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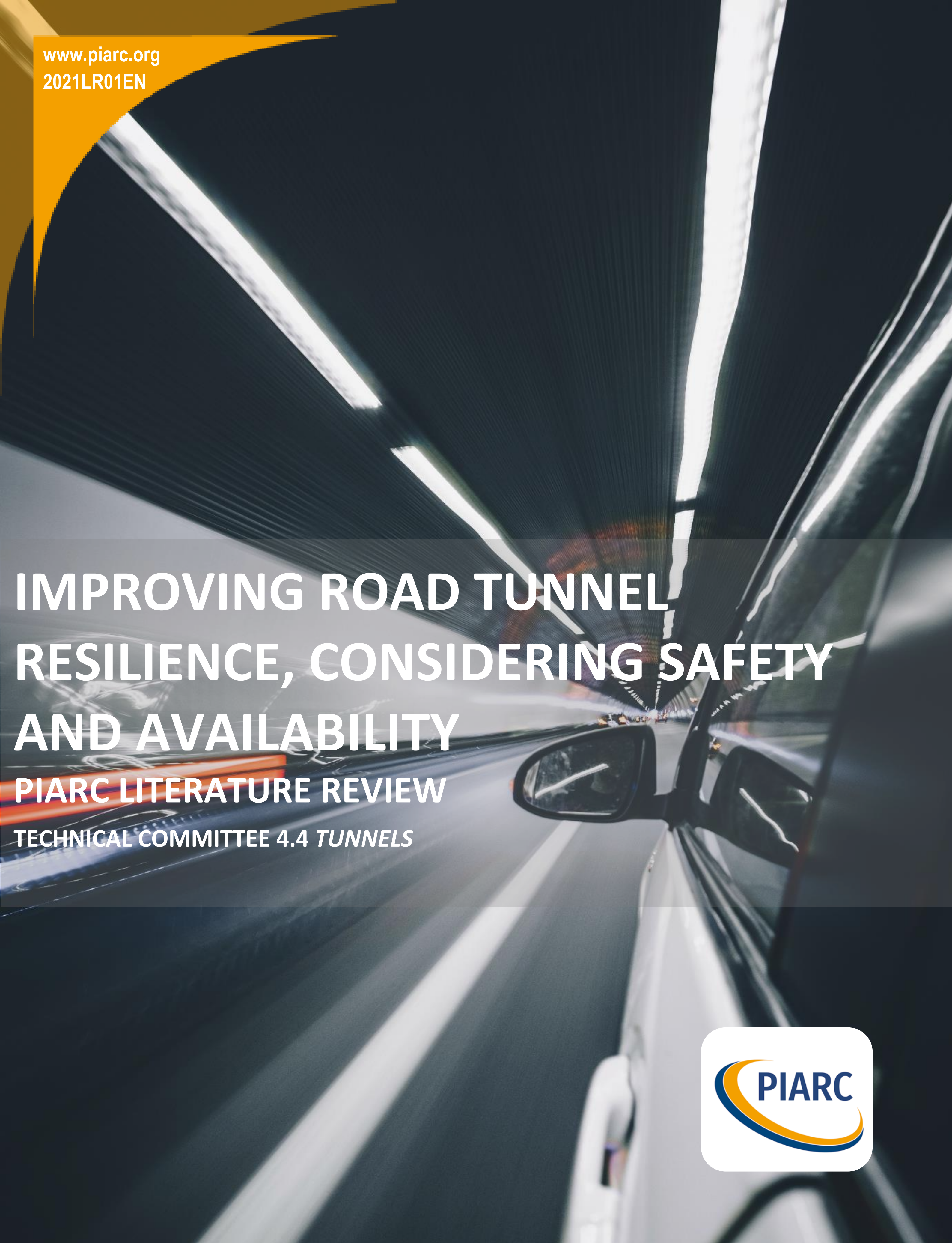

IMPROVING ROAD TUNNEL RESILIENCE, CONSIDERING SAFETY AND AVAILABILITY

PIARC LITERATURE REVIEW

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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PIARC LITERATURE REVIEW

TECHNICAL COMMITTEE 4.4 *TUNNELS*

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EXECUTIVE SUMMARY

2021LR01EN

IMPROVING ROAD TUNNEL RESILIENCE, CONSIDERING SAFETY AND AVAILABILITY

This report contains a review of literature on road tunnel resilience, including more general literature on resilience principles or aspects that could be applied to tunnels. Many definitions for "resilience" were found, but the Working Group decided on the following definition in the context of tunnels:

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

It is acknowledged that the definition of resilience is not yet stabilized and that this is being discussed withing PIARC from different perspectives and committees. For the time being and in the framework of this output, we have settled on the definition above. The work in this document will feed into the PIARC debate on resilience, which will feed the next outputs of the Working Group on resilience in the future months.

The review focusses on the following topics:

- General concepts and approaches for resilience management;
- 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 report is completed with conclusions and recommendations (for decision makers and PIARC), an extensive reference list, a glossary and appendices.

The literature review is the first step in the development of a full technical report on road tunnel resilience.

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.

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[1] 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 when called for is an important contribution to the resilience of the tunnel system. Note that the

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

acceptability of a safety level of a tunnel depends on the (inter)national legislation and policies the tunnel manager is subject to.

The PIARC Road Dictionary[2] does not contain a definition for tunnel (system) resilience. However, in line with 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".

This definition is in line with the general definition by Bruneau et al., but more explicitly adds the dimension of adaption, hence the ability to change or improve. 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). Thus, in consideration of the above mentioned examples, we (PIARC TC 4.4 Working Group 2) propose the following definition for road tunnel resilience:

"The ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential negative effects of events or developments affecting the availability of a road tunnel. 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;
- The tunnel structure;
- The tunnel technical installations (TTI), including the control systems;
- The control centre from which the tunnel is operated (when applicable);
- 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

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

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, as a first step towards a full technical report on the matter. 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 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 expand this report to a briefing note, scheduled for 2022, by adding case studies to the present content. The briefing note will then be expanded to a full technical report, scheduled for 2023.

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.

The literature review was 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.

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.

1.4. Working method

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). For the reviews, a standardized review sheet was used, see Appendix A.

Given the short time span of the study, the presented overview of literature sources is far from complete, and relevant sources may have been overlooked by the Working Group. However, based on the experience of the members, the Working Group feels that the presented overview very well reflects the essence of the concept of resilience, adapted to road tunnels.

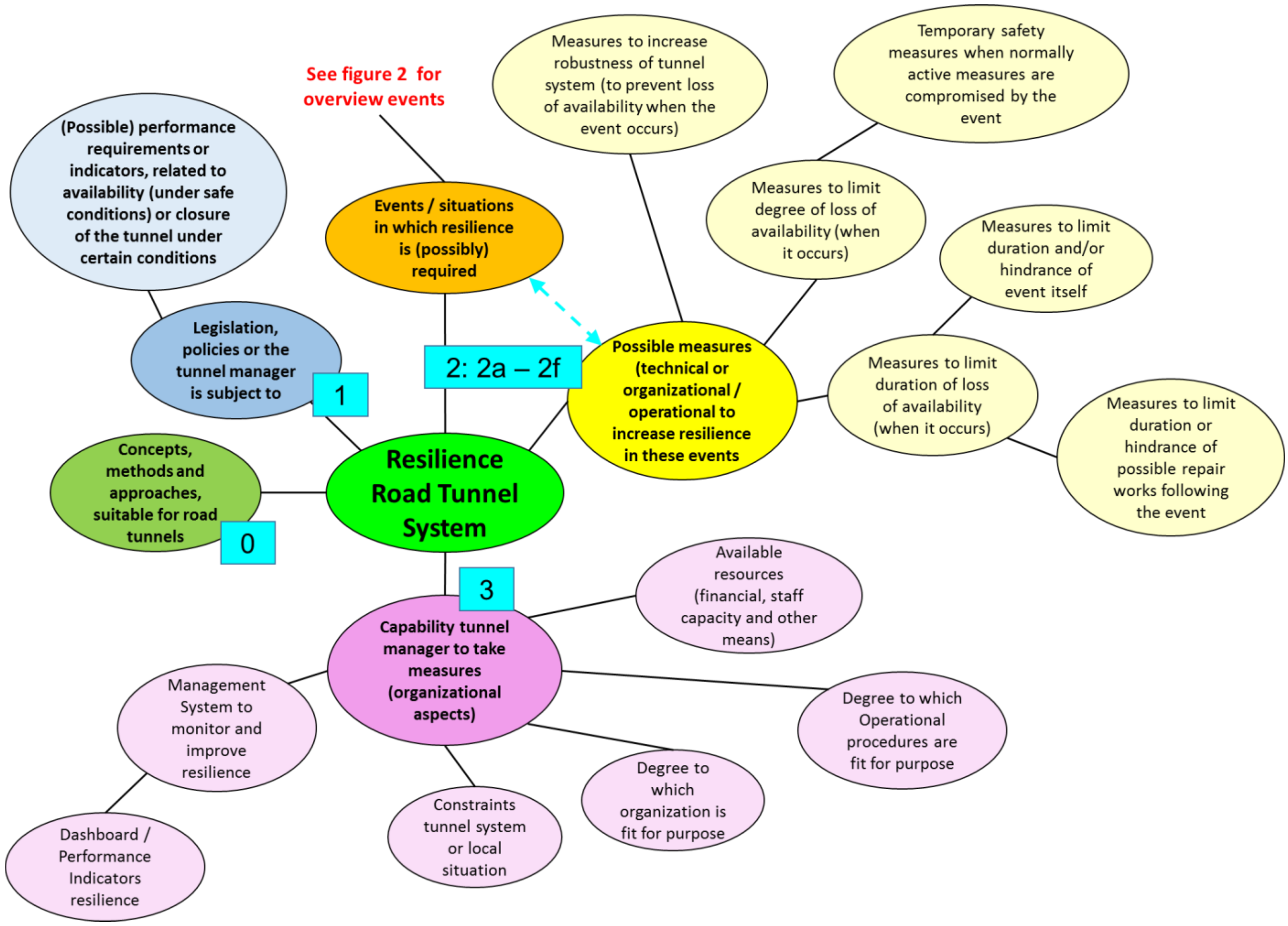

Figure 1. Overview topics related to road tunnel resilience, as a basis for the literature review

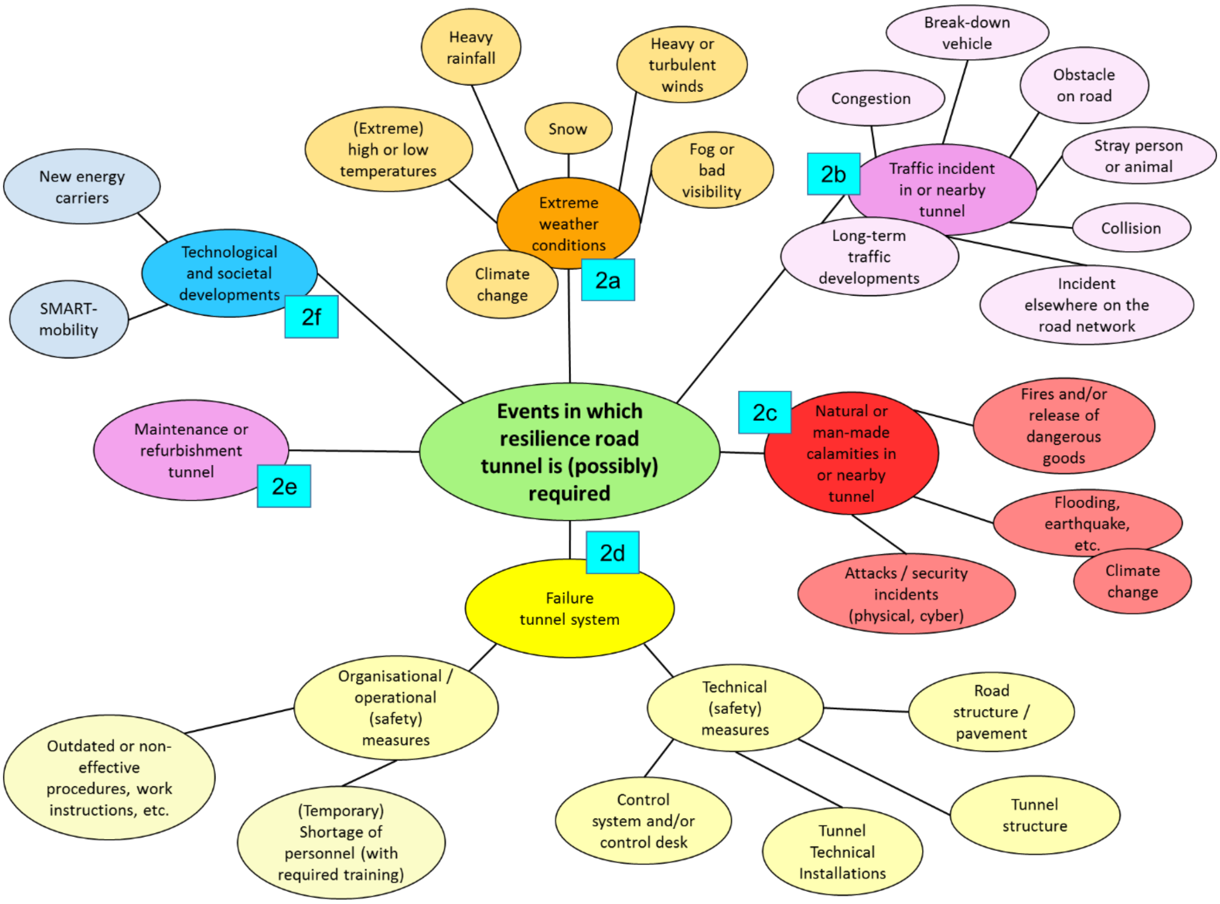

Figure 2. Overview of events or situations in which road tunnel resilience is (possibly) required

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 more often than not 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. The reviews of the literature sources discussed in Chapter 3 are assembled in **Appendix B**.

Last, in **Chapter 4**, 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 several appendices, containing back ground information to the chapters as described above.

2. ROAD TUNNEL RESILIENCE

2.1. CHARACTERISTICS

In section 1.1, road tunnel resilience was defined as:

*"The ability to prepare and plan for, **absorb**, **recover from**, or more successfully **adapt** to actual or potential negative effects of events or developments affecting the availability of a road tunnel. 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 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 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.

Measures to improve resilience (the subject of this literature review) may engage on one or more of these characteristics. Moreover, resilience goals set by the tunnel manager can also be related to one or more of these 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.

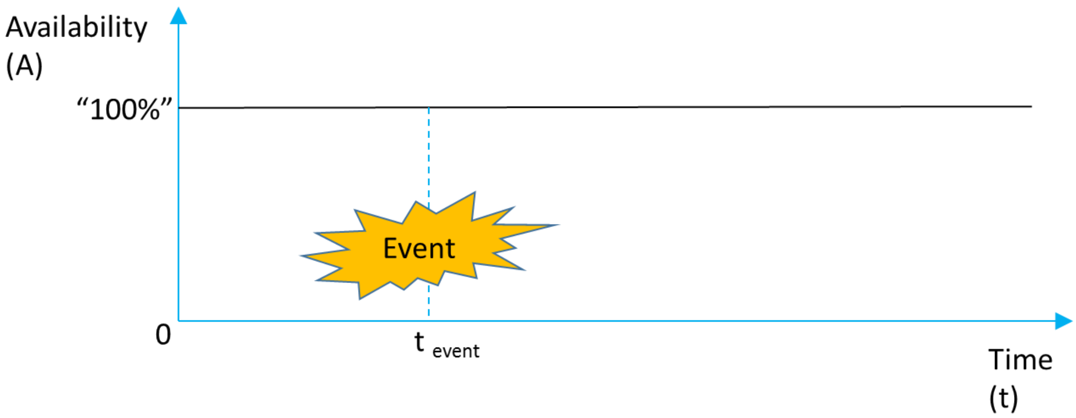

Figure 3. Example of full absorption of negative effects of an event

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.

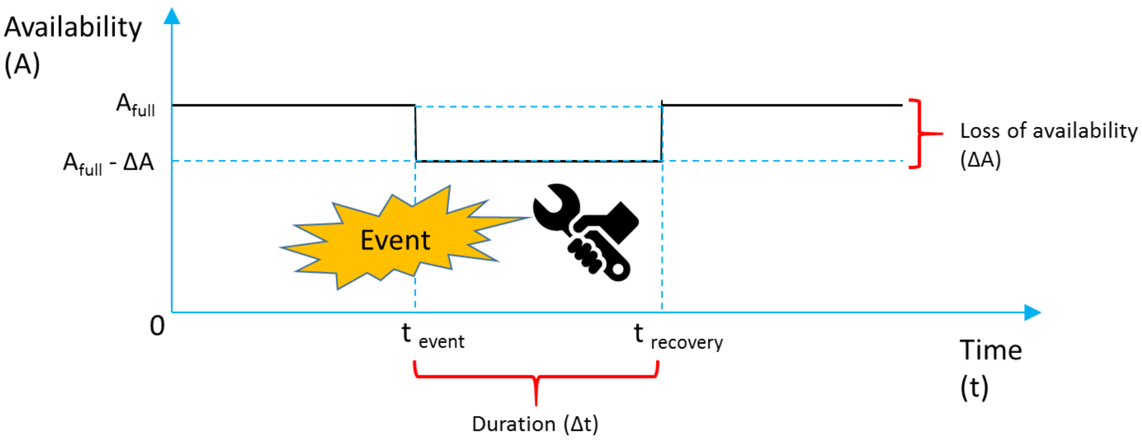

Figure 4. Example of an event leading to temporary loss of availability

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[3].

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

[3] 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.

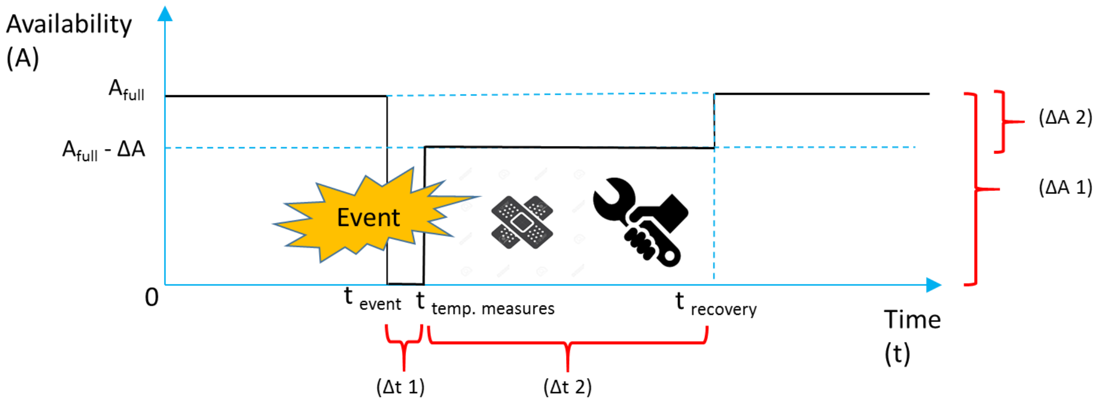

Figure 5. Example of an event with temporary mitigating measures to limit loss of availability

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 if the safety level decreases below a certain level, the availability for the traffic can be limited (because of mitigating measures to compensate for the loss of safety) or the tunnel (tube) can be closed completely.

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

- 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).

Although it varies from country to country (or even from tunnel to tunnel[4]) what an acceptable safety level would be, and , based on applicable legislation and policies, there are several frameworks available to deal with this matter (see **Chapter 3**) the basic principle is usually as follows:

- 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.

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

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

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.

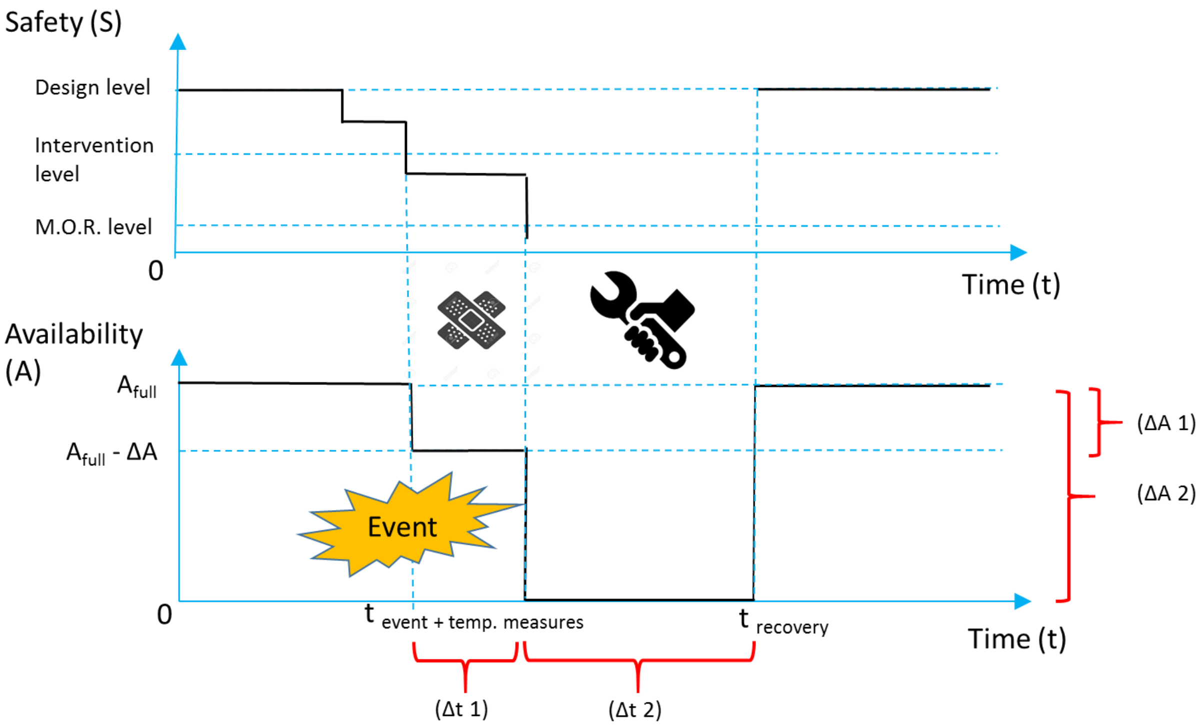

Figure 6. Example of decreasing safety level leading to loss of availability

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.

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).

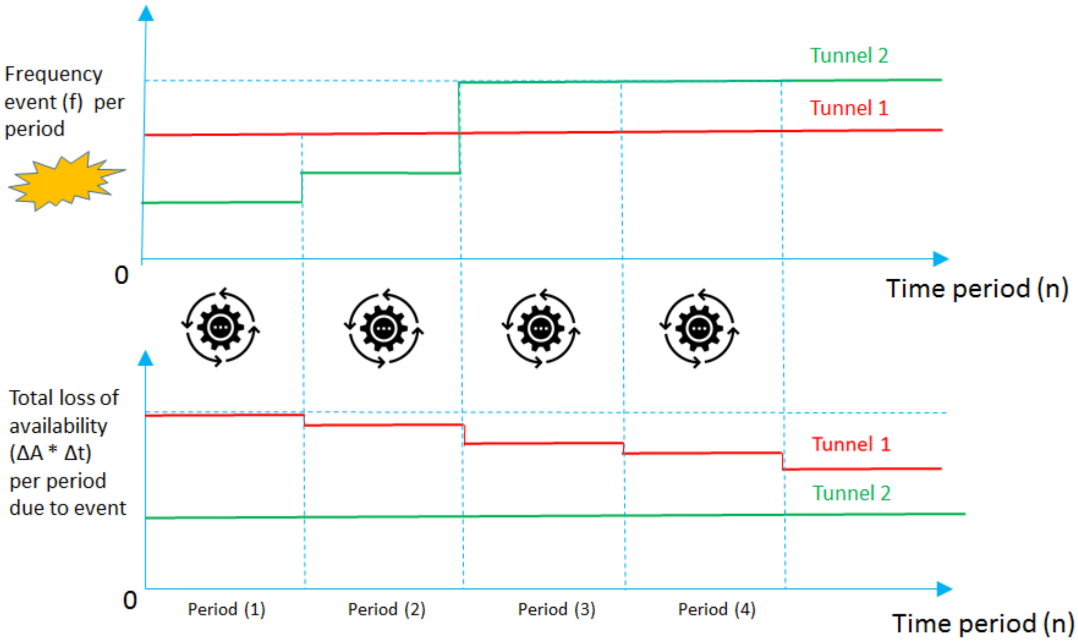

Figure 7. Example of adaptive resilience of two road tunnels

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 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 literature review 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: the lower the impact of a tunnel closure for the road users (at network level, taking into account travel time and traffic load) 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 (and the less measures are needed to enhance resilience).

3. RELEVANT LITERATURE

3.1. LEGISLATION, STANDARDS, POLICIES AND STRATEGIES

3.1.1. Legislation

This section is not meant to give an extensive overview of specific legislation that is 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. Each tunnel manager should check out the specific regulations for tunnel operation in the country in question.

In (inter)national legislation, road tunnel availability and resilience are typically addressed directly or indirectly through (see figure 8):

- Legislation on tunnel safety;
- Legislation on protection of critical infrastructures:
- Various other legislation.

In practice, the role of the legislator 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 the legislation.

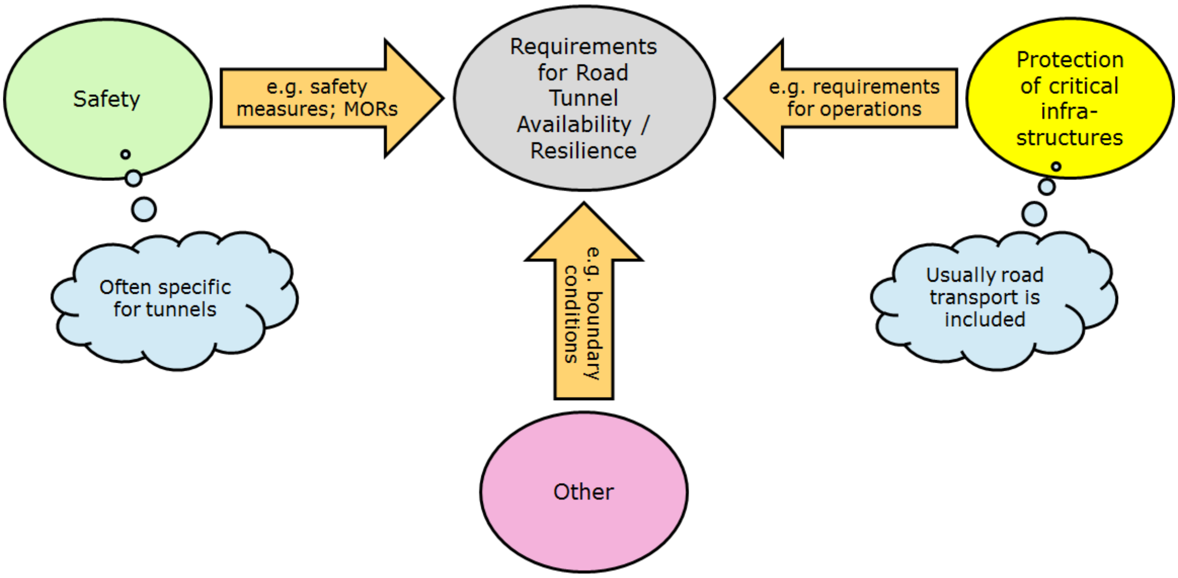

Figure 8. Typical topics of legislation that address or influence road tunnel availability and resilience

<u>Legislation on tunnel safety</u>

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, legislation on tunnel safety may contain rules for defining Minimum Operation Requirements (MORs) or even specified MORs; these are boundary conditions for the availability of the tunnel, because if the conditions of the tunnel system go below a 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 MORs.

Legislation on protection of critical infrastructures

This type of legislation 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”.

The legislation usually sets requirements 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.

Other legislation

Various other legislation could possibly set boundary conditions that limit the possibilities to use or operate the tunnel or the possibilities to improve the availability or resilience of the tunnel. Examples are environmental requirements (allowed noise level, allowed emissions, etc.) or requirements for working conditions.

3.1.2. Standards, policies and strategies

The requirements and boundary conditions set by legislation are often further elaborated in standards[5]. These standards come in various shapes and sizes and with different statuses. There are (inter)national standards (that may have a legal status themselves) 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 (MORs) 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,

[5] The opposite is also possible, that the content or domain of a standard is not yet covered by legilslation. In that case, the standard may even serve as basis for the development of the legislation.

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.

Standards and guidelines

- 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 9) 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.

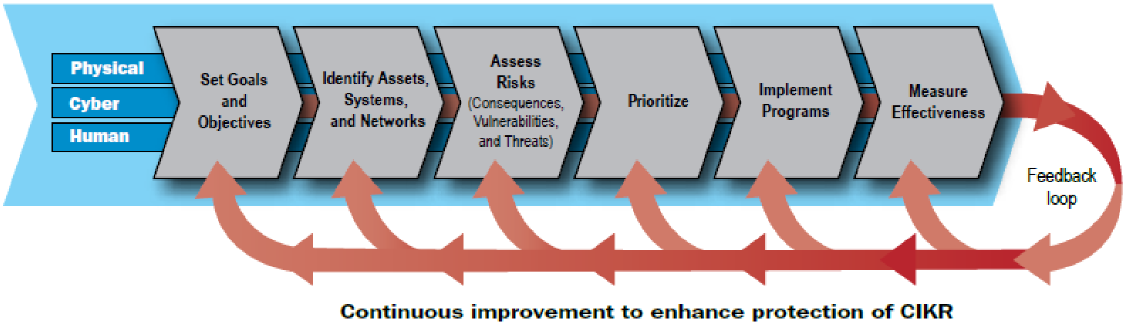

Figure 9. NIPP risk management framework to support and enhance resilience of Critical Infrastructure and Key Resources (CIKR) [18]

- 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[6]; 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 (MORs) [9], [11], [13] and [21]. In addition, the MORs of the Somport tunnel on the French-Spanish border can be mentioned as a tunnel-specific example [27].

