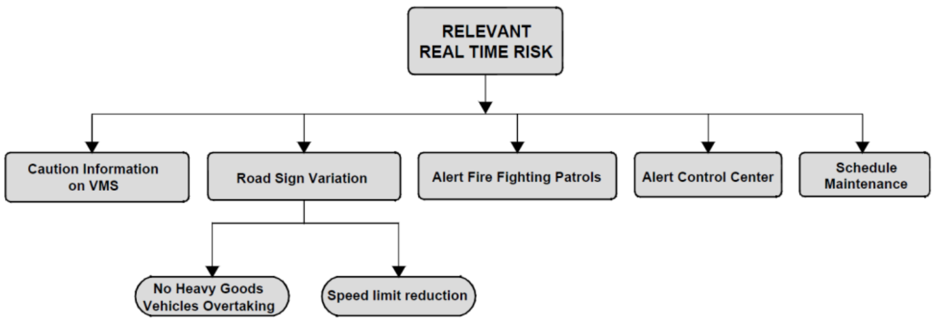


Figure 4 - Relevant real time risk

The equipment installed in tunnels, elaborate their analyses on a series of external input data. These input data have been divided into two macro categories:

• Fixed inputs, i.e. those input data related to the tunnel structure, not variable over time unless structure or tunnel systems changes.

• Variable inputs, that is, input data that may vary over time, such as the weather situation, vehicular flow data and the actual operation of tunnel systems (lighting, ventilation, ...).

The SCADRA subsystem acquires, as dynamic inputs, the input data and the parameters necessary for its processing, directly from the tunnel SCADA.

The level of risk, calculated as Expected Value of Damage (VAD), has been classified according to 4 categories of instantaneous risk:

- Level 1 – Low risk (VAD continuously below reference value) Corresponds to the tunnel in operation under optimal safety conditions in which the implementation of savings strategies could also be permitted (“safe energy” mode)
- Level 2 – Normal risk (VAD close to the reference value) Corresponds to a tunnel in operation under standard safety conditions
- Level 3 – Pre – alert (VAD begins to exceed the reference value)
- Level 4 – Alert (VAD begins to exceed the acceptable risk level)

The risk levels are represented by the system through a graphical interface by a series of differently colored emoticons. Depending on the level of risk, the figures indicated above will be shown on a screen related to the actual level of risk.

The following graph shows the VAD trend related to the surveys of 24 hours in a real tunnel and highlights significant deviations of the main input parameters if they are recorded at the same time as the rise in the level of risk to the attention area (level 3 and level 4).

A browser-based graphical user interface (shown in figure 5) has been developed in order to provide a simple interface through which the Control Center Operator can know the real time level of risk, the reasons for the growth of the risk level and the action to be taken.

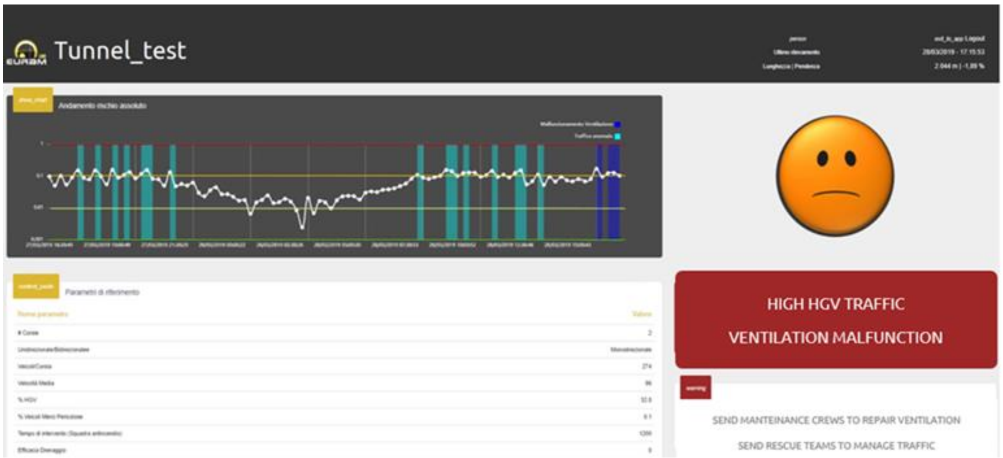


Figure 5 - Graphical interface

Objectives

The SCADRA system installation perfectly fits within improving road tunnel resilience: it is always possible to know real time what happens inside the tunnel, the environmental conditions, traffic data and system status and if it is necessary to apply operational safety measures in order to lower the risk level.