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.

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

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 10; [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.

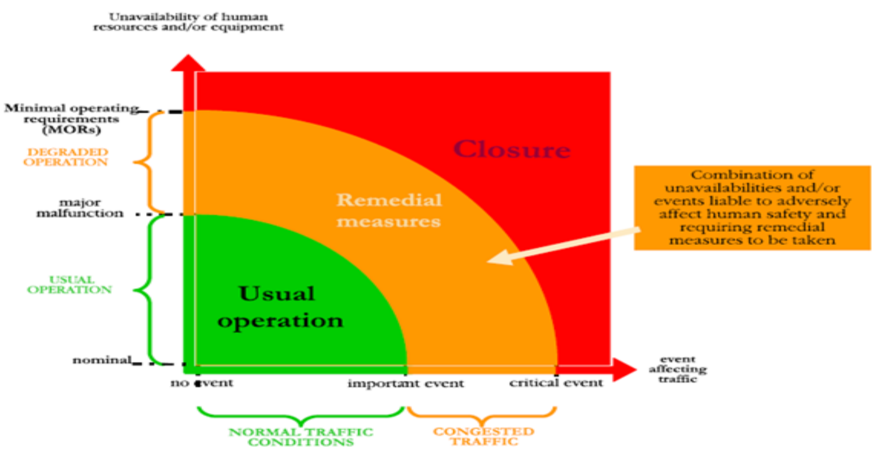

Figure 10. Various degraded operating modes [2], based on [13]

- 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[7]; 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 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 11.

[7] 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.).

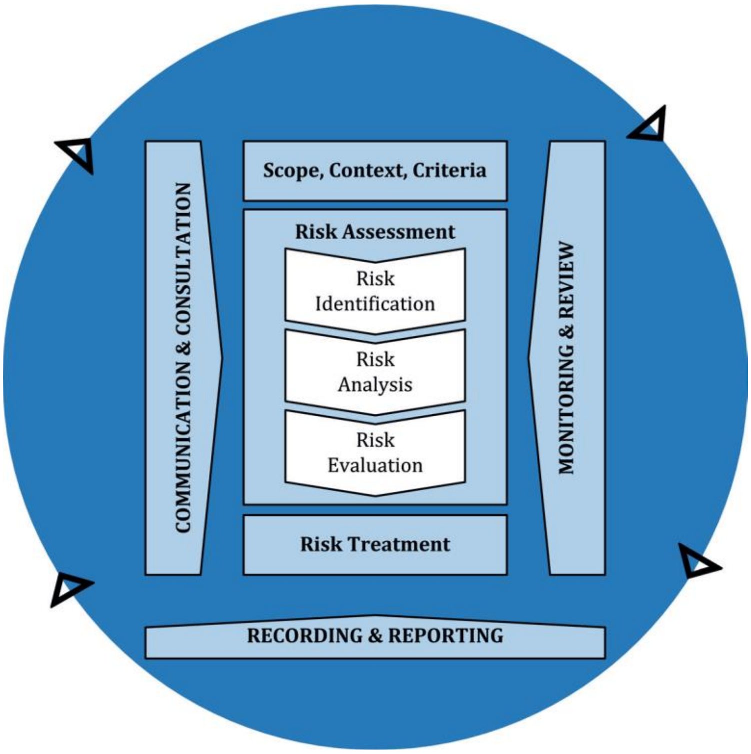

Figure 11. Risk management process according to ISO 31000 [53]

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 12.

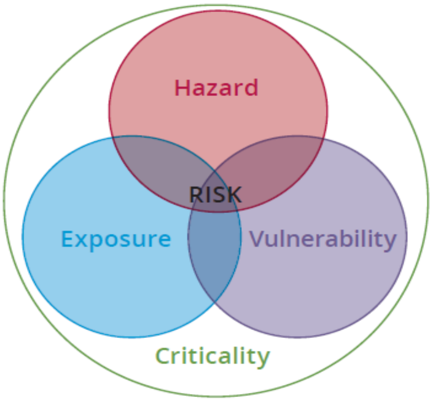

Figure 12. Risks, in terms of hazards, exposure, vulnerability and criticality [67]

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 13.

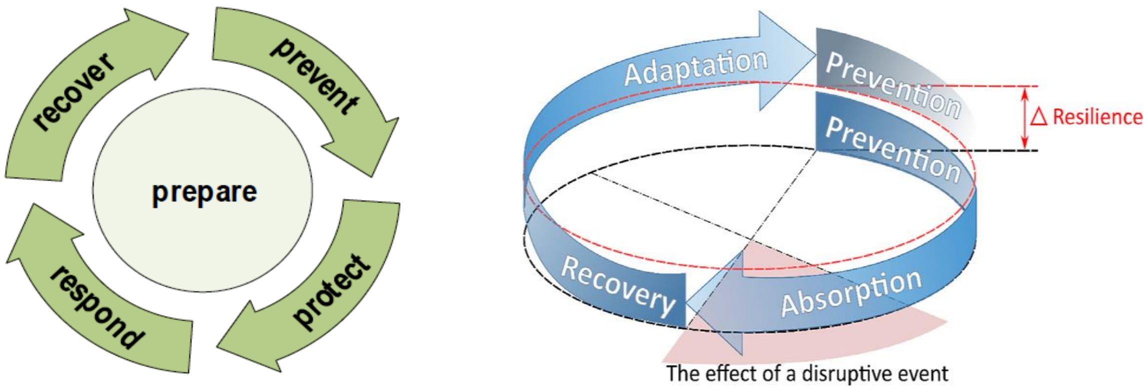

Figure 13. The resilience circle (left: [45], Right: [68]), based on Edwards (2009)

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 14.

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 14 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.

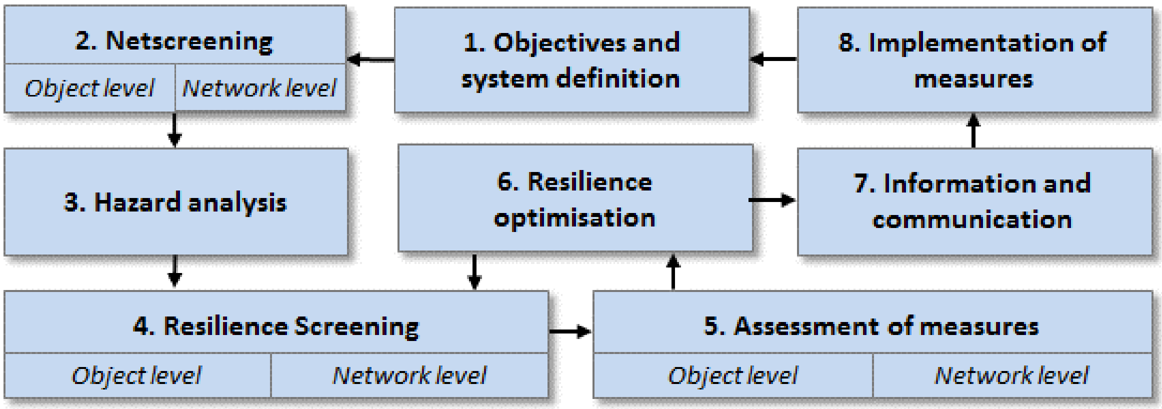

Figure 14. Modules and workflow of the iterative resilience management process [62], based on [80]

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 14.

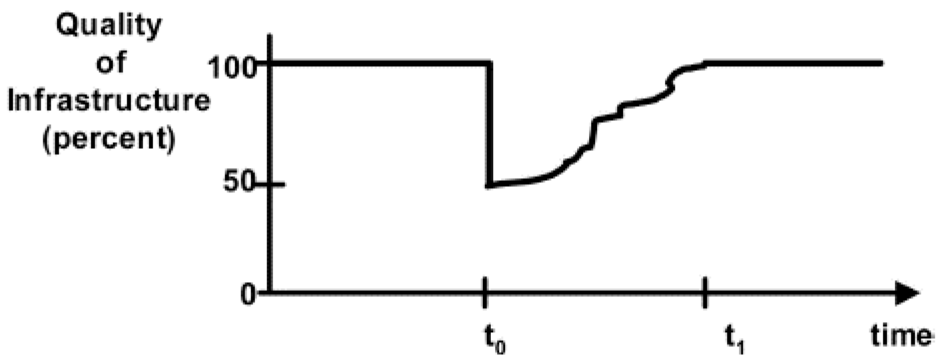

Figure 14. Measure of resilience – conceptual definition according to Bruneau et al. [1]

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 15. Article [24] deals with the entry points (bridges and tunnels) of the island of Manhattan (New York, USA) but figure 15 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.

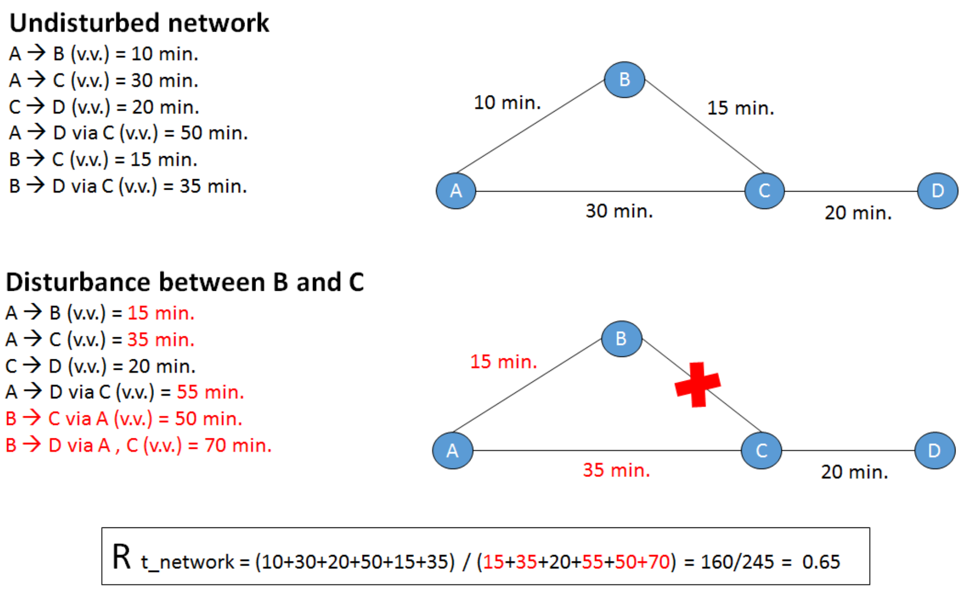

Figure 15. Principle of network resilience according to Omer et al. [24]

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 15, $R_{t\_node\_(B\text{-}C)}$ 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 15 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 16:

$R = P_{fa} - P_f$ (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).

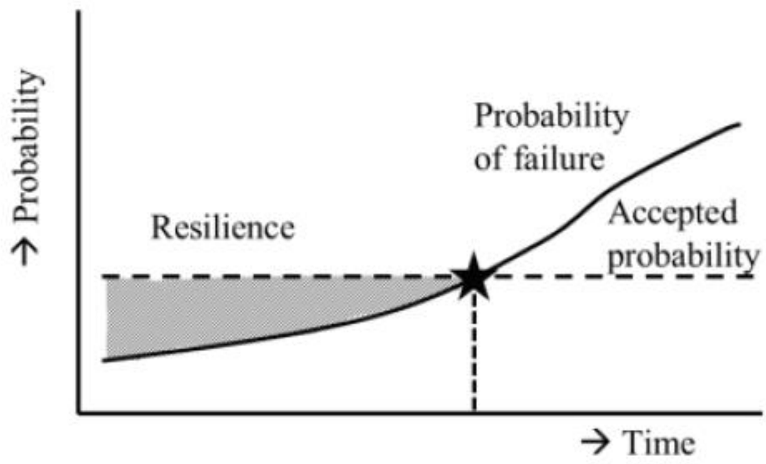

Figure 16. Resilience as the comparison between the probability of failure of the considered system and the accepted probability of failure [26]

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[8]. 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?);

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

- 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;
- 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:

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

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

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

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 17.

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 17. 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[9] 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[10]:

[9] “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.

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

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

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 18.

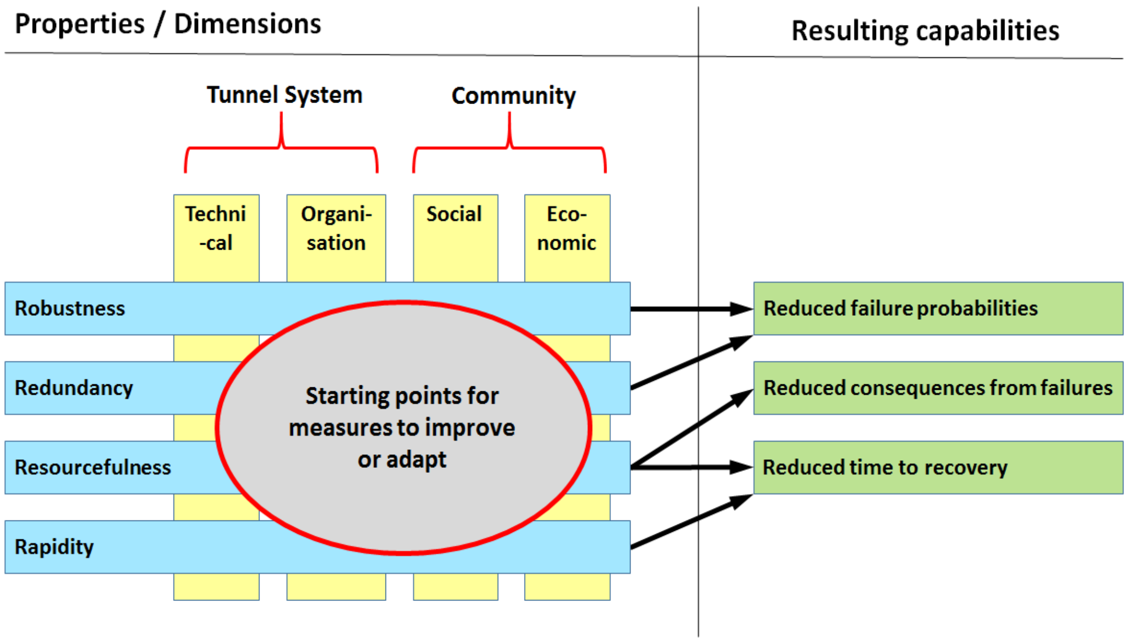

Figure 18. Resilient tunnel system in relation to resilient community according to Bruneau et al., based on [1]

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.

Last but not least, earthquakes also form a natural hazard to take into account.

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).	[-]

3.3.3. 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 19 (and table 7).

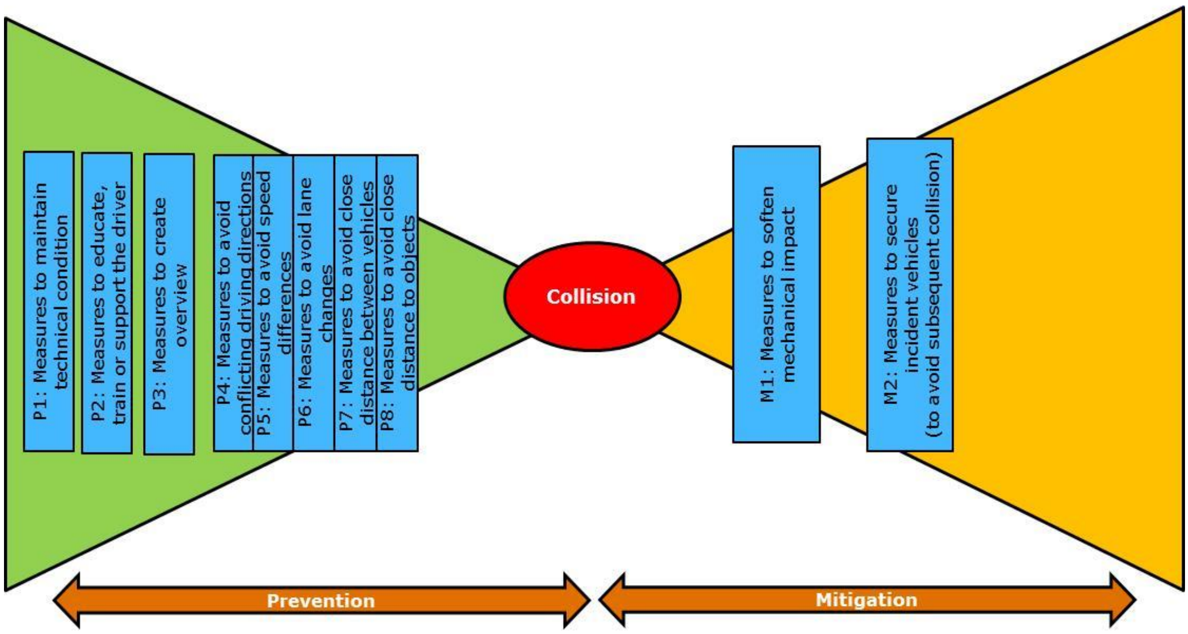

Figure 19: Bow tie model for the prevention and mitigation of collisions [41]

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.	[-]

3.3.4. 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]

3.3.5. 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.	[-]

3.3.6. 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.

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]

3.3.7. 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]

3.3.8. 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].

<u>SMART mobility</u> 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.

<u>New energy carriers (NECs)</u> 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[11] 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

[11] 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.

advantage of this method is that only a little amount of water is required for a great 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 20).

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.

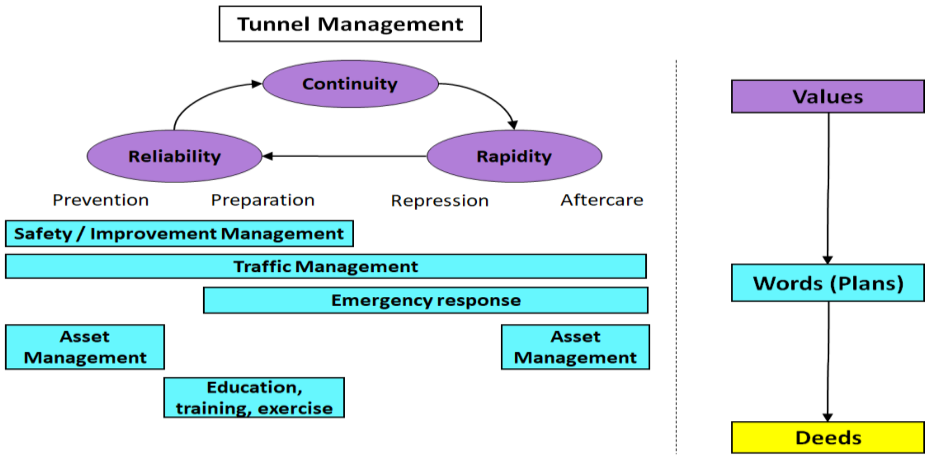

Figure 20. Principles of tunnel management organisation, aimed at a continuous safe traffic flow [9]

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. CONCLUSIONS AND RECOMMENDATIONS

4.1. CONCLUSIONS

This report presents an overview of the literature on resilience of road tunnels and critical infrastructure in general.

The literature sources 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 restored (recovery). 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[12].

The presented approaches are broadly applicable, and in fact independent of the content or strictness of the requirements for availability and safety. 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).

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.

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

- 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);

[12] 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.

- 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.

There is likely to be much practical knowledge and experience that hasn't been documented yet. Therefore, the next step would be to collect case studies to complement the literature sources.

4.2. RECOMMENDATIONS

4.2.1. Recommendations for decision makers

Given the importance tunnels normally have in the road network, resilience is an aspect that should be considered adequately. To manage and improve road tunnel resilience:

- 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 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 requirement when relevant.

4.2.2. Recommendations for PIARC

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

- Collect case studies on experiences with road tunnel resilience improvement in practice, at least involving the topics that would need some more attention, as mentioned in section 4.1; but also "new" topics, that were not covered in this report but appear to be relevant, would be interesting; the effectiveness, Life Cycle Cost (LCC) and the resulting cost-effectiveness would also be important points of interest;
- Develop (guidelines for) a dashboard with performance indicators and other steering information that is suitable for improving road tunnel resilience; the above mentioned case

studies could –along with the available literature sources- provide input for such a development;

- Make an inventory of possible mitigating / alternative measures in case of failure of safety provisions in the tunnel system, and, if possible, quantify / validate their safety effect; again, case studies could provide input for this.

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

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6. GLOSSARY

Term	Definition
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 resilience	The ability of the tunnel system to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential negative effects of events or developments affecting the availability of a road tunnel. 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 tunnels)	The ability of the tunnel system (as a result of adequate planning and preparation) to absorb actual or potential negative effects of events or developments, 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 tunnels)	The ability of the tunnel system (as a result of adequate planning and preparation) to mitigate actual or potential negative effects or developments, so that the loss of availability 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 the negative effects that could not be prevented / absorbed by the preventive resilience of the tunnel system.
Adaptive resilience (road tunnels)	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, 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: 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.
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.
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].

Term	Definition
Minimum Operating Requirements (MOR)	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].
ALARP	"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 [source: PIARC TC 4.4 WG2].

APPENDICES

APPENDIX A: SHEET USED FOR THE REVIEW OF THE LITERATURE SOURCES

As a basis for the review of the individual literature sources, the sheet / format as presented below was used. A summary of the content of the most relevant literature sources, based on this format, is presented in Appendix B.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience	
Reviewing WG member	
Date of review	
Title literature source	
Author(s)	
Reference or ISBN	
Publisher	
City / country of publication	
Year of publication	
Resilience topic(s) covered by literature source	[*Choose: "General overview", "Legislation, policies, strategies and performance requirements", "Events and possible measures", "Maintenance or refurbishment", "Long term developments", "Organisational aspects and management systems", a combination of these or use another fitting description*]
Domain of the literature source	*[Choose: "Resilience in General", or: "Resilience for a specific domain, aspect, organization or business, namely: ….."]*
Nature of the content of the literature source	*[Choose: "analysis", "opinion", "assumptions", "thoughts", "validated study", a combination of these or use another fitting description]*
Is the literature source relevant for tunnels?	*[Choose: "Yes" or "No"; if "No", then stop here; if "Yes", then fill out the rest of the sheet]*
Short general description of content	*[200 words maximum]*
What are the main relevant messages, lessons learned or recommendations?	*[200 words maximum]*
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	*[Choose: "Not applicable" or describe what events are dealt with; when applicable, describe in what way (according to the literature source) these events can cause a decrease of availability and what measures can be taken to prevent or mitigate this (prevention = lowering the probability that the event leads to less availability; mitigation = limiting the hindrance for traffic as much as possible when the availability is compromised)]*
Interesting chapters, sections or annexes for further reading	*[Mention chapters, sections, annexes or pages for further reading by interested members of the target group of our literature study]*

APPENDIX B: SUMMARIES OF RELEVANT REVIEWED LITERATURE SOURCES

Most liturature sources, referenced to in Chapter 5 (Bibliography) were fully reviewed, with the results recorded in a review sheet as presented in Appendix A. However, some sources mentioned in the Bibliography were only referenced to for a specific definition or aspect, without a full analysis / review. Other sources were not fully reviewed because this would not offer added value compared to the other review sheets already available.

The available review sheets are collected in this Appendix B, in the order of the reference numbers compliant with the Bibliography, see Table of Content next page.

CONTENT

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [1]	
Reviewing WG member	Ronald Mante; Ėric Premat; Javier Borja Lopez
Date of review	November 3rd 2020.
Title literature source	**A FRAMEWORK TO QUANTITATIVELY ASSESS AND ENHANCE THE SEISMIC RESILIENCE OF COMMUNITIES**
Author(s)	Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A., Von Winterfeldt, D.
Reference or ISBN	Earthquake Spectra 19 (4), pp. 733-752
Publisher	Earthquake Engineering Research Institute (EERI) / Sage Journals
City / country of publication	USA
Year of publication	November 1ST 2003
Resilience topic(s) covered by literature source	General approaches; resilience criteria.
Domain of the literature source	Resilience of communities, related to earthquake damage to critical infrastructures.
Nature of the content of the literature source	Conceptual framework to quantify resilience for earthquakes and evaluate measures.
Is the literature source relevant for tunnels?	Yes. Although not focussed on tunnels, the presented framework is broadly applicable and very useful to understand and manage resilience.
Short general description of content	The article presents a definition and quantitative measure (criterion) for resilience, as well as characteristics, properties and dimensions of a resilient system, that are useful for derived criteria to evaluate the resilience of a community and to identify possibilities for improvement when required. The effect of these improvements can then be re-assessed on the basis of the same criteria. The key steps for this approach to assure a resilient community are presented in a systems diagram / flow diagram.
What are the main relevant messages, lessons learned or recommendations?	Resilience is defined as the degradation of the quality of the infrastructure (function loss) over time, or, mathematically: R = $\int_{t0}^{t1}[100 - Q(t)]dt$ The characteristics of a resilient system (in this case the community, considering resilience for earthquakes) are: • 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). In relation to this, the properties of a resilient system are: • Robustness; • Redundancy; • Resourcefulness;

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [1]	
	• Rapidity. Moreover, resilience has Technical, Organisational, Social and Economic dimensions (“TOSE” dimensions). The properties and dimensions can serve as a basis for derived “measures” in the sense of resilience performance criteria for certain aspects or elements of the system, but they can also serve the identify starting points for “measures” in the sense of plans and actions to improve the resilience of the system. Moreover, the dimensions can be used to identity different impact categories to express the disruption of an certain event (in this case: earthquakes). The resilience for earthquakes of the community system is viewed on two levels: • The level of infrastructural elements like power supply, water supply and hospitals; the degradation over time of the functionality (protection and recovery) of those elements after an earthquake; • The community level (community response systems / emergency management systems): impact of loss of functionality of the infrastructural elements on society and how the community members deal with this: the degradation over time of social and economic functions / needs. Cost-benefit considerations should always play a role in the decision making / choice of improvement measures (actions, plans).
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Earthquakes. But the framework is broadly applicable.
Interesting chapters, sections or annexes for further reading	The article has an Appendix, presenting examples of resilience measures (criteria, under development) in various matrices, e.g. with the resilience dimensions on one axis and the resilience properties on the other axis, resulting in one or more criteria per matrix cell.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [4]	
Reviewing WG member	Ingo Riess
Date of review	July 7th 2020
Title literature source	**ADAPTATION METHODOLOGIES AND STRATEGIES TO INCREASE THE RESILIENCE OF ROADS TO CLIMATE CHANGE**
Author(s)	PIARC Technical Committee E.1
Reference or ISBN	2019R25EN
Publisher	PIARC
City / country of publication	France
Year of publication	2019
Resilience topic(s) covered by literature source	Methodology and Strategy, Case Studies
Domain of the literature source	Resilience to climate change
Nature of the content of the literature source	Methodology, case studies
Is the literature source relevant for tunnels?	Yes, in general, although it describes no hazards that are tunnel specific.
Short general description of content	The report is a continuation of 2015R03EN, International Climate Change Adaptation Framework for Road Infrastructure. It is based on experience from the application of the framework and includes case studies as examples of the application of the methodology. Section 6 gives a general description of risk assessment. It includes examples of information sharing between road administration and specialists/researchers. Section 7: hazard identification and how to describe and quantify them. Section 8: vulnerability and criticality of road infrastructure. Section 9: the risk assessment process. Section 10: selection and monitoring of adaptation measures. Section 11: including adaptation in appraisal and evaluation.
What are the main relevant messages, lessons learned or recommendations?	The report describes a framework how to address resilience of road infrastructure (existing and new). The main hazards appear connected to severe flooding and rock fall due to loss of permafrost. The methodology has applied in case studies from various countries.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The report does not include case studies related to road tunnels except for the Massachusetts DOT study (simulation of future flooding and storm water events as a basis for the design of tunnel portals).
Interesting chapters, sections or annexes for further reading	[-]

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [7]	
Reviewing WG member	Ronald Mante; Ėric Premat; Javier Borja Lopez
Date of review	October 15th 2020.
Title literature source	**COUNCIL DIRECTIVE 2008/114/EC OF 8 DECEMBER 2008 ON THE IDENTIFICATION AND DESIGNATION OF EUROPEAN CRITICAL INFRASTRUCTURES AND THE ASSESSMENT OF THE NEED TO IMPROVE THEIR PROTECTION**
Author(s)	The Council Of The European Union
Reference or ISBN	2008/114/EC
Publisher	The European Union
City / country of publication	Brussels, Belgium
Year of publication	2008
Resilience topic(s) covered by literature source	Legislation, policies, strategies and performance requirements.
Domain of the literature source	Resilience of European critical infrastructures (ECIs), mainly Energy and Transport as a first step.
Nature of the content of the literature source	Requirements for the protection of ECIs to be implemented by the EU Member States.
Is the literature source relevant for tunnels?	Yes. The road transport sector is explicitly identified as a critical infrastructure the directive is aimed at. As such, road tunnels that are part of an ECI are within the scope of the directive.
Short general description of content	The Directive establishes a procedure for the identification and designation of European critical infrastructures (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.
What are the main relevant messages, lessons learned or recommendations?	A ‘critical infrastructure’ is defined as an asset, system or part thereof located in Member States 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 in a Member State as a result of the failure to maintain those functions. A ‘European critical infrastructure’ or ‘ECI’ is a critical infrastructure located in Member States of which the disruption or destruction would have a significant impact on at least two Member States. The primary and ultimate responsibility for protecting ECIs falls on the Member States and the owners/operators of such infrastructures. The Member States are responsible to take the necessary actions to comply with the directive. The owners/ operators play a key role in the implementation of the protection measures. Coordination between Member State authorities, owners/operators, sectors and Member States is expected to assure the necessary protection level of the ECIs.
If the literature source deals with resilience /	The directive mentions 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.

<table>
<tr><th colspan="2">Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [7]</th></tr>
<tr><td>availability in certain events, what are these events and what are the measures to improve resilience?</td><td>The most important measures to be taken are (see the Directive for a full overview):
• Each Member States shall identify potential ECIs (on a permanent basis) through the procedure provided in Annex III of the Directive:
  ○ Step 1: first selection on the basis of sectoral criteria;
  ○ Step 2: further selection on the basis of the definition of critical infrastructure according to the Directive; significance of impact of disruption or loss to be assessed by national methods or by applying cross-cutting criteria on a national level;
  ○ Step 3: for the potential ECIs that passed the first 2 steps: identify if there are transboundary elements to the impact;
  ○ Step 4: for the remaining potential ECIs that passed step 3: assess the impact on the basis of cross-cutting criteria: casualties, economic effects and public effects; the severity of the impact shall be taken into account, as well as the availability of alternatives and the duration of the disruption. The impact shall be evaluated against cross-cutting criteria thresholds. The precise thresholds shall be determined on a case-by-case basis by the Member States concerned by a particular critical infrastructure.
• On the basis of the results of this procedure, each Member State shall inform the other Member States which may be significantly affected by a potential ECI about its identity and the reasons for designating it as a potential ECI. Bi- or multilateral discussions shall take place between these Member States. This shall result in a mutual agreement and the designation of a potential ECI as ECI by the Member States on whose territory the potential ECI is located. The EC and the owners/operators of the ECIs shall be informed (information shall be classified at an appropriate level).
• Operator Security Plans (OSPs) (or equivalents) shall be drawn up 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 prioritisation of counter-measures and procedures with a distinction between permanent security measures and graduated security measures, which can be activated according to varying risk and threat levels.
• A Security Liaison Officer shall function as the point of contact for security related issues between the owner/operator of the ECI and the relevant Member State authority. The Member States shall implement an appropriate communication mechanism between the relevant Member State authority and the Security Liaison Officer or equivalent with the objective of exchanging relevant information concerning identified risks and threats in relation to the ECI concerned.
• Each Member State shall conduct a threat assessment in relation to ECI subsectors within one year following the designation of critical infrastructure on its territory as an ECI within those subsectors.</td></tr>
</table>

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [7]	
	• Each Member State shall report every two years to the Commission generic data on a summary basis on the types of risks, threats and vulnerabilities encountered per ECI sector in which an ECI has been designated and is located on its territory. • The EC shall support, through the relevant Member State authority, the owners/operators of designated ECIs by providing access to available best practices and methodologies as well as support training and the exchange of information on new technical developments related to critical infrastructure protection. • Each Member State shall appoint a European critical infrastructure protection contact point (‘ECIP contact point’). ECIP contact points shall coordinate European critical infrastructure protection issues within the Member State, with other Member States and with the Commission. The appointment of an ECIP contact point does not preclude other authorities in a Member State from being involved in European critical infrastructure protection issues.
Interesting chapters, sections or annexes for further reading	The full directive would be interesting for the reader.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [8]	
Reviewing WG member	Ronald Mante; Ėric Premat; Javier Borja Lopez.
Date of review	July 2nd 2020.
Title literature source	**DIRECTIVE 2004/54/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL OF 29 APRIL 2004 ON MINIMUM SAFETY REQUIREMENTS FOR TUNNELS IN THE TRANS-EUROPEAN ROAD NETWORK**
Author(s)	The European Parliament and The Council
Reference or ISBN	2004/54/EC
Publisher	The European Union
City / country of publication	Brussels, Belgium
Year of publication	2004 (Official Journal of the European Union L 167 of 30 April 2004)
Resilience topic(s) covered by literature source	Legislation, policies, strategies and performance requirements.
Domain of the literature source	Safety requirements.
Nature of the content of the literature source	Road tunnel safety requirements to be implemented through national legislation of EU Member States.
Is the literature source relevant for tunnels?	Yes.
Short general description of content	This directive describes the minimum safety requirements for all tunnels in the trans-European road network with lengths of over 500 metres, whether they are in operation, under construction or at the design stage. It describes, among other things, requirements for safety measures, tunnel signing and risk analysis, as well as the responsibilities of the various roles involved in assuring the safety of a tunnel and requirements for design approval, safety documentation, commissioning, tunnel modifications and periodic exercises.
What are the main relevant messages, lessons learned or recommendations?	The required safety measures, both technical and operational, clearly support the safety as well as the availability of the road tunnels under the scope of the directive, by preventing incidents and by mitigating the effects should an incident take place. This means that tunnel closures or other hindrance for the traffic also occur less frequently and/or the duration of the hindrance is limited, because the required time for emergency response and normalizing the situation will be shorter. This is also reflected in the considerations for the directive, in particular considerations (2) and (3): "(2) The transport system, notably the trans-European road network defined in Decision No 1692/96/EC of the European Parliament and of the Council of 23 July 1996 on Community guidelines for the development of the trans-European transport network (4), is of paramount importance in supporting European integration and ensuring a high level of well-being among Europe's citizens. The European Community has the responsibility of guaranteeing a high, uniform and

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [8]	
	constant level of security, service and comfort on the trans-European road network. (3) Long tunnels of over 500 m in length are important structures which facilitate communication between large areas of Europe and play a decisive role in the functioning and development of regional economies.” Moreover, road tunnel resilience, considering safety and availability, is addressed more or less explicitly in Annex I, section 3.6, Tunnel Closure. It states: “In the event of tunnel closure (long or short-term), users shall be informed of the best alternative itineraries, by means of easily accessible information systems. Such alternative itineraries shall form part of systematic contingency plans. They should aim to maintain traffic flow as much as possible and minimise secondary safety effects on the surrounding areas. 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.”
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Traffic incidents / accidents, collisions, fires, release of dangerous goods and weather conditions.
Interesting chapters, sections or annexes for further reading	The full directive would be interesting for the reader, including (as mentioned) considerations (2) and (3) and section 3.6 in Annex I.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [9]	
Reviewing WG member	Ronald Mante
Date of review	August 21st 2020.
Title literature source	**RWS TUNNEL STANDARD** **(OR: DUTCH NATIONAL TUNNEL STANDARD)**
Author(s)	Rijkswaterstaat (RWS), Ministry of Infrastructure and Water Management, The Netherlands
Reference or ISBN	RWS00541-1-xxxx (various documents), version 1.2 SP2 B2
Publisher	Rijkswaterstaat (RWS)
City / country of publication	Utrecht, The Netherlands. The standard (consisting of various documents in Dutch) can be downloaded from the following website: https://www.rijkswaterstaat.nl/zakelijk/werken-aan-infrastructuur/bouwrichtlijnen-infrastructuur/aanleg-tunnels/landelijke-tunnelstandaard/index.aspx
Year of publication	April 18th 2019 (version 1.2 SP2 B2).
Resilience topic(s) covered by literature source	• Legislation, policies, strategies and performance requirements; • Events and possible measures; • Maintenance and refurbishment; • Organizational and managerial aspects.
Domain of the literature source	Road tunnel resilience, aimed at a continuous and safe traffic flow.
Nature of the content of the literature source	Standard for (state owned) road tunnels in The Netherlands, managed by Rijkswaterstaat.
Is the literature source relevant for tunnels?	Yes.
Short general description of content	Although the standard does not mention “resilience” by name, it presents an integral framework for road tunnel resilience, with the main goal to offer a safe and smooth traffic flow under normal and abnormal conditions. The operational and technical measures required by the standard are aimed to recover from disruptive events as quickly as possible and to mitigate the negative effects during the time period the situation is not yet normalized. Safety is always considered a boundary condition for availability. The standard sets requirements for the performance of various aspects of a tunnel system, as well as requirements for the business processes (safety management, traffic management, emergency response, asset management and education and training of tunnel personnel) and requirements for the tunnel and traffic equipment needed in these processes, including the operating desk and control systems.

<table>
<tr><th colspan="2">Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [9]</th></tr>
<tr><td>What are the main relevant messages, lessons learned or recommendations?</td><td>
In the standard, the tunnel is considered as a system, see figure 1: tunnel structure, road, tunnel installations, traffic management installations, parts of the traffic centre from which the tunnel is operated and the organisation of the tunnel manager & tunnel staff, including operational procedures.

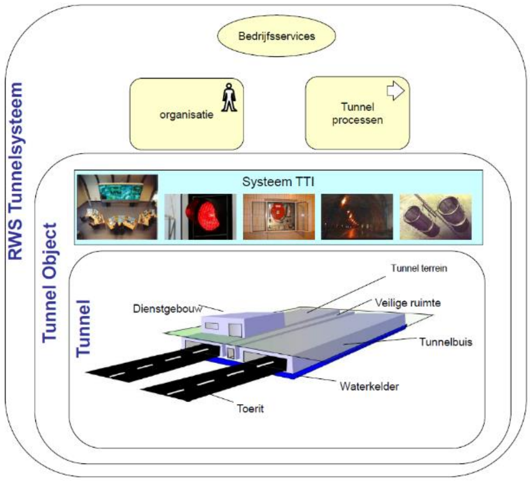


Figure 1. RWS Tunnel System (= tunnel object + services + organization + tunnel processes)

For the tunnel system as a whole, <u>system requirements</u> (performance requirements) were set (see figure 2). The system requirements are primarily focussed on safety and availability for traffic, but also other aspects are included.

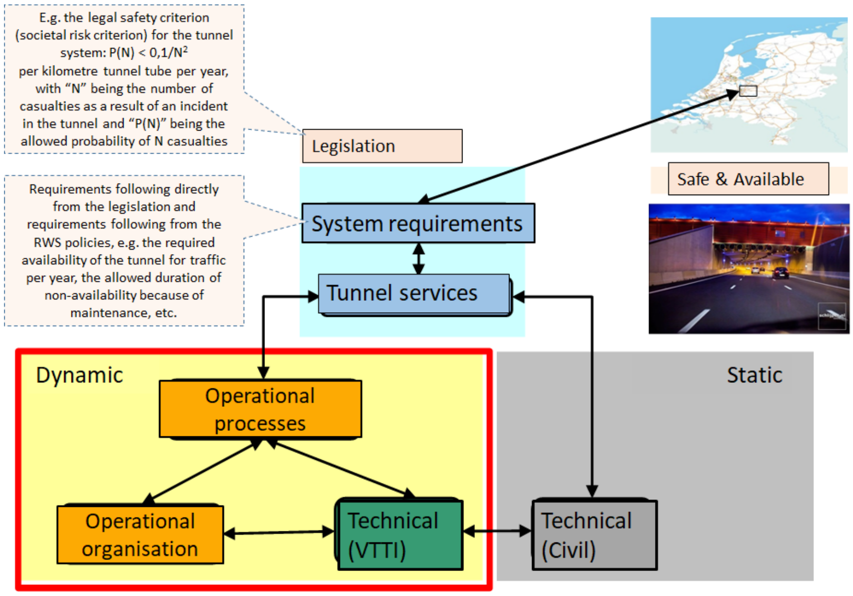
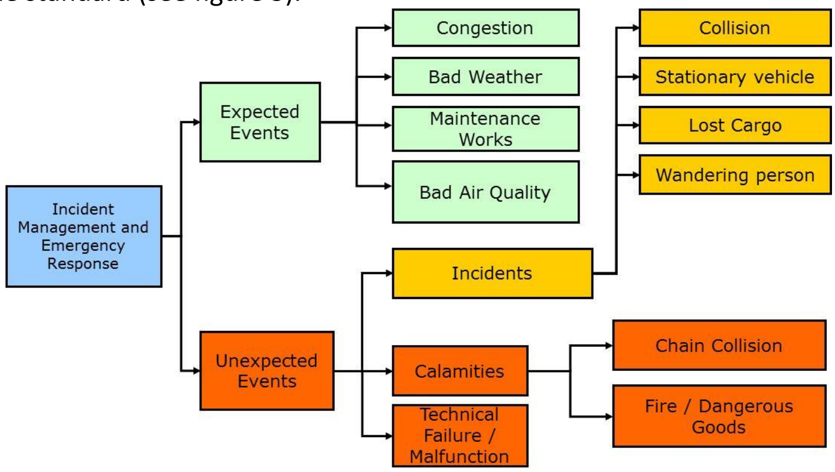


Figure 2. Principle of the RWS Tunnel Standard

To comply with all the system requirements, the tunnel system has to provide various <u>tunnel services</u>:

- Offer road connection;
</td></tr>
</table>

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [9]	
	• Support traffic management; • Assure tunnel safety; • Supporting services; • Quality management (improvement tunnel system). To provide these services, a dedicated set of *operational processes* (primary business processes) was defined and developed, as the "core" of the standard (see figure 3).  *Figure 3. Overview of the operational processes* The system design was made on the basis of these processes: for both the operational procedures and technical measures the requirements were set in such a way that the processes can be served best, to meet the system requirements for safety and availability. Implementing the RWS Tunnel Standard also means that the performance of the tunnel system will be monitored and improved through the quality management procedures the standard requires.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The events are already shown in figure 3, because they formed the basis for the operational primary processes from which the requirements for the safety and availability measures in the RWS Tunnel Standard were derived. The measures are both technical and operational and it has been established in this literature study that (for each event) they can be categorized according to the characteristics of a resilient system as defined by Bruneau et al.
Interesting chapters, sections or annexes for further reading	The RWS Tunnel Standard consists of many documents, so the relevant information is kind of "spread out". The most important requirements, strategies and measures are briefly addressed in the main report.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [13]	
Reviewing WG member	Josep Cursà Danés, Ivan Ricondo Zaldivar

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [13]	
Date of review	03/07/2020
Title literature source	**DEFINITION OF SAFETY FUNCTIONS, APPLICATION TO DEGRADED OPERATING MODES AND MINIMUM OPERATING REQUIREMENTS.**
Author(s)	Centre d'Études des Tunnels (CETU): Jérémie BOSSU, Eric CHARLES, Didier LACROIX, Thierry MANUGUERRA, Jean-Claude MARTIN, Hélène MONGEOT, Marc TESSON & Christophe WILLMANN .
Reference or ISBN	INFORMATION MEMO No.23 <http://www.cetu.developpement-durable.gouv.fr/IMG/pdf/CETU-Info_note_23_EN.pdf >
Publisher	Centre d'Études des Tunnels (CETU). Ministère de l'Écologie du Développement durable et de l'Énergie. République Française.
City / country of publication	Bron, France
Year of publication	2014
Resilience topic(s) covered by literature source	Prevent incidents / accidents, detect, alert and inform, limit the consequences of the incident / accident, ensure a return to normal in road tunnels.
Domain of the literature source	Resilience for road tunnels; Considerations regarding the concept of tunnel safety with respect to the events to be taken into account, the hazards to be identified, the reliability of the systems, degraded operating modes and Minimum Operating Requirements (MOR).
Nature of the content of the literature source	Application guide for road tunnels managers.
Is the literature source relevant for tunnels?	Yes.
Short general description of content	The safety of road tunnel is based on complex technical, human, and organizational systems, which can be subject to failures and lead to a degraded operating situation. It is therefore important to take these failures into account to be sure that the operational response is effective and adapted in the event of an accidental event. Due to the diversity of the equipment present, a global approach based on safety functions has been carried out to ensure the continuity of the operation while guaranteeing a satisfactory level of safety for users.
What are the main relevant messages, lessons learned or recommendations?	○ The particularities of each tunnel, the specifics of the operating modes, the wide variety of the equipment installed (age, characteristics, maintenance procedures, etc.), as well as the varied communication and power supply networks architectures, make them a complex organizational and technical systems different from one tunnel to another. ○ Therefore, it is not easy to define a methodology to characterize the minimum levels of systems reliability required to guarantee the best level of safety for users. ○ IMPORTANT: • The document introduces and defines the safety functions which correspond schematically to the generic actions to be performed by the operator to guarantee the safety of users in tunnels. • It identifies the means necessary for the operator to implement these safety functions.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [13]	
	• It identifies how each safety function is ensured by combinations of means. ○ It clarifies what are the main safety functions that must be ensured in a road tunnel and lists the technical and human resources in order to ensure it. ○ The functions are combined with means of prevention and protection. The combination of the functions to be performed and the resources available have made it possible to classify them into two families: Non-compensable means and compensable means. ○ In the end, a crossing table allows the manager to identify on which means he will have to pay particular attention in order to guarantee at all times a circulation of users in good conditions of safety, fluidity of flow and comfort.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	To help building the resilience of the tunnel the paper distinguishes between two types of resources depending on whether their failure can be compensated by resorting to the use of a different type of system. ○ Non-compensable resources: The resources considered here are those whose malfunction or consequent unavailability cannot be compensated using a different type of equipment. Therefore, their unavailability no longer ensures one or more safety functions and most often leads to closing the tunnel to all or some traffic (i.e. electric power supplies, centralized technical management, operators of the tunnel control centre, also equipment that contribute to a single function such as smoke extraction). ○ Compensable resources: These are the means including malfunctions or temporally unavailable that can be offset by other resources or by operating measures (i.e. user communication systems such as radio and emergency telephones, lane usage signals and Variable Message Signs (VMS), video surveillance cameras, automatic incident detection systems, pollution sensors, etc.
Interesting chapters, sections or annexes for further reading	2. Definition of the main safety functions and means of prevention and protection. 4. Compensable and non-compensable resources and link with degraded operating modes. 5. Development of minimum operating requirements.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [14]	
Reviewing WG member	George Mavroyeni / David Zamora / Heidi Cuypers
Date of review	15 August 2020 / 18 September 2020
Title literature source	**PIARC DOCUMENT- GOOD PRACTICE FOR THE OPERATION AND MAINTENANCE OF ROAD TUNNELS**
Author(s)	PIARC Technical Committee C5
Reference or ISBN	Not applicable
Publisher	PIARC
City / country of publication	Paris, France
Year of publication	2005
Resilience topic(s) covered by literature source	General overview; mentions the importance of policies, strategies and performance requirements, covers maintenance and refurbishment, organisational aspects and management systems.
Domain of the literature source	The good practices described in this paper have a significant impact on tunnel resilience.
Nature of the content of the literature source	Description of good practices based on observed good tunnel management practices from around the world.
Is the literature source relevant for tunnels?	Yes – it is specific to road tunnels.
Short general description of content	It provides a broad description of the management plans, processes and practices that, if well developed and implemented, contribute to tunnel resilience. It provides good insight into the factors that are important to consider for safe and effective tunnel operations. The report covers tunnel management from planning through to operation and renovation.
What are the main relevant messages, lessons learned or recommendations?	The report describes the importance of having a Quality Plan, which 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, the consideration of future widening of the tunnel structure and materials. **Quality Plans – Operation and Management** It is extremely important to develop and implement a proper Quality Plan for every road tunnel. The important features of such a plan are: • to clearly describe the means to secure the required quality of the tunnel operation and management; • to describe an agreed way to implement the operational tunnel strategy into working practice; • to be the key document to guide the daily work of all those involved in providing high quality operational services for the road tunnel; • to provide simple procedures and processes (instructions); • to support revision or change processes, throughout their implementation; • to describe the need and methods to record the reason for changes, so that a historical record can be built up for informing others;

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [14]	
	• to describe an agreed way to seek and implement year on year improvements for service to the road user, whole life cost effectiveness and better working practices. Without a proper preliminary study of these features, it will become really difficult to ensure tunnel resilience. **Safety and Risk Management** This document has great importance for consideration of the safety level for each tunnel. If the study is as complete as needed, then the tunnel design and operation will support resilience objectives. Nowadays it is becoming more and more important to be prepared for Computer Safety. Most of the systems installed in tunnels are reported to a main SCADA system in the tunnel control room. It is a real need to be prepare for cyber-attack. **Maintenance and Operation** Compliant with the Quality Plan, the method should be considered to support the tunnel operator in keeping the tunnel operational with three main objectives: • Safety - for the public travelling through the tunnel. • Safety - in the form of reliable equipment to reduce service time between maintenance. • Safety - for the maintenance staff. Proper execution of these instructions will support resilience. For instance, it is illustrated how a data based tunnel maintenance system (TMS) can aid to reduce traffic hindrance. A TMS can help the operator to call on / initiate maintenance activities for planned works if a decision is made to close a tunnel for other reasons. This can reduce the total number of tunnel closures over a long period. There is also a chapter dedicated to the calculation of the cost of inconvenience to road users. The inconveniences depend on the type of repair, the capacity of the road and the traffic intensity. These inconveniences can normally be reduced by taking special measures that increase the cost of the repair. It is therefore necessary to find the right balance between taking road users into account and the economic resources available, including the quality of the technical solutions. **Training and Emergency Exercises** To ensure that tunnels systems are properly used in the tunnel operation, well recruited and well trained staff is needed; staff members should be trained before starting their tasks and should be continually retrained throughout their career. This requires tailor-made considerations for each individual tunnel. Again, if the underlying study is deep enough, this will support resilience.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [14]	
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The above-mentioned documents are the most directly related to assuring resilience. To summarize, preparing a good Quality Plan and applying it in the proper way, together with good staff recruitment and training, the tunnel operator will be in best situation for assuring tunnel resilience. The Quality Plan should be a living document for resilience improvement.
Interesting chapters, sections or annexes for further reading	IV. Maintenance and operation VI. Renovation of tunnels VIII.4. Whole Life Cost VIII.6. Calculating the cost of inconvenience to road users

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [19]	
Reviewing WG member	Ronald Mante; Ėric Premat; Javier Borja Lopez
Date of review	September 24th 2020.
Title literature source	**NATIONALE STRATEGIE ZUM SCHUTZ KRITISCHER INFRASTRUKTUREN (KRITIS-STRATEGIE)** **[NATIONAL STRATEGY FOR THE POTECTION OF CRITICAL INFRASTRUCTURES (KRITIS-STRATEGY)]**
Author(s)	Federal Ministry of Internal Affairs
Reference or ISBN	BMI09324
Publisher	Federal Ministry of Internal Affairs
City / country of publication	Berlin, Germany
Year of publication	June 17th 2009
Resilience topic(s) covered by literature source	Legislation, policies, strategies and performance requirements.
Domain of the literature source	Resilience of critical infrastructures, like energy supply, IT, transport and traffic, medical care, food, water supply, etc.
Nature of the content of the literature source	National policy / strategy.
Is the literature source relevant for tunnels?	Yes, on a general level. The strategy explicitly identifies transport and road traffic infrastructure as critical.
Short general description of content	The German national strategy is aimed at improving the resilience of critical infrastructures. Infrastructures are considered "critical" if they are of great importance to the functionality of modern societies and if their failure or damage results in permanent disruptions to the overall system. The “criticality” of an infrastructure is defined as: the relative importance in relation to the consequences that a disruption or a functional failure has on society's security of supply of important goods and services. The strategy summarizes the objectives and the political-strategic approach of the German federal government, as already applied. The mission is to continue the results achieved so far on a consolidated basis and to further develop the strategy in view of new challenges. The results already achieved are summarized. Moreover, the focus for the future is described: • Leading principles; • Strategic goals, related to both prevention and reaction, to be implemented through a Deming-circle-like approach; • Conditions for coordination and collaboration between the many public and private parties involved in the implementation of the strategy, stressing that the federal government has an important leading and condition-creating role; • Definition of the work packages for the implementation of strategic goals; • Instruments to be used for the implementation;

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [19]	
	• Ongoing international cooperation that further supports the implementation.
What are the main relevant messages, lessons learned or recommendations?	It is explained that both technical as socio-economic infrastructures can be critical. The technical critical infrastructures in Germany are: energy supply, IT and communication, transport and traffic and (drinking) water supply and sanitation. The socio-economic critical infrastructures are: healthcare, nutrition, emergency and rescue services, civil protection, parliament, government, public administrations and judicial institutions, finance and insurance, media and cultural goods. The hazards that can threaten the critical infrastructures are: • Natural events: extreme weather conditions, forest fires, seismic events, epidemics and pandemics and cosmic events (like cosmic energy storms, meteorites and comets); • Technical or human failure: system failure, negligence, accidents or organizational failures; • Terrorism, sabotage, crime and (civil) war. It is stressed that, in the course of their technological development, societies are more and more sensitive to disruptions, as they are used to very high safety standards and a high reliability level of supplies. The increasing robustness and lower failure susceptibility of the critical infrastructures create a thoroughly deceptive sense of safety, causing the effects of a "nevertheless accident" to be disproportionately high. This is called the “vulnerability paradox”: the less a country is prone to disruption, the greater the impact when any disruption occurs anyway. This paradox is constantly being amplified as technologies continue to increase in almost all areas of society. As a result, the dependence on the availability of electrical power and information and communication systems also increases. Technology impact assessments must therefore continue to gain importance from the perspective of security policy considerations for the protection of critical infrastructures. Related to this, it is concluded that neither the State, nor the operators can guarantee a 100% protection of the of the critical infrastructures and their efficiency. Hence, to make society more robust and resilient in dealing with growing vulnerabilities, a transition is required to a safety culture that is based on the following aspects: • An open risk communication between the State, companies, citizens and the public, taking into account the sensitivity of certain information, • The cooperation of all relevant actors in the prevention and management of incidents, • A greater involvement of operators in the prevention and handling of incidents,

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [19]	
	• An increased and confident ability of the people and facilities affected by disruptions of critical infrastructure services to protect and help themselves.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The work packages to implement the strategic goals are defined as follows: 1. Definition of general protection objectives; 2. Analysis of threats, vulnerabilities and coping capabilities; 3. Hazard assessment; 4. Specification of protection objectives, taking into account existing protection measures; analysis of existing regulations and possibly deriving further measures to achieve goals; adaption of legislation could be a measure, when required or fitting; 5. Implementation of measures to achieve protection goals, mainly through: a. Common solutions and internal regulations; b. Self-commitment statements from companies; c. Development of security concepts by companies; 6. Continuous, intensive risk communication process: dialogue about analysis results, assessments, protection goals and options for measures. The work packages 1-4 are mainly executed by the State, with the support of companies and operators. The execution of the work packages 6-5 is the mainly the responsibility of the companies and operators, as well as public-private cooperations.
Interesting chapters, sections or annexes for further reading	[-]

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [20]	
Reviewing WG member	Ronald Mante; Ėric Premat; Javier Borja Lopez
Date of review	September 18th 2020.
Title literature source	**NATIONALE STRATEGIE ZUM SCHUTZ KRITISCHER INFRASTRUKTUREN 2018–2022** **(NATIONAL STRATEGY FOR THE POTECTION OF CRITICAL INFRASTRUCTURES 2018-2022)**
Author(s)	The Swiss Federal Council
Reference or ISBN	BBl 2018
Publisher	The Swiss Federal Council
City / country of publication	Switzerland
Year of publication	December 8th 2017
Resilience topic(s) covered by literature source	Legislation, policies, strategies and performance requirements.
Domain of the literature source	Resilience of critical infrastructures, like energy supply, passenger and freight transport and medical care.
Nature of the content of the literature source	National policy / strategy.
Is the literature source relevant for tunnels?	Yes, on a general level. The strategy explicitly identifies road traffic infrastructure as critical.
Short general description of content	The Swiss national strategy is aimed at improving the resilience of critical infrastructures. Critical infrastructures are defined as processes, systems and facilities that are essential to the functioning of the economy or the well-being of the population. Thus, the resilience is meant to ensure an undisturbed availability, as well as a quick recovery to the required level in case of failure. 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, the (sub)sector the critical infrastructure is part of, or for more than one (sub)sector; some goals and measures are relevant on a national level. The agencies, parties and operators responsible for the implementation are designated. For the elaboration and implementation of the measures a risk-based approach is presented, identifying the following repetitive process steps (like a Deming circle): Analysis --> Assessment --> (Protective) measures --> Implementation --> Verification. Lastly, a time schedule with mile stones for the implementation of the measures is included.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [20]	
What are the main relevant messages, lessons learned or recommendations?	It is explained that failure of a critical infrastructure can occur when there are relevant vulnerabilities. Such vulnerabilities give rise to risks that can be mitigated with appropriate protective measures. To function properly, a critical infrastructure is dependent on various resources, like personnel, materials, business assets (incl. energy sources) and services (incl. physical infrastructures, like roads). A vulnerability is relevant when a malfunction or disruption of an important resource can lead to the non-availability of the critical infrastructure. The following risks (hazards), related to relevant vulnerabilities, are mentioned: • Natural hazards (e.g. flooding, storms, avalanches or earthquakes); • Technical hazards (e.g. system failure, power failure or a bad network topology); • Social hazards (e.g. sabotage, terrorism and pandemics). The magnitude of the risk is determined by the probability and the potential effect on the population and its means of existence, caused by the failure of the critical infrastructure. Measures to mitigate the risks can be structural, technical, operational, organisational, administrative, legal, or personnel-related. Protection of information is also important. It is stressed that the measures should be proportional: the cost should weigh up to the risk reduction. A complete elimination of all risks is expressly not pursued. On the one hand, this is not technically possible and, on the other, it involves a disproportionate amount of effort economically. The measures chosen must also be constitutionally and legally legitimate. There should also be no market distortions. It is also stressed that the protection of critical infrastructures is a shared or transverse responsibility, involving overlap with the most diverse political and task areas. Coordination between the involved parties is required, including public-private cooperation. Retention of powers and responsibilities is key when organizing and implementing the measures.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [20]	
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The following strategic goals are mentioned: • The critical infrastructures are resilient so that large-scale and serious failures can be prevented as much as possible and functionality can be guaranteed again as soon as possible in the event of an incident. • The population and the economy are resilient so that outages and disruptions of critical infrastructures do not cause serious damage. • Authorities are ready to respond appropriately to the failure of the critical infrastructures. • The operators of the critical infrastructures are effectively supported in dealing with incidents. The measures to be implemented include (among others): • Vulnerability and risk analyses must be performed for the critical infrastructures where no relevant measures have been taken yet; adequate measures on the basis of these analyses must be implemented. • The inventory of critical infrastructure objects must be periodically updated and processed with information about critical IT systems and companies that operate the infrastructure. • The improvement of the resilience of the critical subsectors should periodically reviewed and the findings should be consolidated in a holistic risk overview. • Fundamental research on cross-sectoral topics (e.g. interdependencies and technological, environmental and environmental developments) should be deepened. • The development of a proposal for legal bases requiring operators to report serious safety incidents or malfunctions to the responsible authorities should be examined. • An alternative, fail-safe data network must be implemented, to connect critical infrastructure operators to. For voice communication, selected operators are connected to the POLYCOM security radio network. • The Confederation and the cantons prepare and periodically update precautionary plans to address serious disruptions - especially power supply. • The population and the economy are informed and made aware of self-preventive protection options in the event of failure of critical infrastructures, especially the power supply. • Preventive action plans for the protection of critical infrastructures are developed and updated periodically. • Individual protection aspects should be practiced in a targeted manner as part of already planned exercises.
Interesting chapters, sections or annexes for further reading	[-]