Depending on the expected level of risk, preventive measures like reducing speed limits, minimum distance among vehicles and prohibition of overtaking for HGV can be imposed, but also protective measures can be activated such as communications to users, fire brigade alert or interruption of the energy saving mode of the systems.

The proposed system could also be an effective optimization to manage the fire rescue team in order to reduce the instantaneous residual risk under critical conditions such as congested traffic in a tunnel with longitudinal ventilation positioning the fire rescue team at the entrance of the tunnel.

The dynamic risk analysis by the SCADRA becomes relevant during the maintenance intervention, during which some systems may be out of service or not fully operational.

Through the continuous acquisition and processing of data it is also possible to have a preventive maintenance focused on user safety, reducing the actions, the operating costs, the interventions time, MTTR (Mean Time To Repair), the unavailability, etc.

The Smart Tunnel and the SCADRA system allow controlling the systems in the tunnel and improving the effectiveness of the operational and integrative measures increasing the safety of the users and producing also other advantages like energy savings and the improved scheduling of maintenance.

So, the dynamic risk analysis allows to:

- pre-alert Institutions involved such as the Prefecture and the Fire Brigade;
- interrupt the energy saving mode of the plants;
- identify critical situations in real time;
- alert users in critical situations;
- restore the level of acceptable risk through interventions on the plants or through management interventions;
- plan optimal maintenance focused on user safety;
- reduce maintenance operating costs;
- reduce the intervention time.

Through the implementation of the SCADRA System the closure of the tunnels could be prevented by mitigating measures to assure an acceptable safety level.

Technical challenges

Future developments foresee that the SCADRA will also be able to monitor the structural status of the tunnel and any other structures, such as bridges, viaducts, as well as the presence of any landslides in the surrounding environments as shown in the following figure.

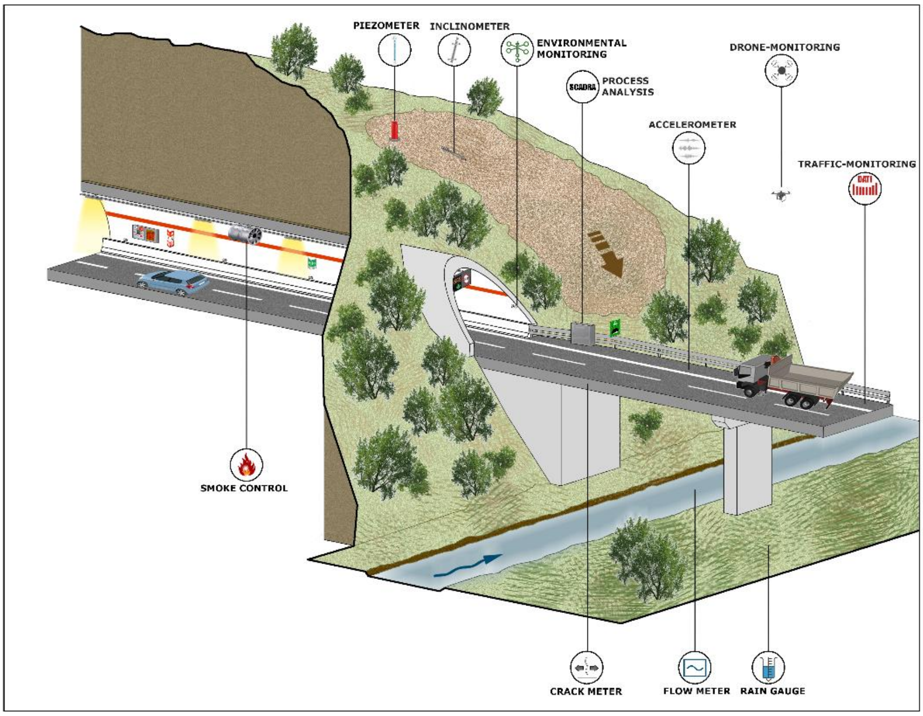


Figure 6 – Sensors for structures and environment monitoring

Non-technical challenges

The SCADRA system is a well-established system currently used to manage and monitor tunnels in various locations in Italy, hence it is a system developed following legislation and technical specifications applied in Italy. Therefore, the SCADRA system could require adaptations to be implemented in other European countries.