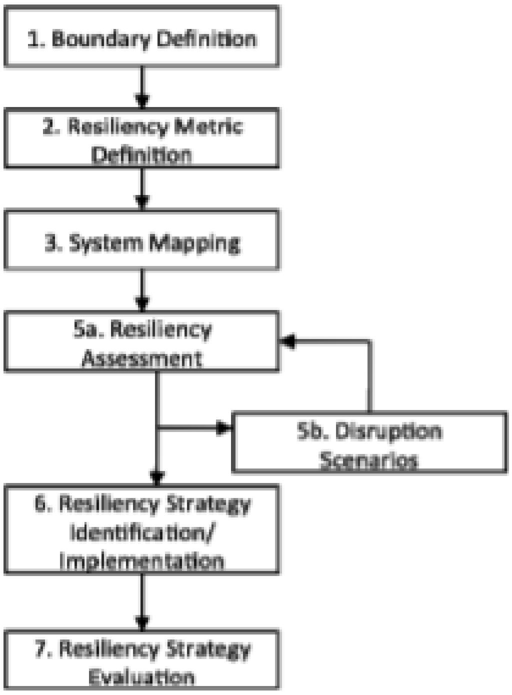
Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [22]	
Reviewing WG member	George Mavroyeni; Heidi Cuypers
Date of review	15 June 2020
Title literature source	**A DATA-DRIVEN APPROACH FOR DIRECT ASSESSMENT AND ANALYSIS OF TRAFFIC TUNNEL RESILIENCE.**
Author(s)	Sandeep Khetwal, Shiling Pei, Marte Gutierrez
Reference or ISBN	Proceedings 3rd International Conference on Information Technology in Geo-Engineering (3rd ICITG2019), pp. 168-177
Publisher	Springer.
City / country of publication	Switzerland
Year of publication	2020
Resilience topic(s) covered by literature source	Tunnel Manager Capability for Tunnel Resilience
Domain of the literature source	Resilience in General
Nature of the content of the literature source	Study and analysis.
Is the literature source relevant for tunnels?	Yes
Short general description of content	The paper presents a simple means of measuring tunnel functionality with a focus on tunnel usage. An ideal data collection framework for tunnels is presented in order to calculate tunnel functionality. Also, a data-driven analysis seeks a correlation between tunnel design and operational parameters with tunnel resilience. An example is provided based on tunnel operational data for large tunnels in Colorado, which demonstrates the gap between existing data collection status and the ideal conditions.
What are the main relevant messages, lessons learned or recommendations?	Resilience study for transportation tunnels is an emerging concept. Studies so far, are limited to specific components or events like fire and lining. A generalised quantitative assessment of tunnel functionality is absent and to develop such a metric is complicated as a tunnel is complex infrastructure with interdependent components. The functionality Q, for any traffic tunnel can be quantified as the ratio of traffic capacity available to the public to the maximum traffic capacity available in tunnel design. This can be plotted as a series of points along the time axis. It is a simple metric that can be easily recorded. As the data is collected over long periods of time it can be used to evaluate the design and operational parameters. A cost-benefit evaluation is possible of the investment made and the monetary value of future maintenance and upgrades can be estimated. At this stage, there is a lack of available data. Researches used a simulation-based approach to assess tunnel functionality.
If the literature source deals with resilience / availability in certain events, what are these events and what are	Not Applicable

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [22]	
the measures to improve resilience?	
Interesting chapters, sections or annexes for further reading	[-]

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [23]	
Reviewing WG member	Ingo Riess
Date of review	23. April 2020
Title literature source	**OPERATIONAL RESILIENCE OF TRAFFIC TUNNELS: AN EXAMPLE CASE STUDY**
Author(s)	S.S. Khetwal, S. Pei, M. Gutierrez
Reference or ISBN	Tunnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art, ISBN 978-1-138-38865-9
Publisher	Taylor & Francis Group
City / country of publication	London, UK
Year of publication	2019
Resilience topic(s) covered by literature source	General overview
Domain of the literature source	Resilience of traffic tunnels
Nature of the content of the literature source	Empirical study
Is the literature source relevant for tunnels?	Yes
Short general description of content	Functionality losses in tunnels can greatly undermine the transportation network efficiency. Severe functionality loss related to fire, earthquake or adverse climate will result in significant economic loss. Even short-term functionality loss due to minor events such as vehicular breakdown, weather conditions and tunnel repair can also hamper the traffic flow. Tunnel management and operation also affect functionality recovery from the loss, since the tunnel "down time" is highly dependent on the immediate measures taken after an event. Understanding tunnel operational resilience requires a holistic approach considering various scenarios, tunnel type, its location, design, and management methods. The paper discusses the importance of tunnel operation data collection in helping establish tunnel functionality loss models. Using a one-year of operation log data from the Eisenhower-Johnson Mountain Tunnel in Colorado, USA, this study illustrated, using limited data, the approach to statistically determine the operational resilience of the tunnel under various events.
What are the main relevant messages, lessons learned or recommendations?	To provide a rational approach for tunnel performance, a simple functionality loss metrics is proposed in this study together with the needed data structure to enable the calculation of this metrics. The available data was analysed as it was provided, without calculating the resilience metrics. Through systematic long-term data collection, the resilience of traffic tunnel can be assessed to justify monetary value of improvements and upgrades in term of resilience improvement. The study suggests a way to collect data to quantify the impact of funding decisions on tunnel infrastructure. While feasibility studies and cost-benefit studies can provide a projected outcome of an investment decision, the data

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [23]	
	collected following the recommended structure will be able to provide more realistic and quantifiable measures of success. A tangible metric for tunnel resilience that can be validated by realistic data is of great value to effective management of the tunnels. This study provided a simple tunnel-focused data structure that can be referenced to reduce the fragmentation of data. Once a large quantity of structured tunnel resilience data is collected, it can be used as a basis for efficiency evaluation, cost-benefit analysis, and additional data mining to identify influential factors for tunnel resilience.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Functionality losses in tunnels (i.e. partial or full loss of use due to natural and human-induced disruptive events) can greatly undermine the transportation network efficiency. Functionality losses can be either long term or short term, with one caused by major natural or man-made disruptive events like fire, earthquake, adverse climatic conditions, or major renovation; and the other related to routing operational, maintenance or minor traffic breakdowns/accidents.
Interesting chapters, sections or annexes for further reading	[-]

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [24]	
Reviewing WG member	Heidi Cuypers - Rafael Lopez Guarga - **Tiago Massingue**
Date of review	27 May 2020
Title literature source	**"MEASURING THE RESILIENCY OF THE MANHATTAN POINTS OF ENTRY IN THE FACE OF SEVERE DISRUPTION",** American J. of Engineering and Applied Sciences 4 (1): 153-161, 2011
Author(s)	Mayada Omer, Ali Mostashari and Roshanak Nilchiani
Reference or ISBN	ISSN 1941-7020
Publisher	© 2010 Science Publications
City / country of publication	Centre for Complex Adaptive Socio-technological Systems, School of Systems and Enterprises, Stevens Institute of Technology, Castle Point on Hudson, Hoboken NJ 07030-5991, USA
Year of publication	2011
Resilience topic(s) covered by literature source	[General overview/Legislation, policies] Hurricane Katrina, the worst in US history since 1700, affected badly the United States of America in August 2005, and renewed the known concern for the need of providing resilient transport infrastructure to citizens and road users. The road network initially connecting to Manhattan in New York and later connecting to other regions in this Study is an example as to how resilient infrastructure can be assessed. Linked to Policy and Legislation, Authors of the Study make specific reference to the Obama-Biden administration where the Department of Homeland Security and other sector partners came together to implement the National Infrastructure Protection Plan (NIPP) (Chertoff, 2009; Lee, 2008) that aims at "A safer, more secure and more resilient America". As a starting point, the Authors have defined Resiliency as the ability of the system to react to major threats or shocks, by means of identifying the infrastructure vulnerabilities and then investigating the different options that reduce the vulnerabilities and increase the adaptive capacity by providing means to the infrastructure to resume regular operations whilst minimizing losses. The overall concern identified here is that in the transportation infrastructure, disruptions cause delays, which will in turn incur substantial economic losses and environmental damages. This is the problem which needs to be addressed so that the tunnel can be made continuously available for use and thus to limit hindrance to traffic during operations, refurbishment or maintenance.
Domain of the literature source	["Resilience for a specific domain, aspect,"] This topic deals with "Measuring the Resiliency of the Manhattan Points of Entry in the Face of Severe Disruption" undertaken by the School of Systems and Enterprises, Stevens Institute of Technology, Castle Point on Hudson, Hoboken NJ 07030-5991, USA
Nature of the content of the literature source	[Opinion]: To undertake the investigation, the Authors used the "Networked Infrastructure Resiliency Assessment" (NIRA) framework, which encompasses the following milestones:

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [24]	
	
Is the literature source relevant for tunnels?	[Yes]
Short general description of content	[Reasoning] The transportation infrastructure is particularly vulnerable to environmental hazards such as heavy snowstorms or floods that temporarily immobilize functionality whilst causing structural damage. Accidents and road works often cause road obstructions that create delays. Additionally, human error and natural factors can result in mechanical failures such as the collapse of bridges and tunnels that not only lead to substantial travel time delays but also the loss of human lives. The authors have established the following structure for their study: • Environmental Hazards: Maintenance Heavy Snow Falls, • Accidents, • Roadworks, • Literature review, • Network resiliency assessment framework, • Application of the NIRA framework on Manhattan's entry points, • Network analysis, • Disruption scenarios, • Resiliency strategy identification, • Resiliency strategy evaluation, • Materials and methods of Resilience assessment, • Discussion, and, • Conclusions.
What are the main relevant messages, lessons learned or recommendations?	**[Reasoning]** Conclusion: One vulnerability reduction strategy is the clever assignment of vehicles to other routes in the network. The adaptive capacity of the system is enhanced through the deployment of other parallel systems such as ferries.

<table>
<tr><th colspan="2">Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [24]</th></tr>
<tr><td></td><td>Due to the large number of people travelling into and out of Manhattan every day,
➢ road obstructions in the entry points of Manhattan result in time delays as well as other negative environmental and financial impacts.
➢ The NIRA framework proposes a methodology for assessing the resiliency of road-based network infrastructure systems that investigates the reaction of the system to disruptions and allows the decision makers to investigate the different resiliency strategies.
➢ Resiliency is achievable through the application of active and proactive measures that reduce the vulnerability of the system and increase its adaptive capacity. One vulnerability reduction strategy is to reroute the traffic through other links in the network, which will also impact on the overall network travel time resiliency.
➢ Increasing the adaptive capacity can be in the form of influencing the traveller's mode choice. Improving the service level of other parallel systems such as ferries and trains will impact the choice for the mode of travel by increasing the probability that more travellers utilize the parallel systems.
➢ Traditional decision analysis tools may be applied to help decision makers identify the effectiveness of various resiliency strategies that can be deployed in cases of emergency with prior knowledge of the initial investment and operation cost.</td></tr>
<tr><td>If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?</td><td>[Resilience availability]
From the Literature review it is understood that:
Infrastructure Resiliency is the ability of the system to bounce back after a shock and return to its normal value delivery levels. Enhancing the infrastructure resiliency creates the need for metrics that assess the current resiliency of the system.

Availability of resilience in certain events entails:
a) In power and water infrastructures, Chang and Chamberlain (2003) measured resiliency in terms of economic loss,
b) Shinozuka and Chang (2004) measure the resiliency of power systems in terms of speed of restoration and repair efficiency.
c) In the telecommunication infrastructure, Cohen et al. (2001) studied the tolerance of the Internet to intentional attack; they proposed a resiliency metric as a measurement of the number of sites needed for the disintegration of the network.
d) In the field of transport infrastructure, Werner (1998) measure the resilience as the increase of travel time preceding a disruption.
e) Murray-Tuite (2006) proposes metrics for evaluating the ten components of the transport infrastructure resiliency and compares the system optimum and user equilibrium traffic assignments.
f) Heaslip et al. (2009) categorize the metrics with regards to the transportation infrastructure into individual resiliency, community resiliency, economic resiliency and recovery metrics;</td></tr>
</table>

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [24]	
	g) resiliency is measured in terms of the impact of disruptions on the system’s performance measures; a service disruption in one of the bridges or tunnels would cause traffic congestion that results in an increase in travel time that is used to calculate the travel time resiliency; h) it is possible to identify several resiliency metrics that measure other network performance measures that are influenced by the disruptive event. The proposed resiliency metric is used to measure the node-to-node resiliency as well as the system-wide resiliency for the duration of the disruptive event since road disruptions can last up to several hours or even several days. The node-to-node resiliency metric measures the resiliency between any two nodes that are directly connected to the disrupted link. The system-wide resiliency measures the impact of one or more link disruptions on the overall network travel time.
Interesting chapters, sections or annexes for further reading	NIPP (Chertoff, 2009); Lee 2008.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [27]	
Reviewing WG member	Rafael López Guarga
Date of review	
Title literature source	**SOMPORT TUNNEL SAFETY DOCUMENTATION**
Author(s)	Somport Tunnel Operator
Reference or ISBN	No Reference
Publisher	
City / country of publication	Spain / France
Year of publication	15/12/2010
Resilience topic(s) covered by literature source	Maintenance or refurbishment, organizational aspects and management systems
Domain of the literature source	Resilience for a specific domain, aspect, organization or business: road tunnels.
Nature of the content of the literature source	Usual practices, established protocols.
Is the literature source relevant for tunnels?	Yes.
Short general description of content	Minimum Operation Conditions (MOC) for the Somport tunnel. Its aim is to define the necessary degree of operation of the different systems in order to be able to operate the Somport Tunnel. The Somport Tunnel is on the E-07 European route, integrated into the Madrid-Zaragoza-Pau-Toulouse road axis, also improving communications on the Valencia-Zaragoza-Pau-Bordeaux road axis. With the construction of the tunnel, the height of the border crossing is reduced to 1,183 m on the Spanish side and 1,116 m on the French side. The length of the tunnel is 8,608 m divided in 5,759 m on the Spanish side and 2,849 m on the French side. It was opened to traffic in 2003.
What are the main relevant messages, lessons learned or recommendations?	It determines the moment in which the unavailability of the equipment prevents to have a sufficient level of security for the users and/or a sufficient level of service quality in the tunnel.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	If the Minimum Operating Conditions limit is exceeded, it leads to automatic closure of the tunnel until the equipment is restored.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [27]	
Interesting chapters, sections or annexes for further reading	Specific sheet for each possible event: a classification by groups has been made to facilitate the consultation and it has been numbered with 3 digits, the first two identify the group or system, the last one is a counter. • Ventilation/Extraction 101, 105, 106 • Command and Control Station 110, 111, 112, 116 • Power Supply 120, 122, 123 • Lighting 130 • Closed Circuit of Television/AID 140, 141 • Radio communications/Emergency Phones 150, 151, 152 • Detectors 160, 161, 162, 163 • Environmental Conditions 170, 171, 172 • Water Supply and Firefighting Vehicles 180, 181,182

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [29]	
Reviewing WG member	Ingo Riess
Date of review	April 8th 2020
Title literature source	**AB HEUTE IST DIE A8 WIEDER DURCHGEHEND (AS OF TODAY, THE A8 IS CONTINUOUS AGAIN)**
Author(s)	Anne-Marie Günter
Reference or ISBN	Jungfrauzeitung Artikel 58007
Publisher	Jungfrauzeitung
City / country of publication	Switzerland
Year of publication	2005
Resilience topic(s) covered by literature source	Flooding due to excessive rainfall
Domain of the literature source	Resilience against flooding
Nature of the content of the literature source	Case report
Is the literature source relevant for tunnels?	Yes
Short general description of content	The article reports of the re-opening of the Lutschinen Tunnel on 28 August 2005 following a flooding event on 22 August 2005. The Lutschinen tunnel (CH) was flooded with water and mud following excessive rainfall. The article describes the re-opening of the tunnel.
What are the main relevant messages, lessons learned or recommendations?	The risk of water intake into the tunnel is increased since the tunnel was built. The safety installations of the tunnel were damaged and had to be refurbished.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Event: Flooding due to excessive rainfall. Measures are not described in the article: During refurbishment works in 2015, the protection of the tunnel from flooding was improved.
Interesting chapters, sections or annexes for further reading	

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [30]	
Reviewing WG member	Bijan Khaleghi
Date of review	October 27, 2020
Title literature source	**PORT OF MIAMI TUNNEL: RESILIENCY THROUGH FLOOD GATES**
Author(s)	Meridiam.com
Reference or ISBN	
Publisher	Meridiam.com
City / country of publication	Albuquerque, New Mexico, USA
Year of publication	January 2019
Resilience topic(s) covered by literature source	Port of Miami Tunnel: Resiliency Through Flood Gates The Port of Miami Tunnel, connecting the city with its port on Dodge Island, is protected against flooding by a pair of heavy flood gates at each end. Activated through hurricane preparation procedures, the gates help to make this modern infrastructure asset highly resilient to the risk of flooding.
Domain of the literature source	Building Resilience To Climatic Risks
Nature of the content of the literature source	Each year during hurricane season, between the beginning of June and the end of November, Florida will be hit by anything from 10 to 20 hurricanes. On occasion, it suffers the brunt of a powerful category four or five storm, like Hurricane Irma which struck the peninsula in September 2017 with wind speeds exceeding 150mph (241kph).
Is the literature source relevant for tunnels?	Yes.
Short general description of content	Greater Miami is particularly vulnerable to damaging floods as well as high winds during hurricane season. Florida is mostly a low-lying state and Miami is one of its most heavily built-up areas, on the state's eastern coast. Severe storm surges, like that experienced from Hurricane Irma, can cause water levels to rise several metres, breaching the city's existing defences; and scientific analysis shows the risk of flooding is likely to get worse. In this context, a road tunnel beneath Miami's port waterway is susceptible to extreme risk of flooding. However, the Miami Tunnel has distinctively iconic yet practical features at each end: concrete portal structures which house a pair of solid steel flood gates.
What are the main relevant messages, lessons learned or recommendations?	Storm surges combined with rising sea levels present an increasing threat to Miami and its surrounding communities, many of whom reside at less than one metre above mean high tide levels. Forecasts vary for how much sea levels will change in future. Regardless of whether climate change is due to human activity or not, which is a separate argument, sea level predictions for the year 2100 vary from a rise of 31 inches (787mm), according to the UN's Intergovernmental Panel on Climate Change, to the 81-inch (2m) rise calculated by the US National Oceanic and Atmospheric Administration.
If the literature source deals with resilience /	Flood gates on the tunnel portals were a necessary solution to a serious predicament for the project. The proposal was for a twin-bore road tunnel to connect the Port of Miami on Dodge Island with the MacArthur

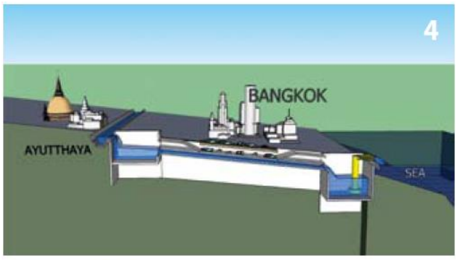
Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [30]	
availability in certain events, what are these events and what are the measures to improve resilience?	Causeway on Watson Island. For road freight and other port traffic, this would provide a highly valuable direct link with the mainland Interstate highway network, bypassing downtown Miami. But risk of flooding was high at the tunnel portals on the two low-lying islands. The organisation responsible for overseeing operation of the tunnel is Miami Access Tunnel Concessionaire, which developed the POMT project in partnership with the Florida Department of Transportation and signed a 35-year concession agreement for the design, construction, financing and operation of the tunnel in 2009.
Interesting chapters, sections or annexes for further reading	• Building Resilience To Climatic Risks, • Increasing Resiliency Globally, and • Closure At Action Level 3

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [31]	
Reviewing WG member	Ingo Riess
Date of review	9 April 2020
Title literature source	**ADAPTATION TO THE IMPACTS OF CLIMATE CHANGE ON TRANSPORTATION**
Author(s)	Henry G. Schwartz Jr.
Reference or ISBN	The Bridge – Linking Engineering and Society, Fall 2010, pp. 5-13
Publisher	National Academy of Engineering
City / country of publication	Washington DC, USA
Year of publication	2010
Resilience topic(s) covered by literature source	General Overview
Domain of the literature source	Resilience for a specific domain, aspect, organization or business, namely: Climate Change
Nature of the content of the literature source	Opinion
Is the literature source relevant for tunnels?	Yes
Short general description of content	The article describes consequences of climate change on transportation (road, rail, air travel). As main impacts of climate change, it describes sea level rise, heat waves, increasingly intense precipitation, increasingly intense hurricanes and arctic warming. It proposes risk analysis procedures to assess the likely impact of climate change during an asset's useful life time and to evaluate mitigating measures. The article emphasises the uncertainty of climate change scenarios, but also emphasises the ability of risk models to give useful information to decision makers even allowing for these uncertainties.
What are the main relevant messages, lessons learned or recommendations?	"If we incorporate climate change into the regular planning processes for transportation and other infrastructure, the marginal costs of building more robust, resilient systems can be readily accommodated. And we will have met our obligations to future generations."
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Several possible adaptations of infrastructure are given for various climate change effects. Some of these measures are applicable to road tunnels, e.g. • Build or enhance levees and dikes to resist higher sea levels and storm surges. • Elevate critical infrastructure. • Abandon or relocate coastal highways. • Revise hydrologic storm and flood frequency maps. • Develop new design standards for hydraulic structures. • Move critical infrastructure inland. • Design for greater storm surges. • Identify infrastructure that will be damaged by thawing permafrost.
Interesting chapters, sections	[-]

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [31]	
or annexes for further reading	

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [32]	
Reviewing WG member	Ingo Riess
Date of review	9 April 2020
Title literature source	**CLIMATE CHANGE IN ASSET MANAGEMENT OF INFRASTRUCTURE: A RISK-BASED METHODOLOGY APPLIED TO DISRUPTION OF TRAFFIC ON ROAD NETWORKS DUE TO THE FLOODING OF TUNNELS**
Author(s)	E. Huibregtse, O. Morales Napoles, L. Hellebrandt, D. Paprotny, S. de Wit
Reference or ISBN	European Journal of Transport and Infrastructure Research 16(1), 2016, pp.98-113
Publisher	
City / country of publication	Delft
Year of publication	2016
Resilience topic(s) covered by literature source	Long term developments
Domain of the literature source	Resilience for a specific domain, aspect, organization or business, namely: risk-based methodology, flooding of tunnels
Nature of the content of the literature source	Analysis
Is the literature source relevant for tunnels?	Yes
Short general description of content	The paper presents a risk-based method to quantify climate change effects on road infrastructure. The method is illustrated by a specific case in which traffic on a road network is disrupted by the flooding of a tunnel due to extreme rainfall. To model a typical climate-change related phenomenon, i.e. rainfall intensity-duration, a model is proposed as well as a method to account for uncertainty using structured expert judgement. The method calculates the risk of flooding of a tunnel, expressed in both probability of occurrence and subsequent additional travel duration on the road network. By comparison of this evolving risk to a societally acceptable threshold, the remaining resilience of the tunnel is evaluated. By application of the method to a tunnel in two different contexts, i.e. in a regional road network and a highway network, it is shown that the consequences of tunnel flooding may differ by an order of magnitude (25-fold for the example).
What are the main relevant messages, lessons learned or recommendations?	Using a risk-based decision-making perspective leads to significant differences in the maximum time-to-intervention. In the example case the year of intervention is determined at 2020 for a tunnel in a highway network, while interventions can be postponed until 2140 in a regional road network.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [32]	
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The method is illustrated by a specific case in which traffic on a road network is disrupted by the flooding of a tunnel due to extreme rainfall. The resilience against flooding is evaluated by pump capacity and the volume of the pump cellars against the intensity and duration of rainfall.
Interesting chapters, sections or annexes for further reading	Section 2 of the paper gives the general outline of the model. Section 4 of the paper describes the application in two examples. Additional reference: J.N. Huibregtse, O. Morales Napoles & M.S. de Wit (2013), Flooding of tunnels: Quantifying climate change effects on infrastructure, Safety, Reliability, Risk and Life-Cycle Performance of Structures & Infrastructures, ISBN 978-1-138-00086-5, pp. 1463-1470

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [33]	
Reviewing WG member	Ingo Riess
Date of review	April 7th 2020
Title literature source	**LONG TERM FLOOD PREVENTION IN CHAOPHAYA BASIN, THAILAND**
Author(s)	Thailand Underground and Tunnelling Group
Reference or ISBN	TUNNEL 3/2012 p.16
Publisher	Bauverlag
City / country of publication	Germany
Year of publication	2012
Resilience topic(s) covered by literature source	Events and possible measures
Domain of the literature source	Resilience against flooding due to excessive rainfall
Nature of the content of the literature source	Project idea
Is the literature source relevant for tunnels?	Yes
Short general description of content	Following a major flood event in Bangkok 2011, ideas are presented for a project with combined use of a tunnel for vehicle traffic and for flood relief. The tunnel consists of two decks with the upper deck being used as a traffic tunnel and the lower deck as a storm water relief duct. The road tunnel is designed to also work as a storm water drain in a major flood situation.  Moderate Flood Situation (upper deck using as motorway, lower deck draining out water)  Major Flood Situation (both upper and lower decks using as flood drain tunnel)

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [33]	
What are the main relevant messages, lessons learned or recommendations?	Flooding due to excessive rain fall is expected to be a more frequent event due to global climate change. Infrastructure shall be developed to relieve urban areas from flooding. The combined use of underground infrastructure for traffic and for as a flood relief is an idea recently proposed in different parts of the world: • Multi-Service Flood Tunnel System (MUSTS) • Storm water Management and Road Tunnel (SMART)
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Flooding due to excessive rainfall: The focus of the article is not only the resilience of the tunnel (the tunnel would be still usable in a moderate flood situation), but the use of the tunnel for the resilience of the surface surroundings.
Interesting chapters, sections or annexes for further reading	[-]

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [34]	
Reviewing WG member	Ingo Riess
Date of review	7 April 2020
Title literature source	**A STUDY AND EVALUATION ON SMART PROJECT, MALAYSIA**
Author(s)	Ram Kumar M. KANNAPIRAN
Reference or ISBN	BSc Thesis, University of Queensland
Publisher	University of Queensland
City / country of publication	QLD Australia
Year of publication	October 2005
Resilience topic(s) covered by literature source	Events and possible measures
Domain of the literature source	Resilience against flooding due to excessive rainfall
Nature of the content of the literature source	Project description
Is the literature source relevant for tunnels?	Yes
Short general description of content	The thesis is a study on the SMART Tunnel in Kuala Lumpur, Malaysia. This tunnel is unique because it combines the wet and dry system. The tunnel is used as a pathway to transport vehicle and also a channel for storm water diversion from the city of Kuala Lumpur. The study includes a general description of tunnels and storm water drains. Then the specific conditions in Kuala Lumpur are explained: geology, construction process, flash floods, traffic requirements. In Chapter 7, the tunnel design and the operation principles are described in more detail. The safety systems are designed to allow flooding of the tunnel, e.g. tunnel ventilation system without jet fans.
What are the main relevant messages, lessons learned or recommendations?	Flooding due to excessive rain fall is expected to be a more frequent event due to global climate change. Infrastructure shall be developed to relieve urban areas from flooding. The combined use of underground infrastructure for traffic and for as a flood relief is an idea recently proposed in different parts of the world: • Multi-Service Flood Tunnel System (MUSTS) • Storm water Management and Road Tunnel (SMART)
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Flooding due to excessive rainfall. The focus of the article is not the resilience of the tunnel, but the use of the tunnel for the resilience of the surface surroundings.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [34]	
Interesting chapters, sections or annexes for further reading	Chapter 7 (p. 86 ff.) gives an overview of the tunnel system with schematics (Figure 7c, p. 92). The project has been completed in 2005 and is considered a success, as described in other articles, e.g. Nuhu Isah, Maimunah Binti Ali (2015), A Relationship between Flood Occurrences and the Maintenance Works of SMART Tunnel, Kuala Lumpur, Malaysia, International Journal of Research & Review, Vol.2; Issue: 7; July 2015

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [36]	
Reviewing WG member	Ingo Riess
Date of review	20. April 2020
Title literature source	**CLIMATE-RESILIENT INFRASTRUCTURE: GETTING THE POLICIES RIGHT**
Author(s)	L. Vallejo, M. Mullan
Reference or ISBN	OECD Environment Working Papers, No. 121
Publisher	OECD Publishing
City / country of publication	Paris / France
Year of publication	2017
Resilience topic(s) covered by literature source	General Overview, Case Studies
Domain of the literature source	Resilience against the impact of climate change
Nature of the content of the literature source	Framework for action of infrastructure owners, the report includes a case study for a road tunnel.
Is the literature source relevant for tunnels?	Yes
Short general description of content	Climate change will affect all types of infrastructure, including energy, transport and water. Rising temperatures, increased flood risk and other potential hazards will threaten the reliable and efficient operation of these networks, with potentially large economic and social impacts. Decisions made now about the design, location and operation of infrastructure will determine how resilient they will be to a changing climate. This paper provides a framework for action aimed at national policymakers in OECD countries to help them ensure new and existing infrastructure is resilient to climate change. It examines national governments' action in OECD countries, and provides recent insights from professional and industry associations, development banks and other financial institutions on how to make infrastructure more resilient to climate change.
What are the main relevant messages, lessons learned or recommendations?	The case study included a tentative process of classification and identification of the facilities - field visits. However, all structures were assessed assuming the same vulnerability. It would have saved time if sensitivity had been discussed at the outset. The initial task was primarily to conduct a vulnerability assessment and suggest possible preventive measures, rather than developing a detailed pathway towards the implementation of adaptation strategies. Involvement of the owner may have resulted in a stronger focus on implementation. The lack of a cost-benefit analysis represents one of the potential shortcomings of the case study. The report quantified the investments needed but not the benefits of those investments. Quantifying these benefits would strengthen the business case for investment in protective infrastructure.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [36]	
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Resilience against the impact of climate change, case study on sea level rise and/or storm water flooding.
Interesting chapters, sections or annexes for further reading	Annex 1: Overview of National Climate Scenarios And Risk Assessments Annex 4: Case Study – Boston Central Artery Tunnel

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [37]	
Reviewing WG member	Ingo Riess
Date of review	21. April 2020
Title literature source	**RESILIENT TUNNEL PROJECT**
Author(s)	Department of Homeland Security (DHS)
Reference or ISBN	DHS Science and Technology Directorate, 11.7.2014
Publisher	Department of Homeland Security (DHS)
City / country of publication	USA
Year of publication	2014
Resilience topic(s) covered by literature source	Events and possible measures
Domain of the literature source	Resilience against flooding
Nature of the content of the literature source	Product development
Is the literature source relevant for tunnels?	Yes
Short general description of content	The Department of Homeland Security (DHS) Science and Technology Directorate (S&T) is researching technologies that can prevent or limit flooding in transportation tunnels. Initially, S&T focused on solutions that can be deployed in subway tunnels. Additional engineering will be needed to address the needs of major highway tunnels, as well as other key nodes of transit systems. The project team developed an inflatable tunnel plug that uses state-of-the-art textile technology and manufacturing techniques to isolate and seal tunnel sections, limiting the spread of damage.
What are the main relevant messages, lessons learned or recommendations?	S&T designed a plug made of high-strength Vectran fabric. During testing of an early plug prototype, scientists found that a single layer of Vectran fabric was insufficient, so S&T developed a tri-layer version with a webbed fabric outer layer. In 2012, S&T successfully tested the modified version in a full-scale test tunnel. The plug has been tested by initially inflating it with air, then filling it with water to achieve full internal pressures. Future tests will attempt to pressurize the plug with air, offering tunnel owners more inflation options to fulfil specific transit system needs. S&T designed the tunnel plug to be pre-installed, in a custom-designed, compact container at strategic locations in underground transportation tunnels. When needed, the tunnel plug can be inflated quickly to halt flooding, minimize loss of life, and limit damage to infrastructure.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [37]	
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Mitigation against flooding of tunnels.
Interesting chapters, sections or annexes for further reading	• https://www.dhs.gov/science-and-technology/news/2017/06/21/snapshot-simple-solution-protect-critical-infrastructure, (Website visited on 21. April 2020) • A. Liao, H. Shang, X. Kou, J. Huang, X. Zhuang (2018), Modelling of 3D Inflatable Large Deformation Air Plug in Contact With Concrete Lining, Proceedings of the International Conference on Advances in Computational Mechanics, February 2018

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [40]	
Reviewing WG member	Ingo Riess
Date of review	9 April 2020
Title literature source	**WIND SHIELD FOGGING IN ROAD TUNNELS – FINAL RESULTS**
Author(s)	R. Bopp, A. Peter
Reference or ISBN	3rd Int. Conf. Tunnel Safety and Ventilation, Graz, 2006
Publisher	VT TU Graz
City / country of publication	Austria
Year of publication	2006
Resilience topic(s) covered by literature source	Events and possible measures
Domain of the literature source	Risk reduction for a specific meteorological event.
Nature of the content of the literature source	Validated study
Is the literature source relevant for tunnels?	Yes
Short general description of content	A research study has been performed regarding sudden wind screen fogging for vehicles entering a bi-directional traffic. Wind screen fogging is connected to certain meteorological conditions regarding the temperature inside and outside the tunnel and the relative humidity inside the tunnel. This kind of event has caused multiple vehicle collisions in Swiss road tunnels. It is suspected also to occur in other countries in similar climate. Several measures are proposed to reduce the probability of wind screen fogging and/or to reduce the consequences of a collision (detection of critical conditions, ventilation (with air intake at the tunnel portals), static or dynamic traffic signs (wind screen wipers) and reduction of posted speed).
What are the main relevant messages, lessons learned or recommendations?	Sudden wind screen fogging is primarily connected to the risk of a vehicle collision in a bi-directional tunnel. It may affect the resilience of the tunnel system if either a measure is applied that affects the capacity or availability of the tunnel (speed limit, temporary tunnel closure) or if the tunnel has to be closed following a vehicle collision.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Event: wind screen fogging due to certain meteorological conditions regarding temperature and humidity. Measures to improve resilience: detection of critical conditions, ventilation (air intake at the tunnel portals), static or dynamic traffic signs (wind screen wipers). Measures that apply traffic management would reduce the capacity or availability of the tunnel.
Interesting chapters, sections	Reference for the complete study (German only):

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [40]	
or annexes for further reading	R. Bopp, S. Haag, A. Peter: Beschlagende Scheiben in Strassentunneln: Synthese, Report Gruner AG, August 2004

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [41]	
Reviewing WG member	Ronald Mante
Date of review	November 7th 2020.
Title literature source	**PREVENTION AND MITIGATION OF TUNNEL-RELATED COLLISIONS**
Author(s)	PIARC Technical Committee C5 on Road Tunnel Operations
Reference or ISBN	2019R03EN / ISBN 978-2-84060-502-7
Publisher	PIARC
City / country of publication	Paris (France)
Year of publication	2019
Resilience topic(s) covered by literature source	Traffic incidents, collisions
Domain of the literature source	Resilience for collision incidents in or nearby the tunnel.
Nature of the content of the literature source	Best practices / recommendations, validated by literature, international case studies (70 in total, collected by the Working Group through interviews) or expert judgement by the Working Group Members.
Is the literature source relevant for tunnels?	Yes. The report focusses on road tunnels entirely. Although not explicitly about resilience, the recommendations in the report will contribute to resilience for collisions.
Short general description of content	The report contains an extensive and structured overview of possible measures to prevent collisions and/or to mitigate the mechanical impact thereof; this includes measures to secure the incident vehicles to prevent a subsequent collision. For each measure, the effectiveness and cost-effectiveness for various collision types is assessed, both for existing and new tunnels.
What are the main relevant messages, lessons learned or recommendations?	As a starting point, a typology for tunnel-related collisions is presented. Next, a comprehensive list of possible measures to prevent or mitigate these collision types is drawn-up, based upon collected case studies and found literature. To structure these measures in a logical coherence, the bow-tie model is used. The bow-tie model is a method to present the causes and effects of a certain incident and the measures (lines of defence) to prevent the incident and to mitigate its effects in a systematic order. For the evaluation of the effectiveness and cost-effectiveness of the individual measures a flowchart is established in order to guarantee a systematic and coherent approach. The results of this process, in which the measures are confronted with the cases studies and literature sources to estimate the potential effects, is documented in fact sheets, compiled in Appendix D of the report. The summary of the results is presented in overview tables in Chapter 4 of the report, using “traffic light” scores for the effectiveness and cost-effectiveness.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [41]	
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The report deals with tunnel-related collisions; collisions in or nearby the tunnel. Other traffic incidents, like stand-still vehicles and congestions are considered, in the context that they can lead to collisions and should therefore also be prevented or mitigated. Although the report does not address the recovery to the normal situation after the collision incident, the measures do contribute to all three characteristics of resilience related to the availability of the tunnel: • Reduced failure probabilities, by preventing collision incidents that could block lanes or the entire roadway for some time; • Reduced consequences from failures, because the mitigation measures prevent escalation in terms of subsequent collisions that could lead to even more lanes to be blocked; • Reduced time to recovery, because an escalated incident would take more time to free the road for traffic again (to restore the full availability of the tunnel).
Interesting chapters, sections or annexes for further reading	Chapter 4 / Appendix D.

<table>
<tr><th colspan="2">Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [44]</th></tr>
<tr><td>Reviewing WG member</td><td>Bernhard Kohl, Bernhard Klampfer</td></tr>
<tr><td>Date of review</td><td>2020-06-19</td></tr>
<tr><td>Title literature source</td><td>MEASURING THE RESILIENCE OF TRANSPORT INFRASTRUCTURE – NZ TRANSPORT AGENCY RESEARCH REPORT 546</td></tr>
<tr><td>Author(s)</td><td>JF Hughes, K Healy</td></tr>
<tr><td>Reference or ISBN</td><td>ISBN 978-0-478-41915-3</td></tr>
<tr><td>Publisher</td><td>AECOM New Zealand Ltd</td></tr>
<tr><td>City / country of publication</td><td>Wellington, New Zealand</td></tr>
<tr><td>Year of publication</td><td>2014</td></tr>
<tr><td>Resilience topic(s) covered by literature source</td><td>General overview, possible measures, organisational aspects</td></tr>
<tr><td>Domain of the literature source</td><td>Transport infrastructure</td></tr>
<tr><td>Nature of the content of the literature source</td><td>Methodology for the assessment of resilience of transport infrastructure in general</td></tr>
<tr><td>Is the literature source relevant for tunnels?</td><td>Yes</td></tr>
<tr><td>Short general description of content</td><td>A qualitative framework for measuring land transport system resilience was developed. The assessment tool of the framework is based on the following dimensions and principles of resilience:
<table>
<tr><th>Dimension</th><th>Principle</th></tr>
<tr><td rowspan="3">Technical</td><td>Robustness</td></tr>
<tr><td>Redundancy</td></tr>
<tr><td>Safe-to-fail</td></tr>
<tr><td rowspan="3">Organisational</td><td>Change readiness</td></tr>
<tr><td>Leadership and culture</td></tr>
<tr><td>Networks</td></tr>
</table>

Thus, parts of a system may be rated using a resilience score from 1 (low resilience) to 4 (very high resilience). In this way systems among each other as well as the effects of measures on a system can be assessed relatively in a qualitative way.

The context and approach of the assessment has to be clear in advance defining relevant issues. The methodology can follow an all-hazard approach or focus on specific hazards, considering shock and stress events. Further the scale of the assessment varies from asset over network to region.</td></tr>
</table>

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [44]	
What are the main relevant messages, lessons learned or recommendations?	Using a qualitative framework, of course, more interpretation is required in comparison to quantitative assessments. Nevertheless such an approach allows more flexibility and engages the involvement of managers and operators, which may provide organisational benefits.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Not applicable
Interesting chapters, sections or annexes for further reading	Chapter 6: assessment process Appendix B: list of possible resilience measures

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [45]	
Reviewing WG member	Bernhard Kohl, Bernhard Klampfer
Date of review	2020-06-19
Title literature source	**EIN INTEGRALER ANSATZ ZUR ERHÖHUNG DER RESILIENZ VON STRAßENTUNNELN – DAS FORSCHUNGSPROJEKT RITUN**
Author(s)	Ulrich Bergerhausen et al.
Reference or ISBN	STUVA Tagung 2019
Publisher	
City / country of publication	Germany
Year of publication	2019
Resilience topic(s) covered by literature source	Events and possible measures, minimum operating requirements, effects on traffic
Domain of the literature source	Method for the assessment of resilience of road tunnels
Nature of the content of the literature source	Research project, Federal Ministry of Education and Research, VDI Technology Center, Framework program “ Research for civil security”
Is the literature source relevant for tunnels?	Yes
Short general description of content	The non-availability of a road tunnel has a direct influence on the capacity of road systems, local as well as regional. Thus, the loss of functionality of tunnels may lead to significant economic losses. The project aims for increasing the resilience in respect to disruptive events. Following the all-hazard-approach potential threats were identified. In order to determine the effects of the resulting damage scenarios on tunnel operation minimum operating requirements were developed. Therefor qualitative and quantitative risk analyses were performed. As disruptive events often lead to restricted operation of road tunnels, the effects on traffic are analysed on local as well as on regional scale. Finally resilience measures, which exceed current rules and standards requirements, are identified, categorized and their effectivity is assessed.
What are the main relevant messages, lessons learned or recommendations?	Up to now conventional approaches like risk analysis and emergency plans focus on how to prevent disruptive events and how to react in case of emergencies. In order to be able to increase the tunnel capacity during the recovery process minimum operating requirements provide a solid basis for decision-making. They allow do decide how to operate the tunnel during this phase complying with safety requirements at any time.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The literature source follows the all-hazard approach.
Interesting chapters, sections or annexes for further reading	The final results of the research project including a practical handbook will be available from September 2020 on www.bast.de/ritun. The handbook will include:

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [45]	
	▪ list of events ▪ list of measures ▪ method for assessing the effect of measures on resilience ▪ method for defining minimum operating requirements ▪ method for assessing effects on traffic on object and network scale

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [46], [47], [48]	
Reviewing WG member	Ciro Caliendo
Date of review	November 3rd 2020.
Title literature source	Various sources, not publicly available: 1. D. Freckleton, K. Heaslip, W. Louisell, J. Collura (2012), **EVALUATION OF TRANSPORTATION NETWORK RESILIENCY WITH CONSIDERATION FOR DISASTER MAGNITUDE,** paper presented at the 91st Annual Meeting of the Transportation Research Board, Washington, DC, 2012) [46]. 2. Faturechi, R., & Miller-Hooks, E. (2015), **MEASURING THE PERFORMANCE OF TRANSPORTATION INFRASTRUCTURE SYSTEMS IN DISASTERS: A COMPREHENSIVE REVIEW**, Journal of Infrastructure System, 21(1), 0414025 [47]. 3. W. Sun , P. Bocchini, B.D. Davison (2020), **RESILIENCE METRICS AND MEASUREMENT METHODS FOR TRANSPORATION INFRASTRUCTURE: THE STATE OF THE ART**, Sustainable and Resilient Infrastructure. Vol.5, Issue 3 [48]
Resilience topic(s) covered by literature source	General resilience concepts and approaches.
Domain of the literature source	Scientific publications, reflecting the state of the art.
Nature of the content of the literature source	**Resilience and resilience metrics in transportation networks.**
Is the literature source relevant for tunnels?	Yes.
Short general description of content	See below for summary and synthesis.
What are the main relevant messages, lessons learned or recommendations?	Infrastructure systems that show adaptive response to a stress are generally described as resilient. However, researchers have not yet converged on a shared concept of resilience, and as a result different definitions of resilience might be found in the literature. With specific reference to a transportation network, resilience can be also defined 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” (Freckton et al. 2012). Resilience has not to be confused with vulnerability, this last is the susceptibility of a transportation system to a given event without considering the recovery process. Given the essential role of transportation networks in supporting the mobility of goods and people, and providing response in emergency circumstances, current research has focused prevalently on certain resilience metrics. Resilience metrics support better decision-making process in transportation networks. Some discussions on resilience metrics in the field of transportation networks can be found in Futurechi and Miller (2015); whereas a more recent extension of the mentioned work with a critical view of available metrics is reported in Sun et al. (2020). Since the resilience of a transportation network is prevalently related to its functionality, traffic-related resilience metrics expressed in terms of traffic flow properties and capacity system should be more especially considered. Obviously resilience

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [46], [47], [48]	
	measures should be also related to topological features of a network (i.e. the concepts of connectivity and centrality of a transportation infrastructure should be considered). However, the present paragraph prevalently focuses on some definitions of certain traffic-related metrics. The disruption caused by an event and the following recovery can lead to increases in the travel time of vehicular flows; therefore the delay time (i.e. the excess time consumed in transportation facility) is a traffic-related resilience metric. The congestion index due to an event (originally defined as the ratio of delay time to acceptable travel time) can also be a measure of resilience. Capacity is often used to quantify transportation network resilience; usually distinguished in adaptive and restorative. Adaptive capacity is the ability of the system to gradually adapt itself from disruption; whereas restorative capability is the ability of the system to restore itself in a reasonable short time. In other terms, if a disruption leads to a functionality loss, the transportation infrastructure may still recover the functionality by reorganizing, for example, two undisrupted lanes characterized originally by unidirectional traffic for bidirectional traffic, when the adjacent carriageway is disrupted (adaptive capacity). If the repair team restores the carriageway disrupted, the functionality recovery through restoration activities corresponds to the restorative capacity. Also the availability of an alternative itinerary, which may be used when the original route is disrupted, can be helpful to represent a measure of the resilience in terms of travel time (i.e. after a disruptive event and the following functionality recovery at different times). An alternative route with a shorter travel time is, for example, closer to how drivers and/or passengers would like to travel, which makes less significant the impact of a disruption, as well as positively influences the effectiveness of the emergency response in terms of people evacuation, rescue, and humanitarian helps; all that is generally desirable for a resilient transportation system. Methods for resilience analysis can be divided in two main groups: qualitative and quantitative. Qualitative methods are used to evaluate the resilience of a transportation infrastructure only in a descriptive way (e.g. high, medium, and low resilience) by using one or more metrics. They are not suitable for measuring resilience of more complex and interdependent transportation networks. Quantitative methods can compute system resilience at transportation networks level accounting for also the intermodal components. Analytical and simulation models are used to perform a quantitative resilience analysis. Analytical models can include event tree, fault tree, scenarios analysis, failure and effect analysis, Bayesian analysis or hierarchy process. These methods might be complicated to apply in very large transportation networks characterized by many possible scenarios. Nowadays, simulation models are often used to quantify the transportation network resilience. By identifying vulnerable components and comparing different scenarios, simulation models appear to represent a better tool for supporting decisions and addressing maintenance activities that should be made for a more resilient transportation network.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [46], [47], [48]	
	However, it is to be mentioned that the randomness of factors that play a role may cause some uncertainties in resilience analysis. Therefore, studies based on uncertainties in resilience analysis should also be made. In intermodal transport, in which transportation infrastructures depends on each other in different ways, the disruption of a system might propagate to the others and lead to significant functionality loss in a large geographic area. This means that, for cases of transportation infrastructures having interactions with other systems, resilience analysis has to account for also this interdependency. Interdependency is to be accounted for also among other systems of a same transportation infrastructure. A tunnel, for example, requires interactions also with traffic control systems and availability of alternative routes to support its functionality, therefore modelling this interdependency is necessary for a more accurate assessment of tunnel resilience.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Not applicable.
Interesting chapters, sections or annexes for further reading	Not applicable.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [55]	
Reviewing WG member	Heidi Cuypers
Date of review	23 June 2020
Title literature source	**COB GROEIBOEK - RENOVEREN KUN JE LEREN (COB LIVING DOCUMENT – YOU CAN LEARN TO REFURBISH)**
Author(s)	COB Project group
Reference or ISBN	Online living document, https://www.cob.nl/wat-doet-het-cob/groeiboek/renoveren-kun-je-leren/introductie/
Publisher	Centrum Ondergronds Bouwen (COB)
City / country of publication	Delft, The Netherlands.
Year of publication	Living document; available since 2018; content accessed on June 9th 2020.
Resilience topic(s) covered by literature source	Maintenance or refurbishment.
Domain of the literature source	Resilience for a specific domain, aspect, organization or business, namely: refurbishment.
Nature of the content of the literature source	Collaborative project.
Is the literature source relevant for tunnels?	Yes
Short general description of content	The document offers advice on various aspects of refurbishment projects, such as risk assessment, selection, planning, collaborative culture, granting process, environment management and communication. It also discusses some case studies, drawn from refurbishment projects in the Netherlands.
What are the main relevant messages, lessons learned or recommendations?	During an 'open' refurbishment project, one should consider carefully the necessary conditions to ensure the safety of the tunnel, and document the assurance of these conditions in a plan.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Not applicable.
Interesting chapters, sections or annexes for further reading	8 Renoveren met de winkel open.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [56]	
Reviewing WG member	Heidi Cuypers
Date of review	June 10th 2020

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [56]	
Title literature source	**COB GROEIBOEK – HINDERARM RENOVEREN** **(COB LIVING DOCUMENT – REFURBISHMENT WITH LITTLE NUISANCE)**
Author(s)	COB Project group
Reference or ISBN	Online living document, https://www.cob.nl/groeiboeken/pdf/hinderarm-renoveren.pdf
Publisher	Centrum Ondergronds Bouwen (COB)
City / country of publication	Delft, The Netherlands.
Year of publication	Living document; content accessed on June 10th 2020.
Resilience topic(s) covered by literature source	Maintenance or refurbishment.
Domain of the literature source	Resilience for a specific domain, aspect, organization or business, namely: refurbishment.
Nature of the content of the literature source	Collaborative project.
Is the literature source relevant for tunnels?	Yes
Short general description of content	The document is a collection of practical suggestions and solutions regarding the refurbishment of road tunnels, with a focus on limiting hindrance, based on the experience of a variety of parties involved during the lifecycle of a tunnel system.
What are the main relevant messages, lessons learned or recommendations?	It serves to inspire new ideas and possibilities for finding solutions problems associated with the refurbishment of tunnels; especially concerning availability and traffic hindrance.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	It also contains some important questions, doubts and uncertainties which were raised during the composition of the document.
Interesting chapters, sections or annexes for further reading	The document discusses different methods for refurbishments, such as ‘big-bang refurbishment’, ‘micro-refurbishment’, ‘parallel construction’, et cetera. For each method, it provides an overview of advantages and disadvantages regarding traffic hindrance.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [57]	
Reviewing WG member	Josep Cursà Danés, Ivan Ricondo Zaldivar
Date of review	03/07/2020
Title literature source	**TECHNICAL NOTE REGARDING THE BIDIRECTIONAL OPERATION OF THE FRESNO TUNNEL FOR IMPROVEMENT WORKS TO ADAPT THE DRAINAGE SYSTEM.**
Author(s)	Ivan Ricondo Zaldivar
Reference or ISBN	FOM13P01-090V01.00
Publisher	Tekia Ingenieros S.A.
City / country of publication	Madrid, Spain.
Year of publication	2017
Resilience topic(s) covered by literature source	Resilience in traffic and operations aspects, and management systems in a degraded mode.
Domain of the literature source	The Fresno tunnel requires an exceptional traffic and management configuration to be able to undertake the rehabilitation works to be done, while maintaining a fluid circulation of users in safety conditions, and comfort.
Nature of the content of the literature source	Guide to define minimum operating requirements while carrying out the rehabilitation works.
Is the literature source relevant for tunnels?	Yes, and mainly for the Fresno tunnel (A-63 Asturias, Spain).
Short general description of content	The Fresno tunnel had an upcoming rehabilitation work to be done for safety improvement purposes. In the paper, after analysing the background and the full situation, Tekia provides a series of recommendations, in the form of conclusions, to consider before starting of the works.
What are the main relevant messages, lessons learned or recommendations?	After analysing the available information and considering the planned operational operations to date, the following actions are recommended, as tasks prior to the start of the works: • Evaluate the capacity of the mechanical ventilation of the tunnel, adjustment and calibration of anemometers, and implementation of algorithms in the control system, and if necessary, calibrate anemometers and redefine the algorithm for situations of fluid traffic and congested / bidirectional traffic:.(ventilation algorithms for bidirectional traffic conditions are normally not defined or implemented in twin tube tunnels). • Design a specific action plan to consider the bidirectional traffic operation in the Fresno tunnel and include it as an annex in the documentation of the existing Emergency Response Plan. • Provide training to control centre operators and field personnel on the new defined action plan. The recommendations were extended to the rest of the tunnels in the same area, and the rest of the areas with tunnels over 500 meters.
If the literature source deals with resilience /	The tunnel resilience has a special section for heavy traffic and dangerous goods:

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [57]	
availability in certain events, what are these events and what are the measures to improve resilience?	The suggestion to divert traffic avoiding the circulation of dangerous goods and heavy vehicles over 7,500 kg is considered adequate, recommending to include 3.500 kg and buses due to uncertainties regarding the ventilation system.
Interesting chapters, sections or annexes for further reading	1.1 Background 3 Conclusions

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [58]	
Reviewing WG member	Rafael López Guarga
Date of review	
Title literature source	**BIELSA-ARAGNOUET TUNNEL**
Author(s)	Bielsa-Aragnouet Tunnel
Reference or ISBN	No reference
Publisher	
City / country of publication	Spain-France
Year of publication	N/A
Resilience topic(s) covered by literature source	Maintenance or refurbishment, organizational aspects and management systems
Domain of the literature source	Resilience for a specific domain, aspect, organization or business, namely: road tunnels
Nature of the content of the literature source	Standard practices, established protocols.
Is the literature source relevant for tunnels?	Yes
Short general description of content	The Bielsa- Aragnouet transboundary tunnel is located between the north of the province of Huesca and the south of the province of Altos Pirineos, in the Pyrenean massif. It is a transboundary tunnel that connects the Spanish A-138 road with the French RD 173, in the so-called Central Pyrenees. The tunnel has a length of 3,070 meters, of which 1,303 are in Spanish territory and 1,767 in France. The border between France and Spain is located at kilometre point 92.490 of the regional road A-138 from Barbastro to France via Bielsa. It was opened to traffic in October 1976. The cross section is composed by two lanes of 3 meters, separated by two continuous lines of 10 cm and sidewalks of 0.75 m. The section height is 5.38 metres, and the gauge is set to 4.30 metres. The longitudinal profile is developed by a ramp of approximately 5%, with the height at the Spanish portal being 1,664 m and at the French portal 1,821 m. The main topics described in the document are: • What measures are implemented to keep the tunnel in service as long as possible when maintenance or improvements are carried out? • How is the work organised so that the disturbance is minimised? • What type of signalling and traffic management is followed to keep the tunnel in service with the minimum of inconvenience?