Evaluation (effectiveness, side-effects, complexity of implementation, life cycle cost, cost-effectiveness)

The implementation of the SCADRA system is quite simple. An industrial PC is installed in the main cabinet of the tunnel and connected with the SCADA system and all the necessary sensors. The software installed in the SCADRA allows dynamic risk analysis.

The cost of the SCADRA is compatible with that of a SCADA system. The benefits that can be obtained from the SCADRA are remarkable as described in the section "Objectives".

Figure 7 - An example of SCADRA installation

On the Italian motorway network, the SCADRA system is already used in several tunnels:

- Rimazzano Tunnel (A12 Livorno- Civitavecchia Motorway – concessionaire company SAT);
- Valico Tunnel – (A15 Parma-La Spezia Motorway – concessionarie company SALT);
- Melarancio Tunnel – (A1 – Milano-Napoli motorway – concessionarie company Autostrade per l'Italia).

In collaboration with concessionaries, an in-depth analysis, of the installed systems is underway, carried out through the analysis of the data and alerts taken from the SCADRA installations for a continuous improvement of the system.

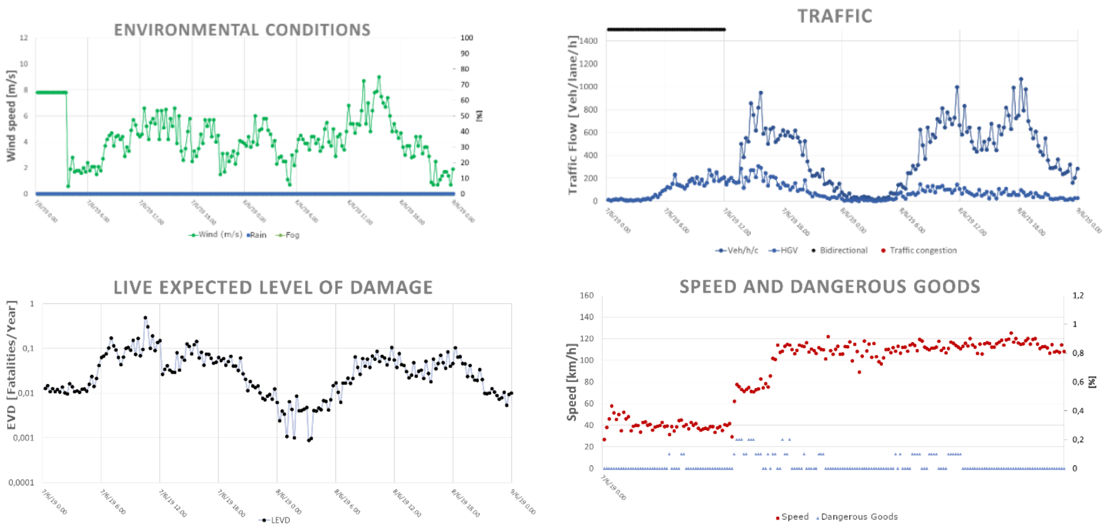


Figure 8 – Data from SCADRA installations

Lesson learned and recommendations
The SCADRA System can be considered a powerful prevention tool that could be integrated into all tunnels to increase their resilience. The proposed system is suitable also for existing tunnel exploiting innovative technologies with low costs that allow also improving safety in old tunnels, through operational measures that integrate the systems and, if necessary, replace the lack of requirements.
Further information
It is expected in the coming months the installation into Caltanissetta Tunnel - (SS640 Agrigento – Caltanissetta – concessionarie company : ANAS). Autostrade per l'Italia (A.S.P.I.), one of Europe's leading concessionaries for the construction and management of toll motorways, has included in its Business Plan 2020-2024 the installation of the SCADRA system in several tunnels.
References or interesting web links
[1] Focaracci, A., Greco G., "Smart Tunnel and Risk Analysis", WTC, 2018. [2] Focaracci, A., Greco, G., Martirano, L. "Smart Tunnel and Dynamic Risk Analysis", in Proc. IEEE Industry Applications Society Annual Meeting, Baltimore, USA, 2019. [3] Focaracci A, "Smart Tunnel and Dynamic Risk Analysis" XXVIth World Road Congress Abu Dhabi, 6-10 October 2019

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