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [58]	
What are the main relevant messages, lessons learned or recommendations?	Both maintenance and improvement measures are based on a proper planning. The perspective is annual, although the horizon is set at the origin of the operation in 2013. However, there are periods of lower frequency than annual (for instance, some Approved Control Bodies develop their maintenance task with a triennial or quinquennial frequency). The annual maintenance is practically the same; it is grouped in two night-time traffic interruptions throughout the year. One during the spring and the other in the autumn coinciding with the moments of least traffic.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The longer traffic interruption usually coincides with the maintenance of the axial fans of the roof, they are located in the highest part and with the use of auxiliary equipment is totally incompatible with the traffic. This usually varies between 6-10 nights, depending on the corrective work detected and if it is decided to take advantage of the interruption to send a motor to the workshop. This implies two shutdowns of one week in different months, generally consecutive so as not to delay the replacement of the equipment. The rest of the maintenance operations that requires the closure of the tunnel or that leads it in minimum operating conditions are grouped together, such as: maintenance of the Power Supply (HV) system and the Transformer Substations, certification of the optical fibre and the CCTV, maintenance of the Firefighting (hydrants) system, etc. To minimize the impact on users, two cases are established: Work at heights carried out at night from 10:00 pm to 6:00 am. Traffic level in that time slot is very low. The rest of the work is carried out during the day by means of lane inhibition. The traffic lane is blocked depending on the installation to be maintained. This guideline is carried out at least twice a month for the maintenance of the S.O.S. Post network. Preventive and corrective maintenance tasks or improvements are grouped together to maximize the effectiveness of the lane closure or inhibition. Depending on the circumstances, the minimum daytime service is established, in order to include more resources during the night. The organization of the prolonged night-time cuts consists of: 1. Historical calendars of external maintenance with the months of activity. 2. Preliminary planning with the contracts companies, counting on their availability. 3. The current year's calendar is filled in, taking into account the holiday periods of both parts. Incompatibilities are analysed, offsetting dates or adding specific guidelines to both internal and external workers (e.g.: High Voltage Maintenance leaves out of service everything that is not supplied from UPS, thus generating incompatibility, for example with ventilation maintenance). 4. Annual planning is defined, with definitive closing dates. 5. The closure is requested to the Tunnel Manager (Consortium) for submission to the authorities.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [58]	
	6. Once the closure has been approved, it is announced in the VMPs and on the web, free phone number for users, and it is published in the media. 7. On day "X" the audio-visual information is changed from "informative" to "closing" in the VMPs. In some exceptional situations, work has been carried out at heights without completely closing the infrastructure, taking advantage of the low traffic rate: In this case, an operator is available at night to stay in the control centre to supervise the cameras. The tunnel is open but with the access control in manual and all the access lights in red. When a vehicle is approaching, the operator warns the workers inside the tunnel (via radio) so that, where possible, they can remove the aids and allow the vehicle in question to pass. A maximum waiting time of 15 minutes is set for the vehicle.
Interesting chapters, sections or annexes for further reading	The signalling is based on standard equipment: VMP, traffic lights and barriers. However, depending on the type of closure, three situations are established: 1. If there is a frontier close by a decree established by the authorities, or the road is closed due to the risk of avalanches, there are manual semi-barriers with a chain and padlock, which allow the total closure of the accesses that they manage. 2. In the event of night-time closure for work, for the protection of workers, they add manual new jersey type barriers at the portals. So, if any user decides to ignore the dynamic signalling of traffic lights and semi-barriers, they will find a mobile barrier (new jerseys). This has happened on several occasions. 3. In the case of lane inhibition, they cancel the lane following the protocol established by the regulations, by means of wedges and dynamic auxiliary signalling. Inside the tunnel, in addition to modifying the dynamic signalling related to the arrow-blades. The speed is reduced by means of the Speed Limit Control panels to 50km/h. and a "barrier" is established by means of a row of cones, spaced approximately 75 - 100m from each other.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [59]	
Reviewing WG member	Michael POTIER - Eric PREMAT
Date of review	June 8th 2020
Title literature source	**OPERATIONAL RESILIENCE OF ROAD TUNNELS, WS TUNNEL SAFETY PRIORITY ITEM**
Author(s)	MONGEOT, H., TESSON, M.
Reference or ISBN	Presentation for the Work Stream Tunnel Safety in Maastricht (The Netherlands) on 26-27 March 2014.
Publisher	CETU, France
City / country of publication	Maastricht, The Netherlands
Year of publication	2014
Resilience topic(s) covered by literature source	Operational resilience; an approach to manage road tunnel safety ?
Domain of the literature source	Resilience in general.
Nature of the content of the literature source	Collected experiences.
Is the literature source relevant for tunnels?	Yes.
Short general description of content	1. Reliability and redundancy of equipment 2. Reliability and redundancy of operational staff 3. Organisational aspects
What are the main relevant messages, lessons learned or recommendations?	1. Reliability and redundancy of equipment The French technical instruction includes the rules for containment and/or redundancy for the equipment that directly condition safety. The maintenance of the equipment contributes to reliability: Preventive maintenance = preserves the availability of the equipment Corrective maintenance = restores the availability of the equipment Safety integrity levels : A quantification of the expected performance for a safety function 2. Reliability and redundancy of operational staff The reliability and the redundancy of the operational staff are to be linked in particular to the following criteria : The methods for staff organisation, recruiting and training The stakes linked to the management of the “operator - emergency teams” interface Operator qualification 3. Organisational aspects : Relationship between Safety functions and Means (equipment + operational staff) Emergency Response Plans (and Minimal Operating Requirements)
If the literature source deals with resilience / availability in certain events,	N/A

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [59]	
what are these events and what are the measures to improve resilience?	
Interesting chapters, sections or annexes for further reading	The presentation as a whole describes an approach which combines physical resilience and community resilience (focus on the group and on the collective aspects).

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [60]	
Reviewing WG member	Jens König
Date of review	2020-09-22
Title literature source	**MERKBLATT FÜR DIE KONTROLLE, WARTUNG UND PFLEGE VON STRAẞENTUNNELN (LEAFLET FOR THE INSPECTION, MAINTENANCE AND CARE OF ROAD TUNNELS)**
Author(s)	Arbeitsgruppe Infrastrukturmanagement, Arbeitsausschuss Straßenbetriebsdienst
Reference or ISBN	
Publisher	Forschungsgesellschaft für Straßen- und Verkehrswesen
City / country of publication	Germany
Year of publication	2015
Resilience topic(s) covered by literature source	Maintenance or refurbishment
Domain of the literature source	Resilience for the specific aspect of revision works. Preservation of resilience in general by comprehensive tunnel maintenance.
Nature of the content of the literature source	Code of practice
Is the literature source relevant for tunnels?	Yes
Short general description of content	The code of practise describes the scope of work for inspection, maintenance and cleaning of road tunnels. It specifies the concerned parts of the tunnel including attendant facilities and provides organisational instructions for the execution of works as: - General structure - Escape ways - Service rooms - road drainage - structure drainage - groundwater transition structures - technical equipment, e.g. ventilation, CCTV, lights etc. - extinguishing installations The information includes relevant guidelines and standards, lists and overviews and practical advices. An additional chapter deals with the winter service. The organisational instructions demand a bunching of works, gives advice for the traffic routing for bidirectional and directional tunnels including the required adaption of technical equipment, coordination of tunnel closures and public announcements.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [60]	
What are the main relevant messages, lessons learned or recommendations?	Measures of the organisation of operational works to minimize hindrances and to improve the availability during the maintenance work itself are addressed directly. The entity of the single measures of inspection, maintenance and cleaning can be understood as a strategy to achieve a long-term availability of road tunnels. Savings in these procedures reduce the resilience of tunnels finally.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Improvement of tunnel availability during inspection, maintenance and cleaning: 1. All works affecting the traffic should be bunched at a certain time with low traffic periods. 2. Installation of a bidirectional traffic in one tube of a twin bore tunnel during revision of the other tube if reasonable. 3. Annual planning of tunnel closures to minimize hindrance of traffic by consideration of boundary conditions and participation of further authorities.
Interesting chapters, sections or annexes for further reading	Chapter 5 describes the organisation of the revision works to minimize traffic hindrance.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [61]	
Reviewing WG member	Jens König
Date of review	2020-11-13
Title literature source	**SACHSTANDSBERICHT 2017 - INSTANDSETZUNGSSTRATEGIEN UND - VERFAHREN FÜR VERKEHRSTUNNEL**
Author(s)	STUVA-Arbeitskreis „Instandsetzung von Verkehrstunneln“
Reference or ISBN	ISBN 978-3-433-03253-4
Publisher	ASFINAG, DB Netz AG, STUVA
City / country of publication	Berlin / Germany
Year of publication	December 2017
Resilience topic(s) covered by literature source	Maintenance or refurbishment
Domain of the literature source	Resilience during and by refurbishment and strategies and methods.
Nature of the content of the literature source	Situation report
Is the literature source relevant for tunnels?	Yes
Short general description of content	The report provides an overview of the situation and approach for the corrective maintenance and refurbishment of traffic tunnels in Austria and Germany (road and railway). The content focuses on the structure of the tunnel, not the technical equipment. In Chapter 2 several influencing factors are considered as age of tunnels, monitoring and inspection of the structure, budget, human resources, administrative approval procedures, politics, operational safety, route availability and existing guidelines. In result measures have to be bundled to achieve a high availability of the tunnel and the road net. The different life cycles of the structures and of the technical equipment have to be considered as well. Well defined periodically executed inspections of the tunnel system enable to find the suitable date for the suitable action from preservation measures to general refurbishment. The chapter contains a detailed matrix of typical structure damages in relation to materials and components. Based on a valid evaluation of the tunnel condition preventive and long-term or preserving reactive strategies of repair activities are developed within Chapter 3. These strategies complement one another and increase life cycle and availability of the tunnel. Chapter 4 describes a set of repair techniques to remedy damages listed in matrix of Chapter 2. **Furthermore, operational boundary conditions are considered, focusing on the availability of the traffic route with highest priority.**

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [61]	
	In subsequent chapters practical examples including recommendations and innovative solutions and developments for the refurbishment of tunnels are presented.
What are the main relevant messages, lessons learned or recommendations?	Regular inspections form the base for corrective maintenance and refurbishment measures and leads to the minimisation of hindrances by damages and failures. The broad knowledge of proven measures for the treatment of structural damages, the correct selection and accurate call for tenders could increase the availability of the tunnel. Furthermore, the knowledge of innovative techniques could allow works under traffic conditions, otherwise have to be executed with complete permanent closure of the tunnel.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	[-]
Interesting chapters, sections or annexes for further reading	- **4.2.3.2 Betriebliche Randbedingungen bei Straßentunneln in Deutschland und Österreich (Operational boundary conditions for road tunnels in Germany and Austria)** - **4.2.3.3 Verfahren / Randbedingungen für eine bauzeitliche Verkehrsführung – Strasse (Procedures / boundary conditions for the traffic routing during the construction period - roads)** - 5.4.1 Bosrucktunnel - 7.2.2.1 Trennung der Fahrbahn und der Instandsetzungsbereiche (Dividing of pavement and repair areas) - 7.3 Automatisierte Vernetzung zur Ausbau-und Felssicherung (Automated cross-linking for rock consolidation) - 7.4 Betonabtrag und Spachtelung im Ulmen- / Wandbereich (Concrete removal and filling at wall areas) - 7.5 Konzepte zur Verbesserung zukünftiger Instandsetzungsarbeiten (Concepts for the improvement of prospective corrective maintenance)

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [63]	
Reviewing WG member	Bijan Khaleghi
Date of review	October 27, 2020
Title literature source	**ALTERNATIVE FUEL VEHICLES IN TUNNELS**
Author(s)	Chris B. LaFleur, Austin M. Glover, Austin R. Baird, Cyrus J. Jordan, Brian D. Ehrhart
Reference or ISBN	
Publisher	SANDIA REPORT - SAND2020-5466
City / country of publication	Albuquerque, New Mexico, USA
Year of publication	Printed May 2020
Resilience topic(s) covered by literature source	Many types of vehicles using fuels that differ from typical gasoline and diesel are in use throughout the world tunnels. These include vehicles running on the combustion of natural gas and propane as well as electrical drive vehicles utilizing batteries or hydrogen as energy storage. These alternative fuels pose hazards that are different from traditional fuels and the safety of these vehicles are being questioned in areas such as tunnels and other enclosed spaces.
Domain of the literature source	Fire hazards associated with alternative fuel vehicles in Tunnels
Nature of the content of the literature source	This report provides a comprehensive, concise summary of the literature available characterizing the various hazards presented by all alternative fuel vehicles, including light-duty, medium- and heavy-duty, as well as buses. Research characterizing both worst-case and more plausible scenarios and risk-based analysis is also summarized. Gaps in the research are identified in order to guide future research efforts to provide a complete analysis of the hazards and recommendations for the use of alternative fuel vehicles in tunnels.
Is the literature source relevant for tunnels?	YES, it is relevant to tunnels.
Short general description of content	The intent of this document is to help illustrate the level of risk for all types of fuel, provide a full understanding of what codes & standards are applicable to these alternative fuel vehicles, and to review relevant research that has been conducted to date. Risks to life safety and infrastructure damage always exist, regardless if the fuel type is traditional or alternative. The goal for acceptance of alternative fuel vehicles may be to maintain the same level of risk that is generally accepted for traditional fuel vehicles. For each fuel type, including traditional fuels such as gasoline and diesel, an overview with a summary of fuel properties and hazards, applicable codes and standards, and tunnel-specific research in the literature is provided. Additionally, information to compare the various classes of vehicles such as passenger, light-duty, heavy-duty, and cargo are reviewed where available. This information helps characterize the severity of the hazard for each classification of vehicle.
What are the main relevant messages,	Tunnel owners, authorities, and other stakeholders have raised concerns about alternative fuel vehicles traveling through tunnels, particularly in urban and high commuter areas. Natural gas and propane are used to

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [63]	
lessons learned or recommendations?	replace traditional fuels as cleaner or more efficient alternative fuel in combustion engines. Alternative fuel vehicles also include those powered by electricity using lithium-ion batteries or hydrogen fuel cells. The different codes and standards applicable come from organizations such as National Fire Protection Association, Society of Automotive Engineers, Underwriters Laboratories, and more.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The literature source deals with events of fire and explosion hazards in tunnels of alternative fuel vehicles such as natural gas leak from a vehicle in a tunnel and how the flammable mass and overpressures change based on those events. hydrogen release and combustion.
Interesting chapters, sections or annexes for further reading	Fire and explosion hazards in tunnels of alternative fuel vehicles.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [64]	
Reviewing WG member	Stanislaw Lopacinski
Date of review	27.08.2020
Title literature source	**"ELECTRIC MOBILITY AND ROAD TUNNEL SAFETY, HAZARDS OF ELECTRIC VEHICLE FIRES"**, 9th Symposium "Tunnel Safety and Ventilation", Graz, Austria, June 2018.
Author(s)	L. D. Mellert, U. Welte, M. Hermann, M. Kompatscher, X. Ponticq,
Reference or ISBN	ISBN: 978-3-85125-606-2
Publisher	Prof. Dr. H. Eichlseder
City / country of publication	Graz, Austria
Year of publication	2018
Resilience topic(s) covered by literature source	Tunnel infrastructure/additional equipment
Domain of the literature source	Electric vehicles
Nature of the content of the literature source	Scientific research, experiment description
Is the literature source relevant for tunnels?	Yes
Short general description of content	The main goal of experiments described in this paper was to investigate the effects of a fire of a lithium-ion battery in a road tunnel environment. For the experiment, the batteries were charged with >95% of their capacity. Since potential causes for electric vehicle fires are mechanical (e.g. crash) and/or thermal (e.g. fire), battery modules were damaged in four scenarios: 1. Thermal stress (a module was heated evenly with propane gas fire until the module caught fire); 2. (Mechanical) central puncturing with a projectile that was shot at the module; 3. (Mechanical) blunt impact: explosive charges pressed a steel plate against an entire surface of a module; The module thus suffered a blunt impact over its entire surface so that all cells were structurally damaged without penetration. 4. (Mechanical) wedge shaped penetration: explosive charges pressed wedges mounted on a steel plate into a module. In the immediate vicinity and in unfavourable ventilation situations, electric vehicle fires may lead to new and more severe chemical hazards. Analyses point also to critical concentrations of heavy metals such as cobalt, lithium and manganese in form of aerosols.
What are the main relevant messages,	In the beginning (of the experiments), every battery emitted large amounts of black and very dense smoke.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [64]	
lessons learned or recommendations?	After initial similarity, two types of behaviour occurred: 1. the thermal stress damaging scenario led to a chain reaction from one cell to another, 2. while three other mechanical damaging scenarios led to almost simultaneous thermal runaways of all cells. After the tests, the batteries had no voltage. The temperature rose up to 750 °C within the batteries but at a distance of 2 m, practically no temperature rises were registered. Increased amounts of toxic heavy metals: Cobalt, Manganese and Lithium (as dust-bound aerosols) were recorded. Those metals typically don't occur, when vehicles with conventional internal combustion engine (ICE) are on fire. Scenarios of damage had almost no influence on the amount of released pollutants. It is believed, large amounts of very toxic hydrogen fluoride (HF) were realised but it reacted quickly with the moisture from the environment due to hygroscopic nature of HF. The ventilation, 1,0-1,5 m/s, carried the reaction products and deposited them on the way to the measuring site, locates about 160m further downstream. For that reason, only small quantities of HF were detected.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Fire of electric cars can hardly be prevented by a tunnel-manager. A measure to improve resilience would be to provide sufficient water - probably more water would be needed than in conventional ICE vehicle fires. Firefighting with water has further the advantage that undamaged cells may be cooled and hence protected against a thermal runaway.
Interesting chapters, sections or annexes for further reading	Paper/Chapter: L.D. Mellert, "Electric mobility and road tunnel safety, hazards of electric vehicle fires", p. 258-263

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [65]	
Reviewing WG member	Stanislaw Lopacinski
Date of review	27.08.2020
Title literature source	**“COMPARISON OF THE FIRE CONSEQUENCES OF AN ELECTRIC VEHICLE AND AN INTERNAL COMBUSTION ENGINE VEHICLE”**, 2nd International Conference on Fires In Vehicles - FIVE 2012, Sep 2012, Chicago, USA.
Author(s)	A. Lecocq, M. Bertana, B. Truchot, G. Marlair
Reference or ISBN	HAL Id: ineris-00973680
Publisher	
City / country of publication	France
Year of publication	2012
Resilience topic(s) covered by literature source	Tunnel infrastructure/additional equipment
Domain of the literature source	Electric vehicles
Nature of the content of the literature source	Scientific research, experiment description
Is the literature source relevant for tunnels?	Yes
Short general description of content	The paper describes full scale experiments on two electric vehicles (EV) and two corresponding internal combustion engine (ICE) vehicles. In total, four passenger cars were tested using identical test procedure. A gas burner of 6 kW, activated for 1 minute, orientated to the left front seat was used to set fire to the vehicle. In order to quantify emitted gases and energies, the tests were performed in a confined space, operated like a large-scale fire calorimeter. Fire consequences of an EV and the corresponding ICE vehicle were analysed and compared.
What are the main relevant messages, lessons learned or recommendations?	Fire development was found similar for all vehicles. The maximal heat release rate (HRR) and the overall dissipated effective heat were similar for corresponding vehicles: 4.2 / 4.8 MW for smaller and 4.7 / 6.1 MW for larger cars and 6300 / 6900 MJ for smaller and 8500 / 10000 MJ for larger cars. The measured mass loss, around 20% of the initial mass, was also close for EV and ICE vehicles. The production of very toxic hydrogen fluoride (HF) was different for EV and ICE vehicles: small EV produced 1.540 g and small ICE produced 621 g of HF. larger EV produced 1.470 g and larger ICE produced 813 g of HF.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [65]	
	The production of other gases was similar.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Fire of electric cars can hardly be prevented by a tunnel-manager. Those experiments confirm results of other experiments, that HRR and the overall effective heat is similar for an EV and a corresponding ICE vehicle. This important message says that additional fire protection in tunnels against heat from EV vehicles fires would not be required. However, for the issue of hydrogen fluoride (HF) or products of its reactions, more research seems to be needed.
Interesting chapters, sections or annexes for further reading	The whole Paper, 11 pages, is interesting.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [67]	
Reviewing WG member	Bernhard Kohl, Bernhard Klampfer
Date of review	2020-11-02
Title literature source	**RAINEX HANDBOOK, RISK-BASED APPROACH FOR THE PROTECTION OF LAND TRANSPORT INFRASTRUCTURE AGAINST EXTREME RAINFALL**
Author(s)	Kalliopi Anastassiadou, Harald Kammerer, Ingo Kaundinya, Evangelos Mitsakis, Iraklis Stamos
Reference or ISBN	N/A
Publisher	RAINEX Consortium
City / country of publication	Bergisch Gladbach, Germany
Year of publication	2016
Resilience topic(s) covered by literature source	Events and possible measures – heavy rainfall
Domain of the literature source	Impact of extreme rainfall on land transport infrastructure
Nature of the content of the literature source	EU research project: Prevention, Preparedness and Consequence Management of Terrorism and other Security-related Risks Programme (CIPS)
Is the literature source relevant for tunnels?	Yes
Short general description of content	The main objective is to ensure the availability of land transport infrastructure in case of extreme rainfall-induced hazards. After defining the relevant network to be investigated a **criticality analysis** is carried out. Sections with high criticality are further investigated, performing a detailed **exposure** and **vulnerability analysis** on object level. The result of the two steps is a quantifiable assessment using a scoring system to categorise the individual assets. The output of the method is a risk categorisation of each asset with respect to all local phenomena in relation to heavy rainfall.
What are the main relevant messages, lessons learned or recommendations?	The developed methodology allows to assess infrastructure objects in respect of heavy rainfall induced risks. The prioritization enables operators and infrastructure managers to set measures more target-oriented and effective.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Heavy rainfall. The Document provides a methodology for assessing the risks related to heavy rainfall, but do not give specific measures.
Interesting chapters, sections or annexes for further reading	[-]

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [71]	
Reviewing WG member	Bernhard Kohl, Bernhard Klampfer
Date of review	2020-11-02
Title literature source	**ALL-HAZARD GUIDE FOR TRANSPORT INFRASTRUCTURE**
Author(s)	Jürgen Krieger, Bernhard Kohl, José Mateus de Brito, Jan Spousta
Reference or ISBN	N/A
Publisher	AllTraIn Consortium
City / country of publication	Germany
Year of publication	2015
Resilience topic(s) covered by literature source	Events and possible measures
Domain of the literature source	Land transport infrastructure (road and railway)
Nature of the content of the literature source	EU research project: Prevention, Preparedness and Consequence Management of Terrorism and other Security-related Risks Programme (CIPS)
Is the literature source relevant for tunnels?	Yes
Short general description of content	The methodology makes use of the dual-entrance approach and includes two ways to deal with different kinds of hazards. It allows to identify, on the one hand the specific hazards that could potentially have a significant impact on a given infrastructure, on the other hand the infrastructure elements in the network which might be susceptible to a specific hazard. As it follows the all-hazard approach man-made hazards (intentional and unintentional) as well as natural hazards are covered.
What are the main relevant messages, lessons learned or recommendations?	The comprehensive compilation of hazards provide a solid basis in order to identify all relevant threats for given infrastructure objects following the all-hazard approach instead of concentrating on particular threats.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	All-hazard approach
Interesting chapters, sections or annexes for further reading	The **AllTraIn Hazard Fact Sheets** provide a comprehensive catalogue with all identified hazards including a short description, main effects on certain infrastructures and possible measures. The **AllTraIn Tool** allows to receive information about relevant hazards to specific assets. (both are available on the project website www.alltrain-project.eu)

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [72]	
Reviewing WG member	Bernhard Kohl, Bernhard Klampfer
Date of review	2020-11-02
Title literature source	**SECMAN – SECURITY MANUAL FOR EUROPEAN ROAD INFRASTRUCTURE**
Author(s)	Jakob Haardt, Harald Kammerer
Reference or ISBN	N/A
Publisher	SecMan Consortium
City / country of publication	Germany
Year of publication	2013
Resilience topic(s) covered by literature source	Events and possible measures – security
Domain of the literature source	Protection of road infrastructure against man-made intentional threats
Nature of the content of the literature source	EU research project: Prevention, Preparedness and Consequence Management of Terrorism and other Security-related Risks Programme (CIPS)
Is the literature source relevant for tunnels?	Yes
Short general description of content	The manual describes the protection of road infrastructure, such as tunnels and bridges, against man-made intentional hazards. In a 4-step procedure the infrastructure, e.g. a tunnel, is assessed in respect to its **criticality** for the network, **attractiveness** for an attack and **vulnerability** of the object itself. Thus, weak spots in respect of security in the road network may be identified to implement measures more target-oriented and efficiently. Possible measures are provided on different levels: network level, general object level, measures for bridges, measures for tunnels, measures for accompanying infrastructures
What are the main relevant messages, lessons learned or recommendations?	At the moment, many safety measures are already included in the design and operation of tunnels. In order to include security related hazards too, the decision support tool enables the selection of measures for structures or network sections which have been prioritised in the assessment regarding security.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	man-made intentional threats
Interesting chapters, sections or annexes for further reading	Part 4 of the document provides a broad list of measures on network level as well as on object level (general and tunnel-specific).

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [73]	
Reviewing WG member	Bernhard Kohl, Bernhard Klampfer
Date of review	2020-10-16
Title literature source	**FELSSTURZ: FELBERTAUERN-STRAßE AUF TEILSTÜCK VÖLLIG ZERSTORT (ROCK FALL: PART OF THE FELBERTAUERN ROADWAY COMPLETELY DESTROYED)**
Author(s)	Brigitta Luchscheider
Reference or ISBN	-
Publisher	Kurier Zeitungsverlag und Druckerei GmbH
City / country of publication	Austria
Year of publication	2013
Resilience topic(s) covered by literature source	Natural hazards ("calamities")
Domain of the literature source	Rock fall in alpine regions
Nature of the content of the literature source	Newspaper article
Is the literature source relevant for tunnels?	Yes
Short general description of content	Due to a rock fall with approx. 35.000 m³ an avalanche gallery was destroyed over a length of about 100 m on an important north-south connection in Austria in the year 2013. The picture below shows the setting and extent of the event.  To stabilize the slope blasting operations on the top were necessary in order to create safe working conditions. Aiming to reopen the road as fast as possible, a provisional alternative route was constructed. After two months and investments of about 2,5 million euros it was possible to provide at least a partial availability until the final new route was finished. Because of the challenging conditions in an alpine environment it took more than years and approx. 18,5 million euros to construct the new road with a length of about 3,5 km.
What are the main relevant messages, lessons learned or recommendations?	As all the existing alternative routes lead to significant longer travel times, building a temporary used road as a provisional arrangement with much lower requirements turned out to be an ideal solution to optimize the recovery process.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [73]	
	Although in the present case a gallery was damaged, cut-and-cover tunnels may be affected considerably by rock falls too. But also driven tunnels could be influenced, in particular in areas close to the tunnel portals.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Rock fall, Construction of a provisional alternative route to provide at least a partial availability.
Interesting chapters, sections or annexes for further reading	Link to the newspaper article with more pictures: https://kurier.at/chronik/oesterreich/matrei-in-osttirol-felbertauernstrasse-nach-felssturz-auf-teilstueck-voellig-zerstoert/12.348.506 (access on 16th October 2020)

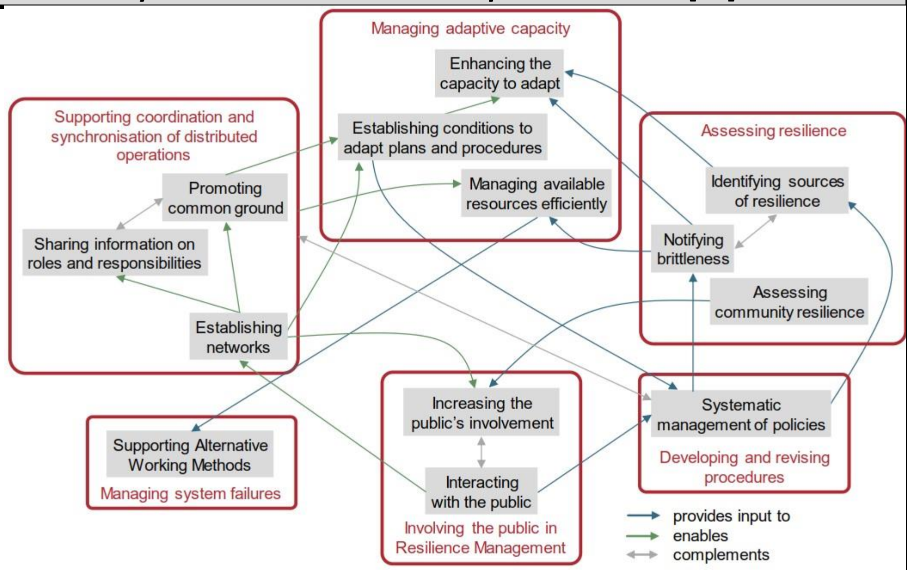
Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [74]	
Reviewing WG member	Bernhard Kohl, Bernhard Klampfer
Date of review	2020-07-06
Title literature source	**RESILIENCE MATURITY MODEL HANDBOOK**
Author(s)	Smart Mature Resilience Project
Reference or ISBN	
Publisher	Tecnum, University of Navarra
City / country of publication	Spain
Year of publication	2018
Resilience topic(s) covered by literature source	organisational aspects and management systems, policies and strategies, possible measures
Domain of the literature source	Resilience of critical infrastructure in urban environment
Nature of the content of the literature source	Research project, EU Horizon 2020, Crisis management topic 7: Crises and disaster resilience – operationalizing resilience concepts
Is the literature source relevant for tunnels?	Yes, relevant for critical infrastructure in urban environment in general
Short general description of content	Development of the European Resilience Management Guideline (ERMG) to increase the resilience of European cities. The following strategic tools have been evolved, which are used in an iterative process: - Resilience Maturity Model “Where am I now?” - Risk Systemicity Questionnaire “Which risk scenarios are a priority?” - City Resilience Dynamics Model Experimentation: “Why/Why not?” (support for disaster managers) - Resilience Building Policies “How can we improve?” (sample applications, support for cities and authorities in implementing resilience strategies)
What are the main relevant messages, lessons learned or recommendations?	The following dimensions are considered as fundamental to succeed in terms of resilience: - leadership and governance - preparedness - infrastructure and resources - cooperation For each dimension a broad list of measures are presented, subject to various stages of resilience maturity.
If the literature source deals with resilience / availability in certain events,	Not applicable

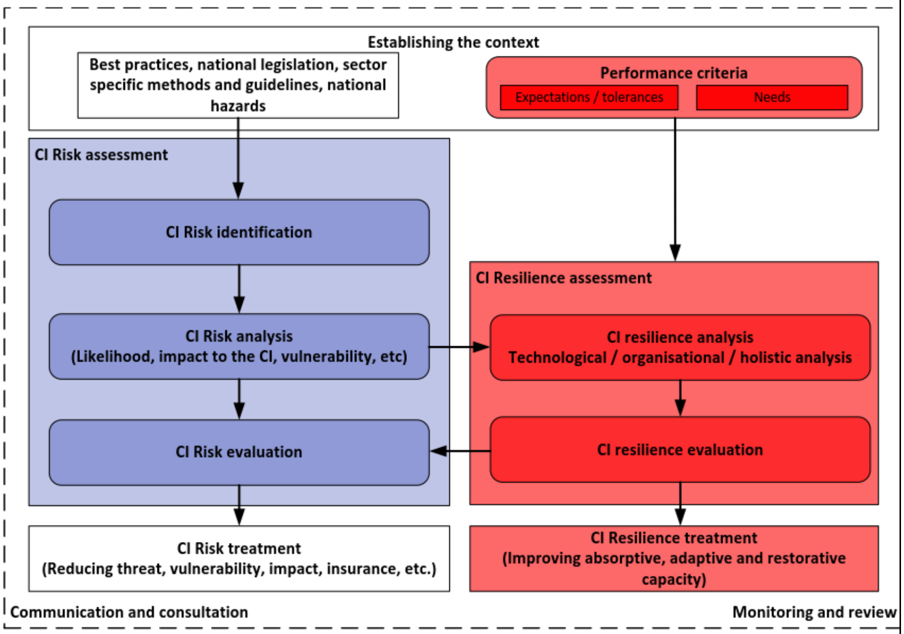
Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [74]	
what are these events and what are the measures to improve resilience?	
Interesting chapters, sections or annexes for further reading	On the project website (smr-project.eu) an interactive Resilience Maturity Model is available to illustrate and facilitate the use of the method.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [75]	
Reviewing WG member	Bernhard Kohl, Bernhard Klampfer
Date of review	2020-07-06
Title literature source	**RESILENS – REALISING EUROPEAN RESILIENCE FOR CRITICAL INFRASTRUCTURE**
Author(s)	
Reference or ISBN	
Publisher	
City / country of publication	
Year of publication	2016
Resilience topic(s) covered by literature source	Organisational aspects and management systems
Domain of the literature source	Resilience in General
Nature of the content of the literature source	Research project, EU Horizon 2020, Crisis management topic 7: Crises and disaster resilience – operationalizing resilience concepts
Is the literature source relevant for tunnels?	Yes, relevant for critical infrastructure in general
Short general description of content	The project outputs support the practical application of the concept of resilience in respect of critical infrastructure. Further a methodology for assessing resilience and identifying fields of action was developed. This methodology is supported by the following interactive methods and tools: - European Resilience Management Guideline (ERMG) support organisations to put into practice the concept of resilience - Critical Infrastructure Resilience Assessment Tool (CI-RAT) assessment of resilience by means of a list of criteria - Post Assessment Resilience Enhancement Tool (PARET) identifying fields of action on the base of the resilience assessment - Resilience Management Matrix and Audit Toolkit (ReMMAT) digitalization of CI-RAT and PARET All methods are provided on a web-based platform , where also an e-learning environment is available.
What are the main relevant messages, lessons learned or recommendations?	Three broad areas were identified as the domains, in which resilience is defined: information, physical and societal. It is a comprehensive project with a very general approach.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [75]	
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Not applicable
Interesting chapters, sections or annexes for further reading	The project website provides a quick overview as well as the reports to the working packages: resilens.eu

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [76]	
Reviewing WG member	Bernhard Kohl, Bernhard Klampfer
Date of review	2020-07-06
Title literature source	**DARWIN RESILIENCE MANAGEMENT GUIDELINES (DRMG BOOK)**
Author(s)	Ivonne Herrera, Matthieu Branlata, Tor Olav Grøtana, Luca Saveb, Daniele Rusciob, Rogier Woltjerc, Jonas Hermelinc, Jiri Trnka, Thomas Feuerled, Peter Försterd, Odeya Cohene, Laura Cafierof, Valentina Cedrinif, Maurizio Mancinif, Giancarlo Ferraraf, Giuseppina Mandarinog, Luca Rosig, Carl Oscar Johnsonh, Euan Morinh, Eddie Shawni, Judith Kierani, Meadhbh Costelloi
Reference or ISBN	
Publisher	
City / country of publication	
Year of publication	2018
Resilience topic(s) covered by literature source	Organisational aspects and management systems, possible measures
Domain of the literature source	Resilience in General
Nature of the content of the literature source	Research project, EU Horizon 2020, Crisis management topic 7: Crises and disaster resilience – operationalizing resilience concepts
Is the literature source relevant for tunnels?	Yes, relevant for critical infrastructure in general
Short general description of content	The literature focuses on improving responses to expected and unexpected events. It supports organisations in creating, assessing and improving their own resilience procedures and guidelines and helps to develop a critical view on its own crisis management activities. Resilience management guidelines allow infrastructure operators to facilitate faster, more effective and highly adaptive responses to crisis. Definition of 13 topics (“Capability Cards”, grey boxes), which represent different courses of action to enhance resilience management capabilities. They belong to six higher-level themes (red fields). Since resilience management capabilities are not independent, they are organized and related accordingly:

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [76]	
	 Measures are identified for each capability card before, during and after a disruptive event. Further thoughts about responsibilities, challenges, benefits and costs are given. The information of each Capability Card is structured around five main sections: purpose, implementation fields, background and context information, relevant material, navigation fields.
What are the main relevant messages, lessons learned or recommendations ?	"Expect the unexpected and know how to respond." Currently risk analysis focus on already known events, in contrast to resilience engineering complement this approach by anticipating threats and opportunities to resist them.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Not applicable, it deals with expected and unexpected, natural and man-made events.
Interesting chapters, sections or annexes for further reading	To facilitate the usage of the DRMG, the following tools of assistance are available on the project website h2020darwin.eu: ▪ training material ▪ knowledge portal (DARWIN Wiki)

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [77]	
Reviewing WG member	Bernhard Kohl, Bernhard Klampfer
Date of review	2020-07-06
Title literature source	**IMPROVER – IMPROVED RISK EVALUATION AND IMPLEMENTATION OF RESILIENCE CONCEPTS TO CRITICAL INFRASTRUCTURE**
Author(s)	
Reference or ISBN	
Publisher	
City / country of publication	
Year of publication	2018
Resilience topic(s) covered by literature source	Organisational aspects and management systems
Domain of the literature source	Resilience in General
Nature of the content of the literature source	Research project, EU Horizon 2020, Crisis management topic 7: Crises and disaster resilience – operationalizing resilience concepts
Is the literature source relevant for tunnels?	Yes, relevant for critical infrastructure in general
Short general description of content	In Analogy to the framework for risk management of ISO 3100 the report presents a framework for resilience management. Combining these the result is a Critical Infrastructure Resilience Management Framework for the integrated process of risk and resilience management:  Operating companies can monitor resilience over time and compare critical infrastructures among each other. For this purpose three methods were developed:

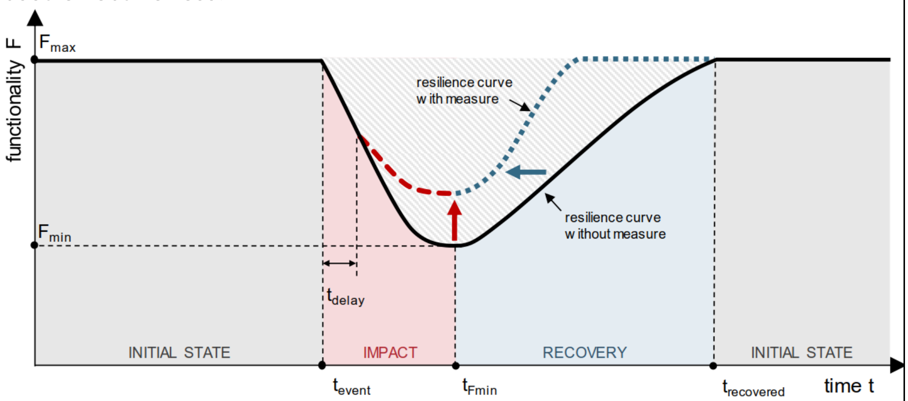
Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [77]	
	- Critical Infrastructure Resilience Index CIRI Predicated on indicators it forms the basis for more detailed methods. - IMPROVER Technological Resilience Analysis (ITRA) Quantify resilience as the area between the resilience curve and the 100% functionality line. - IMPROVER Organisational Resilience Analysis (IORA) in-depth interviews about past events
What are the main relevant messages, lessons learned or recommendations ?	comprehensive project with a very general approach
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Not applicable
Interesting chapters, sections or annexes for further reading	[-]

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [78]	
Reviewing WG member	Bernhard Kohl, Bernhard Klampfer
Date of review	2020-06-19
Title literature source	**"RESILIENCE-BY-DESIGN": STRATEGIE FÜR DIE TECHNOLOGISCHEN ZUKUNFTSTHEMEN**
Author(s)	Klaus Thoma
Reference or ISBN	
Publisher	acatech – Deutsche Akademie der Technikwissenschaften
City / country of publication	Freiburg, Germany
Year of publication	2014
Resilience topic(s) covered by literature source	General overview
Domain of the literature source	Resilience in general
Nature of the content of the literature source	Conceptual description of resilience in general
Is the literature source relevant for tunnels?	Yes
Short general description of content	The study is based on three expert workshops relating to national / international perspectives on resilience and resilient organizations. It aims to frame the fundamentals and the potential of the concept of resilience. Further potential difficulties are depicted. Both technical and social aspects have to be considered to be able to create resilient systems.
What are the main relevant messages, lessons learned or recommendations?	The study provides 10 recommended courses of action: - implement a holistic approach - develop metrics and indicators for assessing vulnerability and resilience - modelling and simulation of high-relevance socio-technical systems - establish Resilience Engineering as independent area of expertise - stimulate personal responsibility of members of the public - highlight the long-term additional value of resilience for society - incent companies and organizations to increase their resilience - introduce a notification requirement in terms of an early-warning system - elaborate a national strategy for resilience on a large scale - establish resilience as key component of sustainable development

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [78]	
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Not applicable
Interesting chapters, sections or annexes for further reading	Chapter 6 describes 10 recommended courses of action at organizational level. They are based upon the findings made in the previous chapters.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [79]	
Reviewing WG member	Bernhard Kohl, Bernhard Klampfer
Date of review	2020-09-18
Title literature source	**LEITFADEN ZUR STEIGERUNG DER RESILIENZ VON STRAßENTUNNELN**
Author(s)	Bernhard Kohl, Harald Kammerer, Bernhard Klampfer
Reference or ISBN	BASt Tunnelsymposium 2020
Publisher	
City / country of publication	Germany, Bergisch Gladbach
Year of publication	2020
Resilience topic(s) covered by literature source	Events and possible measures, minimum operating requirements, effects on traffic
Domain of the literature source	Method for the assessment of resilience of road tunnels
Nature of the content of the literature source	Research project, Federal Ministry of Education and Research, VDI Technology Center, Framework program " Research for civil security"
Is the literature source relevant for tunnels?	Yes
Short general description of content	Existing guidelines and regulations focus on avoiding incidents and protecting the tunnel and tunnel users in the event of an disruptive event. Recommendations on how to react appropriately in the event of an incident in order to reduce the extent of functional loss of the tunnel and accelerate the recovery process back to normal operation are often missing. However, increasing the availability of road tunnels should only be achieved while complying with the minimum requirements of tunnel safety. Pursuing a measure-oriented and risk-oriented approach, a method for the development of minimum operating requirements for the temporary operation of road tunnels was developed. As disruptive events often lead to restricted operation of road tunnels, the effects on traffic are analysed on local as well as on regional scale. Finally resilience measures, which exceed current rules and standards requirements, are identified, categorized and their effectivity is assessed.
What are the main relevant messages, lessons learned or recommendations?	The definition of minimum operating requirements is an essential prerequisite for maintaining the availability of road tunnels after an incident. Thus possible compensation measures were examined which reduce the resulting risk and could maintain a defined traffic flow immediately after an incident as well as during repair work until the tunnel is fully reopened.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [79]	
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The literature source follows the all-hazard approach.
Interesting chapters, sections or annexes for further reading	The final results of the research project including a practical handbook are available on www.bast.de/ritun. The handbook includes: ▪ list of events ▪ list of measures ▪ method for assessing the effect of measures on resilience ▪ method for defining minimum operating requirements ▪ method for assessing effects on traffic on object and network scale

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [80]	
Reviewing WG member	Bernhard Kohl, Bernhard Klampfer
Date of review	2020-07-23
Title literature source	**REAKTIONS-UND WIEDERHERSTELLUNGSPROZESS FÜR DIE STRAßENINFRASTRUKTUR NACH DISRUPTIVEN EREIGNISSEN**
Author(s)	M. Deublein, F. Roth, F. Bruns, C. Zulauf
Reference or ISBN	
Publisher	Federal Highway Research Institute BASt
City / country of publication	Germany, Bergisch Gladbach
Year of publication	2020
Resilience topic(s) covered by literature source	Organisational aspects and management systems
Domain of the literature source	Assessment of the resilience of road infrastructure and prioritization of measures
Nature of the content of the literature source	Research project, BASt research program FE 89.0330/2017
Is the literature source relevant for tunnels?	Yes, road infrastructure in general
Short general description of content	The aim is to develop a methodology to optimize the response and recovery process after disruptive events. In three main steps the methodology enables an assessment and prioritization of measures regarding their impact on resilience. First the **resilience screening** examines the resilience of the system based on a catalogue of criteria concerning organisational, economic and technical issues. In doing so the fields of action are limited to currently least resilient aspects and a pre-selection of potential measures is made. After defining the system functionalities the resilience effect of the pre-selected measures is determined. **(measure evaluation)** The impact of measures in the respond and recover phases on the functionality of a system is showed on the following figure of the resilience curve. The last step **resilience optimization** aims to generate an optimal ranking list of the prioritized measures with respect to the system´s resilience. Therefore the costs of the measures have to be recorded to evaluate the cost-effectiveness. 

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [80]	
What are the main relevant messages, lessons learned or recommendations ?	Many potential user groups already consider aspects of resilience in their daily work. New in this context is the systematic approach by an efficient decision making. The methodology allows to compare very different types of measures with each other and to compare their effects with regard to resilience.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Not applicable
Interesting chapters, sections or annexes for further reading	Part A of the document describes the methodical approach. Part B provides a guideline to work through the method as well as an example of use.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [81]	
Reviewing WG member	Toshi Sakaguchi
Date of review	June 29, 2020
Title literature source	**MANAGING UNANTICIPATED PROBLEMS AND RESILIENCE ENGINEERING**
Author(s)	Shigeru Haga
Reference or ISBN	Technical Report IEICE, SSS2011-10, 2011 (in Japanese)
Publisher	The Institute of Electronics, Information and Communication Engineers (Japan)
City / country of publication	Tokyo, Japan
Year of publication	2011
Resilience topic(s) covered by literature source	General overview
Domain of the literature source	Resilience in General in technical systems
Nature of the content of the literature source	Invited lecture at the IEICE with the reference of eleven (11) publications on system resilience
Is the literature source relevant for tunnels?	Yes
Short general description of content	Provided successful and failing behaviours in the socio-technical systems at the time of the East Japan Earthquake in 2011, when many people and organizations faced unanticipated incidents and had to behave beyond manuals, training, precedent, rule, and law.
What are the main relevant messages, lessons learned or recommendations?	Rigid procedures and instructions do not work in a huge emergency situation. People at the system forefront are forced to make local judgement by themselves and behave autonomously where and when resilience is requested. To support resilience of individuals and organizations the "just culture" becomes critically important. The "just culture" means that people causing human errors won't be blamed for their failures.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The report describes cases involving a helicopter pilot, JR train drivers and a well-known aircraft pilot, who successfully landed his airplane on the Potomac River, DC and saved passengers' life in mid-winter. The literature source puts emphasis on the view that operators are to be considered as a resource that manages difficulties in order to lead to a better situation. No measures are provided to improve resilience.
Interesting chapters, sections or annexes for further reading	Chapter 3 and 4.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [82]	
Reviewing WG member	Toshi Sakaguchi
Date of review	June 29, 2020
Title literature source	**RESILIENCE ENGINEERING: SHIFTING FROM PREVENTION OF ALREADY-OCCURRED INCIDENTS TO PROACTIVE SAFETY MANAGEMENT**
Author(s)	Shigeru Haga
Reference or ISBN	The Journal of Medical Quality and Safety, Vol. 7, No. 3, 2012 (in Japanese)
Publisher	Japanese Society for Quality and Safety in Healthcare (Japan)
City / country of publication	Tokyo, Japan
Year of publication	2012
Resilience topic(s) covered by literature source	General overview.
Domain of the literature source	Resilience in general, in healthcare systems.
Nature of the content of the literature source	Opinion paper, published in the Journal with five English books and three Japanese papers.
Is the literature source relevant for tunnels?	Yes, to some extent.
Short general description of content	The Safety-I and Safety-II concepts are described, where Safety-I means prevention of already-occurred incidents and Safety-II proactive safety management. In addition, it is proposed to see people as a system component that proactively solves problems instead of seeing people as a threat, because they make a mistake from time to time. Successful behaviours at the ER in a hospital are presented.
What are the main relevant messages, lessons learned or recommendations?	Adapt healthcare systems from a Safety-I to Safety-II culture, and see people a critical resource for problem solving. A change into a just culture is proposed, in which people causing human errors won't be blamed for their failure.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The literature source deals with a treatment at the ER in a hospital where they needed a longer oxygen tube; the staff took and cut the other tube to connect it to the oxygen tube. Whether saving patient life or not is the measure to improve resilience.
Interesting chapters, sections or annexes for further reading	Not applicable.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [83]	
Reviewing WG member	Toshi Sakaguchi
Date of review	June 28, 2020
Title literature source	**NEW CONCEPT OF SAFETY PURSUED AND IMPLEMENTED BY RESILIENCE ENGINEERING**
Author(s)	Masaharu Kitamura
Reference or ISBN	IEICE Fundamentals Review Vol. 8, No. 2, pp84-95, 2014 (in Japanese)
Publisher	The Institute of Electronics, Information and Communication Engineers (Japan)
City / country of publication	Tokyo, Japan
Year of publication	2014
Resilience topic(s) covered by literature source	General overview.
Domain of the literature source	Resilience in general, in technical systems
Nature of the content of the literature source	Analysis and survey of twenty-six (26) publications on the system resilience
Is the literature source relevant for tunnels?	Yes
Short general description of content	Extends the Safety-I concept to Safety-II concepts, where Safety-I means no undesirable incident taking place while Safety-II means system continuing to operate even against very large and rare, usually unexpected, incident. Investment under Safety-I tends to be viewed as an insurance (outcome-oriented), while investment under Safety-II viewed for the purpose of improving system performance (process-oriented). Provides four functions which make a technical system resilient: responding, monitoring, anticipating and learning. Learning will help the other three to continue to improve their performance.
What are the main relevant messages, lessons learned or recommendations?	Provides a thought and hint to implement the resilience in road tunnel monitoring system. Anticipating function will be implemented by running a road tunnel online simulator which does not currently exist in monitoring system. The Safety-II concept will be useful in designing the role of human operators, who are considered a resource and asset.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Not applicable. No measures provided to improve resilience.
Interesting chapters, sections or annexes for further reading	Chapter 2 describing how to implement a resilient system in general.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [84]	
Reviewing WG member	Toshi Sakaguchi
Date of review	July 7, 2020
Title literature source	**FROM SAFETY-I TO SAFETY-II: INTRODUCTION TO RESILIENCE ENGINEERING**
Author(s)	Erik Hollnagel (translated by Takayuki Yoshizumi)
Reference or ISBN	The Operations Research Journal, No. 8, pp435-439, 2014 (in Japanese)
Publisher	The Institute of Operations Research (Japan)
City / country of publication	Tokyo, Japan
Year of publication	2014
Resilience topic(s) covered by literature source	General overview
Domain of the literature source	Resilience in general, in technical systems
Nature of the content of the literature source	Introduction to resilience engineering: migrating Safety-I to Safety-II
Is the literature source relevant for tunnels?	Yes
Short general description of content	Provides the definition of Safety-I and Safety-II concept. Safety-I is built on a theory of hypothesis of different causes which means causes leading to a failure and those leading to success exist in exclusive. We can focus on eliminating the causes leading to a failure. Safety-II is built on a theory that we should guarantee things moving in the right direction and understand why things move in the right direction. Provide major difference in Safety-I and Safety-II. In Safety-I, we try to prevent causes leading to a failure, we will respond to incident only when it occurs, and we see people a responsible entity. In Safety-II, we try to ensure as many things as possible move in the right direction, we anticipate possible incidents and predict their outcomes, and we see people a resource in the system.
What are the main relevant messages, lessons learned or recommendations?	It is not easy to migrate from Safety-I to Safety-II concept. Provide some practical guidelines on how to migrate. We should see not only what goes wrong but also what goes right. When something went wrong, spend time to explore different options in daily operations, instead of narrowing down to the source of a failure. Observe what is happening from time to time, and focus on the frequency of an incident not on the seriousness of it. Take into account of the time to think, learn and communicate. Be sensitive to possible failure and prepare for it before it occurs.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Not applicable. No measures provided to improve resilience.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [84]	
Interesting chapters, sections or annexes for further reading	Chapter 2 describing definition of Safety-I and Safety-II concept.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [85]	
Reviewing WG member	Toshi Sakaguchi
Date of review	June 28, 2020
Title literature source	**SYSTEMS AND RESILIENCE**
Author(s)	Hisashi Tamaki, Nobutada Fujii and Itsuo Hatano
Reference or ISBN	Journal of the ISCIE, Vol. 60, No.1, pp18-23, 2016
Publisher	The Institute of Systems, Control and Information Engineers
City / country of publication	Kyoto, Japan
Year of publication	2016
Resilience topic(s) covered by literature source	General overview
Domain of the literature source	Resilience in General in technical systems
Nature of the content of the literature source	Analysis and survey of twenty-three (23) publications on the system resilience
Is the literature source relevant for tunnels?	Yes
Short general description of content	Define environment as modelled, assumed and hidden environment. Provide three resilient strategies to each of the system environments (within model, outside model and unexpected). For example, one strategy is to avoid, withstand and recover for with model, outside model, and unexpected environment). Introduce a study project on system resilience, where resilience is a combination of resistance and recovery. Study resilience strategy in existing systems such as biology, business planning, computer system, law and environment. They identify a common strategy for resilience in these systems: redundancy, diversity, reproduction, crisis management. Resistance means a priori response and recovery a posteriori response to unexpected disturbance to systems. Resilience is studied as a response strategy to unexpected incident.
What are the main relevant messages, lessons learned or recommendations?	Resilience is a strategic response to an unexpected incident and disturbance. It can be a combination of resistance and recovery. Resistance can be an automated response while recovery needs interactive and heuristic means because of posterior response.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Not applicable.
Interesting chapters, sections or annexes for further reading	Chapters 2, 4 and 5.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [86]	
Reviewing WG member	Rafael López Guarga
Date of review	
Title literature source	**FRÉJUS TUNNEL**
Author(s)	Fréjus tunnel
Reference or ISBN	No reference
Publisher	
City / country of publication	France / Italy
Year of publication	
Resilience topic(s) covered by literature source	Maintenance or refurbishment, organisational aspects and management systems.
Domain of the literature source	Resilience for a specific domain, topic, organization or business: road tunnels
Nature of the content of the literature source	Usual practices, established protocols.
Is the literature source relevant for tunnels?	Yes
Short general description of content	The 12.87 km long Fréjus road tunnel, opened in 1980, is located at the crossroads of two important regional and international trade routes connecting France and Italy. This connection between Savoy and Piedmont, is now one of the main road crossings in the Northern Alps. The Fréjus tunnel consists of a single two-way tube that contains two traffic lanes of 3.55 metres. It is designed to allow the circulation of heavy vehicles with a maximum height of 4.30 meters. The French and Italian portals are located at 1,228 and 1,297 metres above the sea level respectively. The longitudinal profile has a slight slope of 0.54% in the France-Italy direction. The questions answered in this article are the following: • What measures are taken to keep the tunnel in service as long as possible when maintenance or upgrading operations are carried out? • How is the work organized so that the traffic disturbance is minimized? • What type of signalling and traffic management is implemented to keep the tunnel in service with the minimum of inconvenience?
What are the main relevant messages, lessons learned or recommendations?	Most of the works that affect traffic lanes are scheduled at night and under alternative traffic conditions. Thus, they allow traffic to pass in one direction for a period of between 30' and 1h. Afterwards, the tunnel is checked and then opened in the other direction for an equivalent period of time. In this way at least one lane is always available allowing most of the maintenance or improvement works in a tunnel.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [86]	
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	When more complex interventions are needed, the tunnel is closed completely. These interventions must be scheduled at least 2 months in advance and validated by the Prefecture of Savoy. In general, periods of low IMD are chosen.
Interesting chapters, sections or annexes for further reading	To inform users, the information is published in the local press, on the SFTRF website (French side) and on the SITAF website (Italian side), and it is also distributed via the MVPs on the road at both portals of the tunnel.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [87]	
Reviewing WG member	Rafael López Guarga
Date of review	
Title literature source	**MAPPO MORETTINA TUNNEL**
Author(s)	Mappo Morettina Tunnel
Reference or ISBN	No reference
Publisher	
City / country of publication	Switzerland
Year of publication	N/A
Resilience topic(s) covered by literature source	Maintenance or refurbishment, organizational aspects and management systems.
Domain of the literature source	Resilience for road tunnels during maintenance / refurbishment works
Nature of the content of the literature source	Common practices, established protocols.
Is the literature source relevant for tunnels?	Yes
Short general description of content	The tunnel Mappo-Morettina (in Italian Galleria Mappo-Morettina) is a single-tube tunnel forming part of the bypass of Locarno, Muralto and Minusio through the cantonal semi-motorway A13 (N13), located in the canton of Ticinio in Switzerland. With a length of 5518 m, it opened to the traffic in June 13, 1996. The main topics described in the document are: • Which measures are adopted to keep the tunnel as long as possible in service when maintenance or refurbishment works are performed? • How are organized the works so as to minimize the disturbs to the traffic? • Which kind of signposting and traffic management are used in order to keep the tunnel on service with the minimum disturbance?
What are the main relevant messages, lessons learned or recommendations?	Maintenance works are carried out during night since it is a tunnel that bypass a city with tens of thousands of vehicles per day. During maintenance works, they divert the traffic through the city.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Along with the technicians, they study the Minimum Operation Conditions. If the technical systems do not guarantee the users' safety, traffic management measures are taken in order to minimize the risk (speed reduction, traffic lights in yellow, lorries only in one direction, increase of the video-surveillance, ….).
Interesting chapters, sections or annexes for further reading	The signalling is based on the standard means: Variable Message Panels, traffic lights and barriers. In case of works in the tunnel, the closure is carried out by traffic lights in red, diversion signalling before the tunnel and in the city of Locarno (manual and dynamic signalling). Barriers are put to block the traffic.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [88]	
Reviewing WG member	George Mavroyeni
Date of review	7 July 2020
Title literature source	**MANAGEMENT OF NATURAL CONDITIONS ON NATIONAL ROADS**
Author(s)	Bernard Gogniat, Phillip Arnold, Matthias Foley, Alain Jeannerat, Reto Siegenthaler, Urban Rieder, Urs Vollmer, Luuk Dorren, Thomas Eglio, Selina Alioth, Hans-Heini Utelli
Reference or ISBN	
Publisher	Federal Office of Roads (Switzerland)
City / country of publication	
Year of publication	2014
Resilience topic(s) covered by literature source	Tunnel Manager Capability for Tunnel Resilience
Domain of the literature source	Resilience in General
Nature of the content of the literature source	
Is the literature source relevant for tunnels?	Study and analysis.
Short general description of content	In 2014 the Federal Council (Switzerland) established the foundation for uniform handling of risks for administration by the Federal Government.
What are the main relevant messages, lessons learned or recommendations?	Applies to all phases of asset management – planning, construction, operation and maintenance. Applies to risks which are triggered by natural gravitational hazards (such as rock falls, collapse) and non-gravitational hazards (such as earthquakes, storms). The paper describes the process for risk analysis, development of potential mitigations measures, cost-effectiveness analysis to optimise selection of measures. It describes some issues that need to be considered in the process of planning and implementing mitigation measures. It also describes responsibilities of various organisations for event management, and the importance of monitoring the potential for natural events and the use of warning devices.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	It is a process for risks management for the resilience of road assets.
Interesting chapters, sections or annexes for further reading	It is generic about risks triggered by gravitational and non-gravitational hazards as they apply to road assets. It is not specific to road tunnels.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [89]	
Reviewing WG member	George Mavroyeni
Date of review	11 July 2020
Title literature source	**RISK MANAGEMENT FOR EMERGENCY SITUATIONS.**
Author(s)	PIARC's TC 1.5, Chaired by Keiichi Tamura (Japan)
Reference or ISBN	2016R26EN
Publisher	PIARC
City / country of publication	Paris, France
Year of publication	2016
Resilience topic(s) covered by literature source	Tunnel Manager Capability for Tunnel Resilience
Domain of the literature source	Resilience in General
Nature of the content of the literature source	Study and analysis.
Is the literature source relevant for tunnels?	Yes
Short general description of content	The paper presents analysis of road system management for emergency situations based on case studies. It includes recommendations for road authorities to prepare for emergencies. ITS is noted as an effective risk management tool. Recommends use of emergency traffic management plans for quick evacuation of users and safe and effective access of rescue services. Mentions the importance of traffic management centres and describes their sub-systems. Describes various systems for emergency management on the broader road network. Most principles can be applied to the resilience of tunnels, but the paper does not include anything particular to road tunnels.
What are the main relevant messages, lessons learned or recommendations?	Emergency management principles for the road network that could also be applied in the context of road tunnel resilience.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Describes major natural disasters – applicable to the broad road network.
Interesting chapters, sections or annexes for further reading	[-]

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [92]	
Reviewing WG member	Heidi Cuypers - Rafael Lopez Guarga - **Tiago Massingue**
Date of review	28 May 2020
Title literature source	**IMPACT OF FIXED FIRE FIGHTING SYSTEMS ON ROAD TUNNEL RESILIENCE, VENTILATION AND OTHER SYSTEMS**
Author(s)	Anurag Jha, MS; Aixi Zhou, PhD, PE The University of North Carolina at Charlotte Charlotte, NC
Reference or ISBN	FPRF-2017-06
Publisher	RESEARCH FOUNDATION – RESEARCH FOR THE NFPA MISSION
City / country of publication	2017 Fire Protection Research Foundation 1 Batterymarch Park, Quincy, MA 02169-7417, USA
Year of publication	June 2017
Resilience topic(s) covered by literature source	[General overview] Many infrastructure tunnels around the world were built during the last century and are in need of refurbishment and maintenance to address the current safety demands imposed by heavy goods vehicles moving regularly through them. National Road Agencies on the other hand face the increasing challenge of managing limited budgets and substantial costs for refurbishment or/and upgrading of existing tunnel infrastructures. New technologies to promote tunnel resilience in operation require different intervention strategies. Reliable maintenance is essential and can be enhanced by the use of new technologies to maximize reduction in maintenance and refurbishment costs. The safety demands to allow modern heavy goods vehicles (with their larger fire loads compared to vehicles of 20-50 years ago) means that FFFS becomes a viable option at the time of tunnel refurbishment (the alternatives being (extra) passive fire protection, or a larger ventilation system to provide smoke control for the larger fire). [Legislation, policies] DIRECTIVE 2004/54/EC of 29 April 2004 Minimum safety requirements for tunnels in the trans-European road network The European Union initiative to improve tunnel safety is one of the many pieces of legislation aimed at promoting a high, uniform and consistent level of safety, service and comfort for users of the trans-European road network. Not only does it promote a high level of protection for all European citizens in road tunnels, it promotes equally new harmonised safety requirements at community level by introducing a Tunnel Safety Management System for all member countries. The National Fire Protection Association (NFPA) is one of the global, non-profit organizations devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards in the United States of America. It delivers information and knowledge through more than 300 consensus codes and standards, research, training, education outreach and advocacy.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [92]	
	The study under consideration "Impact of Fixed Fire Fighting Systems on Road Tunnel – Resilience, Ventilation and Other Systems" discussed below reflects some technical contribution by research professionals from the University of North Carolina at Charlotte, USA and it is aligned to the extensive work done by the World Roads Association PIARC in variety of working streams to protect tunnels users and to maximize tunnel availability for traffic during maintenance and refurbishment. Tunnel Infrastructure Resilience includes a resilience-informed decision-making process which triggers multisector interdependencies, both in terms of tunnel operators and road network managers.
Domain of the literature source	["Resilience for a specific aspect"]: This review process relates to the Fixed Fire Fighting Systems (FFFS) - resilience for fire incidents.
Nature of the content of the literature source	[Opinion]: Based on the experiments and computational fluid dynamic (CFD) calculations made by these authors (Anurag Jha and Aixi Zhou), they hold a firm view that FFFS commonly used in Japan and Australia but with limited use in the USA show a potential in reducing fire risks in tunnels thus promoting additional safety and protection against damage to tunnel infrastructure.
Is the literature source relevant for tunnels?	[Yes]
Short general description of content	[Reasoning] A worldwide problem for tunnel owners is the need to protect life and the tunnel infrastructure against catastrophic fire events which may be caused by heavy goods vehicles (HGV) and tankers when moving through these facilities. Firefighting systems can save lives by keeping the fire size low and maintain a tenable environment for the tunnel user and enhance the ability of the first responders to aid in evacuation and fight fire. Reducing the design fire size and fire growth rate has significant economic benefit to the tunnel owner since the scale of expensive fire and life safety systems can be substantially reduced.
What are the main relevant messages, lessons learned or recommendations?	[Reasoning] The assessment made by Anurag Jha and Aixi Zhou are particularly aligned to the recommendations derived from an "EU expert team comprising Tunnel Engineers and Fire Fighting Specialists" who conducted two major experiments in Asturias (Spain) in 2011 to assess the impact of 100 MW fire loads subjected to fixed firefighting systems. Test results which were later discussed at the Leipzig June Conference in 2012 provided the following outcomes for the effectiveness of the FFFS. Development of Fixed Fire Fighting Systems (FFFS) FFFS are aimed to improve both life safety and asset protection. This is achieved by means of: 1. Improving the self-rescue/evacuation conditions for people;

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [92]	
	2. Improving access and operating conditions for the fire brigade and rescue services; 3. Prevention of fire spread from one vehicle to another; and 4. Limiting structural damage to the tunnel Improving the self-rescue / evacuation conditions in the tunnel environment has a multitude of advantages which may include a) immediate cooling effect to provide lower temperatures within the fire zone, b) reducing smoke production significantly by controlling and suppressing the fire and c) reducing the production of blinding smoke and soot. Improving access and operating conditions for fire and rescue services is achieved by means of limiting the Heat Release rate (HRR) with suppression and control, lowering temperatures and in the process blocking radiant heat transfer. Prevention of fire spread from one vehicle to another is another important measure to be pursued because it will limit fire area and consequently limit the HRR. Limiting structural damage to the tunnel is essential. This is essentially achieved by limiting the fire area as well as the HRR. Examples of this may include the current modern upgraded tunnels with FFFS in Cologne Train station in Germany or Newcastle and Dartford River crossing in the United Kingdom.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	[Resilience availability] The literature indicates that information available for researchers, practitioners, and specialists interested in resilience of road tunnel infrastructure namely professionals of FHWA, AASHTO, NFPA, ASHRAE provides some consensus and consolidated viewpoint that the integration of Fixed Fire Fighting Systems considered long overdue is required and it would contribute to reducing the design fire size in road tunnels. This was not a superficial assessment. It is based on comprehensive studies which have included Road Tunnel safety practices, the Road tunnel construction environment, as well as a detailed assessment of different tunnel fire incidents. The analysis has provided some insightful examples as to how the impact of fire event/scenario in the road tunnels can be mitigated, using FFFS. In its conclusions, the study has shown that FFFS as active fire protection can: • Detect the fire in its early growth stage, • Prevent the spread of fire to other vehicles, • Limit the fire size to help fire fighters reach the fire, and, • Completely extinguish the fire.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [92]	
	The use of FFFS causes reduction from major fires to: • smaller fires that generate less heat, • less emission of smoke, and consequently • Reduce the overloading of the ventilation system.
Interesting chapters, sections or annexes for further reading	FFFS (PIARC, 2016), "Fixed Fire Fighting Systems in Road Tunnels: Current Practices and Recommendations, World Roads Association, Singapore; SOLIT (2012), Engineering guidance for a comprehensive evaluation of tunnels with fixed firefighting systems, Scientific Report of the SOLIT 2 Consortium, 2012.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [93]	
Reviewing WG member	Bijan Khaleghi
Date of review	October 27, 2020
Title literature source	**ASSESSING AND IMPROVING THE RESILIENCE OF HIGHWAY AND RAIL TUNNELS TO BLAST AND FIRE**
Author(s)	Spencer Quiel, Ph.D., P.E.
Reference or ISBN	2020
Publisher	Lehigh University - UTC Consortium Member
City / country of publication	Bethlehem, Pennsylvania, USA
Year of publication	2016
Resilience topic(s) covered by literature source	Resilience of Highway and Rail Tunnels to Blast and Fire
Domain of the literature source	Performance-based assessment of vulnerability and resilience of transportation tunnel structures to blast and fire hazards
Nature of the content of the literature source	• Improve decision making about deployment of mitigation strategies and techniques • Enable prioritization of mitigation among tunnel inventories or within tunnel segments
Is the literature source relevant for tunnels?	YES
Short general description of content	• Tunnel Types and Structural Systems with Potential Modes of Failure and Damage • Damage Types such as: Cracking and Spalling of concrete liners, material Weakening and Creep, Flexural and Shear Cracking or • Yielding of reinforcement
What are the main relevant messages, lessons learned or recommendations?	Recommendations, Outcomes and Impact of this literature are: • Develop a framework that can be adapted for varying blast and fire hazards for varying tunnel types • Demonstrate the framework using case studies Quantify the loss of functionality based on the type of damage • Calculate resilience as a function of the damage type and magnitude • Determine ranges of performance to aid decision making for the deployment of mitigation or the design of improvements
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	This literature source deals with tunnel resilience including: • Hazard Potential and Intensity using available data regarding past events, vehicle frequency, and hazard access • Initially use computational tools with experimentally derived data to determine the intensity and extent of hazard effects such as Fire Dynamics Simulator, Blast Air3D, LS-Dyna. • Develop analytical models to improve computational efficiency for parametric and evaluation of Damage Level and Location • Identify research needs for damage quantification • Develop a computational framework for mapping hazard effects and resulting damage • Resilience Quantification and Investigate the loss of functionality associated with varying damage types

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [93]	
Interesting chapters, sections or annexes for further reading	Interesting chapters, sections include: • Structural damage Types: Cracking and Spalling of concrete liners, Creep, Flexural and Shear Cracking or Yielding of reinforcement • Develop analytical models for Damage evaluation of Location • Develop a computational framework for mapping hazard effects and resulting damage

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [94]	
Reviewing WG member	Heidi Cuypers
Date of review	June 9th 2020
Title literature source	**COB GROEIBOEK - CYBER SECURITY: DIGITALE WEERBAARHEID (COB LIVING DOCUMENT – CYBER SECURITY: DIGITAL DEFENSIBILITY)**
Author(s)	COB project group
Reference or ISBN	Online living document, www.cob.nl/groeiboek/cybersecurity
Publisher	Centrum Ondergronds Bouwen (COB)
City / country of publication	Delft, The Netherlands
Year of publication	Living document; content accessed on june 9th 2020.
Resilience topic(s) covered by literature source	Maintenance or refurbishment, Organisational aspects and management systems.
Domain of the literature source	Resilience for a specific domain, aspect, organization or business, namely: cyber security and digital resilience.
Nature of the content of the literature source	Collaborative project.
Is the literature source relevant for tunnels?	Yes.
Short general description of content	The collaborative effort focuses on cyber security in light of security, availability and privacy in the infrastructure; specifically for road tunnels. The document does not contain comprehensive descriptions of systems, designs or procedures. Rather, it provides important considerations and insights drawn from practical experience among a variety of government institutions and stakeholders.
What are the main relevant messages, lessons learned or recommendations?	The document gives an overview of national (the Netherlands) and international (European Union) norms and laws concerning or related to cyber security. It also provides some important considerations concerning organisation, personnel and procedures.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The document deals with resilience pertaining to a threat to or breach of cyber security. A lack of cyber security can have a serious impact, not limited to 'merely' financial damage. A loss of the operational continuity of vital and non-vital processes can have significant societal and economic consequences, including the endangerment of the safety of individuals.
Interesting chapters, sections or annexes for further reading	In order to improve resilience, the document suggests both preventative and mitigating measures, such as 'layered security', physical entry security, network security, logical entry security, anti-malware and patches, signalling, action perspective, back-ups and asset management.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [96]	
Reviewing WG member	Ingo Riess
Date of review	20. April 2020
Title literature source	**SICHERHEIT DES VERKEHRSSYSTEMS STRASSE UND DESSEN KUNSTBAUTEN – SZENARIEN DER GEFAHRENENTWICKLUNG**
Author(s)	B. Schneeberger, M. Kost, A. Eckhardt, M. Marti, A. Schönenberger, A. Tutel, N. Høj, M. Faber
Reference or ISBN	Forschungsauftrag AGB2005/105, Bericht Nr. 621
Publisher	Bundesamt für Strassen
City / country of publication	Switzerland
Year of publication	2009
Resilience topic(s) covered by literature source	General Overview
Domain of the literature source	Resilience in General
Nature of the content of the literature source	Assumptions and analysis
Is the literature source relevant for tunnels?	Yes
Short general description of content	The safety of the road as a traffic system and of its civil engineering structures is constantly being challenged by new developments. These developments can be attributed to various influences such as changes in the amount of traffic or advances in traffic and vehicle technology. All these influences have their roots in fundamental societal or natural processes, such as the economic situation or climate change. Scenarios that could influence future traffic system safety were developed as part of the "Risk Development Scenarios" research project. The project differentiated between evolutionary scenarios reflecting developments and trends that appear probable from today's viewpoint and visionary scenarios that indicate the scope of potential scenarios. With respect to road tunnels, the following scenarios were evaluated: · increase in temperature and flooding / heavy rainfall. The effect of a temperature increase on road tunnel operation is considered to be small. The effects of heavy rainfall and flooding could be significant, i.e. flooding of a tunnel or risk of collisions at the transition between tunnel and ambient conditions.
What are the main relevant messages, lessons learned or recommendations?	The report gives a recommendation that all significant developments and trends be observed and the scenarios regularly updated. In future, an effort will have to be made to gather more accurate data on road traffic safety and to improve that data's accessibility. The societal aspects of far-reaching technological and, in some cases, societal developments should be fathomed with the help of specific estimations of technological consequences, as should the scope of the available options for counteracting these developments effectively and in good time.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [96]	
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The report deals with risk and a modification of the risk due to a variation of the operation condition. If the risk is evaluated against an acceptable risk level, the risk translates into the resilience of the tunnel operation.
Interesting chapters, sections or annexes for further reading	[-]

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [97]	
Reviewing WG member	Ingo Riess
Date of review	20 April 2020
Title literature source	**CITY RESILIENCY AND UNDERGROUND SPACE USE**
Author(s)	R. Sterling, P. Nelson
Reference or ISBN	Advances in Underground Space Development, 2013, pp. 43-55
Publisher	Research Publishing
City / country of publication	Singapore
Year of publication	2013
Resilience topic(s) covered by literature source	General Overview
Domain of the literature source	Resilience in General
Nature of the content of the literature source	Thoughts and Opinion
Is the literature source relevant for tunnels?	Yes
Short general description of content	This paper examines the importance of understanding and improving the resilience of cities — particularly with regard to underground space use in cities and the critical infrastructure systems that are placed in the underground. With regard to the increasingly complex and interconnected infrastructure systems that support our cities, the paper argues that the overall reliability of these systems is becoming increasingly difficult to predict when subjected to the stresses caused by major catastrophes. Furthermore, just restoring physical systems is not sufficient in terms of resiliency. The goal of resiliency is to restore a well-functioning and stable social system after a disaster. This means that the dependencies and interactions of social systems with the economy, mobility and utility provision must be better understood. Underground space use enhances many aspects of resiliency for cities but must consider in particular the dangers of flooding and internal fire, explosion or chemical releases. The paper provides a general table of advantages and disadvantages of underground facilities with respect to various types of catastrophic events and also discusses particular risks and behaviours associated with various types of underground facilities.
What are the main relevant messages, lessons learned or recommendations?	Road tunnels have generally shown an excellent resilience to most types of catastrophic events. In addition, flooding of a road tunnel does not typically result in a long-term outage of operation. In fact, the recent SMART tunnel in Kuala Lumpur is designed to be switched from a traffic tunnel to a flood relief tunnel several times a year. Recent major fires in Alpine road tunnels have prompted changes in the design of long road tunnels to provide additional egress possibilities and/or improved safe refuges.
If the literature source deals with	As disruptive events for road tunnel operation, only flooding and fire are mentioned.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [97]	
resilience / availability in certain events, what are these events and what are the measures to improve resilience?	
Interesting chapters, sections or annexes for further reading	[-]

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [98]	
Reviewing WG member	Heidi Cuypers
Date of review	June 9th 2020
Title literature source	**HOW SMART SENSORING IMPROVES TUNNEL RESILIENCE: FROM THEORETICAL MODEL TO FUTURE APPLICATION**
Author(s)	D.M. Zhang, H.W. Huang, Q.F. Hu and Y.J. Zhang
Reference or ISBN	ISBN 978-0-7277-6127-9
Publisher	The authors and ICE Publishing
City / country of publication	Shanghai, China
Year of publication	2016
Resilience topic(s) covered by literature source	Maintenance or refurbishment, Organisational aspects and management systems.
Domain of the literature source	Resilience for a specific domain, aspect, organization or business, namely: metro and road tunnels.
Nature of the content of the literature source	Theoretical model, preliminary study.
Is the literature source relevant for tunnels?	Yes.
Short general description of content	The smart sensoring technique, e.g., wireless sensoring network (WSN), nowadays is becoming an effective way to implement a real-time monitoring on the structural health state (Huang, et al., 2013). It might be generally accepted that smart sensoring could in some way assist in the decision for preventive maintenance. But quite often, in view of the additional cost during the long-term monitoring before a real disruption happens to the tunnel structures, the benefit of real-time monitoring usually is not well appreciated by the decision makers.
What are the main relevant messages, lessons learned or recommendations?	The authors (Huang and Zhang, 2016) have presented a resilience model for shield tunnel linings under extreme surcharge. This model has been applied to a real tunnel disruption case in Shanghai. From the case study, the effect of real-time monitoring on the tunnel resilient ability has been firstly discussed but without a rigorous derivation. Thus, this paper tries to rigorously derive the effect of real-time monitoring on resilient ability of tunnels. Based on the real-time monitoring technique, preliminary study on resilience based design of repair strategy for two types of repair is discussed at the end. Before that, the resilience analysis model for tunnels is briefly reviewed.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	Coupling with the smart sensoring technique, the resilience model could be applied into the design of two types of repair works: firstly, the repair for unexpected disruption of tunnel caused by hazard, and secondly, the repair for preventive maintenance for naturally degraded tunnel due to material time effect in long-term.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [98]	
Interesting chapters, sections or annexes for further reading	4. Resilience-based repair strategy

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [99]	
Reviewing WG member	Michael POTIER - Eric PREMAT
Date of review	June 8th 2020
Title literature source	**THE MONT BLANC TUNNEL INCIDENT RESILIENCE ASPECTS 17 YEARS AFTER**
Author(s)	Marc Tesson, Hélène Mongeot
Reference or ISBN	
Publisher	CETU
City / country of publication	France
Year of publication	2016
Resilience topic(s) covered by literature source	Description of measures to ensure resilience.
Domain of the literature source	Resilience in general.
Nature of the content of the literature source	Franco-German Workshop Urban Resilience and Crisis Management Perspectives, Barriers, and Innovative Pathways 28-30 September 2016, Lyon, France
Is the literature source relevant for tunnels?	Yes.
Short general description of content	1 The Mont Blanc tunnel fire 2 Was this tunnel “resilient”? 3 Description of measures to ensure resilience : ? Reliability and redundancy of equipment ? Incident and traffic management ? Reliability and redundancy of operational staff ? Handling long term evolution of traffic demand
What are the main relevant messages, lessons learned or recommendations?	The measures described are integrated in a systemic approach with 4 items: users/operation/vehicles/infrastructure.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	After the tunnel Mont Blanc Fire in 1999, description of the measures which have been taken to prevent the probability that a new major event leads to less availability.
Interesting chapters, sections or annexes for further reading	Content number 3.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [100]	
Reviewing WG member	Bijan Khaleghi
Date of review	November 20, 2020
Title literature source	**2019 RESILIENCY REPORT: UPDATE ON AGENCY-WIDE CLIMATE RESILIENCY PROJECTS**
Author(s)	Don Spero, MTA Headquarters, and Porie Saikia-Eapen, Environmental Sustainability & Compliance, MTA Headquarters
Reference or ISBN	
Publisher	MTA Climate Adaptation Task Force
City / country of publication	New York, USA
Year of publication	2019
Resilience topic(s) covered by literature source	Extreme weather, climate change.
Domain of the literature source	The MTA risk management and post flood event functionality and resilience. In the immediate aftermath of Sandy, both the MTA and the metropolitan region we serve found resilience in operational means. The New York City set up a bus bridge to transport passengers that the flooded subway river tubes. Climate science is ever-changing and the Task Force is committed towards keeping the climate adaptation in concordance with the latest science to ensure that the latest analyses, models, and projections are baked into climate preparedness.
Nature of the content of the literature source	The Climate Adaptation Task Force was formed in 2013, one year after Super storm Sandy caused unprecedented destruction to virtually every part of the MTA system. Boats washed up onto commuter railroad tracks, tunnel and all but one subway river tubes flooded and damaged. This current iteration of the Resiliency Report focuses on the work that has been completed thus far in addition to providing updates on the larger, more complex projects. The report will ensure that the latest analyses, models, and projections are baked into MTA climate preparedness as we move forward.
Is the literature source relevant for tunnels?	YES, it is about urban subway tunnels.
Short general description of content	New standards evolved with structural designs to adapt to this new normal we were now facing. One design standard in particular stands out: the Design Flood Elevation the height that flood waters are expected to rise to in a future storm, and therefore the height against which we must defend our facilities. This new standard was arrived at through extensive analysis. This will ensure that the latest analyses, models, and projections are baked into MTA climate preparedness as we move forward. At street level, we built flood gates into flood-prone train station entrances, while hatches and manhole covers were redesigned to withstand large volumes of standing water. Underground, marine cabling replaced the regular wiring in the under-river tubes to increase flood resiliency. This current iteration of the Resiliency Report focuses on the work that has been completed thus far in addition to providing updates on the larger, more complex projects that remain in progress.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [100]	
What are the main relevant messages, lessons learned or recommendations?	As part of the climate adaptation portfolio, the MTA has planted green roofs to absorb precipitation, reduce storm water discharge, and alleviate the urban heat island effect. These initiatives, however, do come with a capital cost. Looking forward, as we expand our focus to include climate mitigation, we are continuing to leverage roofs as an asset, but with an alternative financing structure. On Earth Day 2019, the MTA launched the MTA Solar initiative to generate clean, emission-free electricity that will open a new frontier of untapped revenue: leasing industrial roof space and commuter parking lots to companies for solar power development. These properties present an opportunity to develop more than 100 megawatts of emission-free electricity for New Yorkers – enough to power 18,000 households. The MTA hopes to achieve a significant new revenue stream from this activity, with little to no capital investment of its own. MTA Solar creates a new path for the MTA to lead in Climate Change mitigation.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The hurricane Sandy caused unprecedented flood into the New York subway transit tunnels requiring post flood event functionality and resilience. In the immediate aftermath of Sandy, both the MTA and the metropolitan region we serve found resilience in operational means. As part of the climate adaptation portfolio, the MTA has planted green roofs to absorb precipitation, reduce storm water discharge, and alleviate the urban heat island effect. These initiatives, however, do come with a capital cost. Looking forward, as we expand our focus to include climate mitigation, we are continuing to leverage roofs as an asset, but with an alternative financing structure.
Interesting chapters, sections or annexes for further reading	Interesting chapters, sections include: • MTA New York City Transit Subways and Staten Island Railway • MTA Metro-North Railroad Substations • MTA Bridges & Tunnels • Hugh L. Carey Tunnel

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [101]	
Reviewing WG member	Bijan Khaleghi
Date of review	November 20, 2020
Title literature source	**RESILIENCE OF OPERATED TUNNELS UNDER EXTREME SURCHARGE: FIELD STUDY**
Author(s)	Hongwei Huang and Dongming Zhang
Reference or ISBN	http://doi.org/10.3208/jgssp.ATC6-06
Publisher	Japanese Geotechnical Society Special Publication
City / country of publication	Japan
Year of publication	2016
Resilience topic(s) covered by literature source	In the operation of a complex tunnel system, the vulnerability and the recovery of the segmental linings and their the ability to absorb the disruption caused by the hazards and post hazard recovery to the acceptable level of the functionality is necessary for safety and for tunnel operation.
Domain of the literature source	Tunnel resiliency and operation under extreme surcharge including the field study In Shanghai where soil surcharge from construction site found were disposed at the ground surface above the operated tunnels causing segmental lining damage.
Nature of the content of the literature source	The robustness of the tunnel response to the extreme surcharge and the recovery from such a disaster are the key aspects for a lifetime performance assessment. These two aspects compose the basic concept of a system resilience.
Is the literature source relevant for tunnels?	YES, it is about urban tunnels
Short general description of content	The vulnerability and the recovery of the segmental linings subjected to unexpected disruptions are of major concerned by the engineers and owners. The analysis of segmental lining resilience and the ability to absorb the disruption caused by the hazards and to recover to the acceptable level of the functionality, is necessary for the safety of the tunnels. The functionality curve is described using the measured data from a detailed monitoring program. The calculated metric of resilience indicates that the functionality of the tunnels can be bounced back to a certain level by unloading the liner and by grouting the damaged areas. Finally, some discussion and concluding remarks on the resilience of operated tunnels subjected to this extreme surcharge load are presented.
What are the main relevant messages, lessons learned or recommendations?	The main take away is a detailed framework for the assessment of the tunnel resilience in terms of the performance is illustrated by using a field case study. Some concluding remarks can be drawn as follows: By applying to the field case, the detailed frame of the resilience metric is found to be reasonable and applicable for the resilience assessment for the lifetime performance of tunnel linings. The smart structural health monitoring (SSHM) and inspection techniques would be greatly helpful to monitoring the structural response in real time and, on the other hand, will increase the structural resilience to ensure the safety of the structures and lives.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [101]	
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	This literature source deals with tunnel resilience including: The robustness of the tunnel response to the extreme surcharge and the recovery from such a disaster are the key aspects for a lifetime performance assessment. These two aspects compose the basic concept of a system resilience.
Interesting chapters, sections or annexes for further reading	Interesting chapters, sections include: • Resilience definition • Field case study and monitoring • Resilience metric, degradation curve and Structure recovery curve • Discussion and conclusions

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [102]	
Reviewing WG member	Bijan Khaleghi
Date of review	November 20, 2020
Title literature source	**FIRE LIFE SAFETY SYSTEM OVERVIEW OF I-90 TUNNEL AND HOV OPERATIONS**
Author(s)	Jacobs Engineering Group
Reference or ISBN	
Publisher	Jacobs Engineers for Washington State Department of Transportation
City / country of publication	Seattle, USA
Year of publication	2014
Resilience topic(s) covered by literature source	The fire life safety systems consist of a number of systems that are monitored and controlled in a manner that will operate the tunnels in a safe and tenable condition. The systems are designed to manage traffic and normal traffic issues in a safe and efficient manner. In addition the systems are designed to handle fire emergencies up to a worst case flammable liquid fire in a manner that maintains tenable conditions for all but those exposed directly to the fire.
Domain of the literature source	The following section of this report, titled System Descriptions, is an overview of each system and how it works with the other systems. It is based on numerous reports that have studied each fire life safety system in these two tunnels and made recommendations for upgrades and changes. All the reports recommending changes to fire life safety systems have received extensive review by experts in the field and by the local fire department Fire Marshal offices and are referenced at the end of the report.
Nature of the content of the literature source	The following section of this report, titled System Descriptions, is an overview of each system and how it works with the other systems. It is based on numerous reports that have studied each fire life safety system in these two tunnels and made recommendations for upgrades and changes. All of the reports recommending changes to fire life safety systems have received extensive review by experts in the field and by the local fire department Fire Marshal offices and are referenced at the end of the report.
Is the literature source relevant for tunnels?	YES, it is about urban tunnels
Short general description of content	To ensure tunnel safety and efficiency, WSDOT has installed numerous fire life safety systems and measures within each tunnel that are designed to manage traffic efficiently and safely and respond to incidents. The incident of most consequence in a tunnel is a major fire. I-90 is a major trucking route from Seattle to the rest of the state and with a tank farm located in Seattle is a major route for transportation of fuels to the eastside of Lake Washington and to eastern Washington. When the I-90 tunnels were designed and constructed in the 1980's it was determined that without a toll booth there was no practical way to ban flammable cargo from the tunnels all the time. Therefore the most thorough fire detection and suppression systems of the time were installed. This included an Aqueous Film Forming Foam (AFFF) fire suppression system that covered the roadway in approximately 150 ft.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [102]	
	zones. Though not exclusively, the fire suppression systems were installed to protect against fires and incidents caused by fuel tankers, which are allowed to travel unrestricted through the tunnels except when the fire suppression system is off line.
What are the main relevant messages, lessons learned or recommendations?	The main relevant message is Fire Detection with Infrared video (IR) detectors that are located in each tunnel for each fire zone. The detectors are tuned to monitor the temperature of CO_2 gas and include a video camera that is monitored in the control rooms. Detectors have been very reliable and quick to alarm with test fires and have shown no nuisance alarms during our testing. Upon reaching alarm the system is set to bring up a video from the first detector to alarm. This provides the operator the ability to quickly understand the situation in the tunnel. Linear fire detectors are installed in each tunnel are designed to form a redundant system such that if a fire or other accident breaks the detector loop each portion will continue to operate. These linear detectors are designed to monitor temperature at points along the detector spaced no more than 5 meters apart. The ambient temperature of the tunnel is tracked and any deviation from ambient is identified as a possible fire. When the rate of rise or deviation reaches a set point an alert or alarm is sent along with notification of the location.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The following section of this report, titled System Descriptions, is an overview of each system and how it works with the other systems. It is based on numerous reports that have studied each fire life safety system in these two tunnels and made recommendations for upgrades and changes. All of the reports recommending changes to fire life safety systems have received extensive review by experts in the field and by the local fire department Fire Marshal offices and are referenced at the end of the report.
Interesting chapters, sections or annexes for further reading	Interesting chapters, sections include: • Emergency Responses • Fire Detection, Fire Suppression, and Fire Hydrant systems • Roadway ventilation system • Tunnel closure and gates • Carbon monoxide detection

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [105]	
Reviewing WG member	Nobuharu Isago
Date of review	January 2, 2021
Title literature source	**REPORT ON MECHANICAL BEHAVIOUR AND COUNTERMEASURES AGAINST EARTHQUAKES FOR MOUNTAIN TUNNELS**
Author(s)	Nobuharu Isago, Takaaki Koide, Atsushi Kusaka, Tomoya Yoshioka and Noriaki Kishida
Reference or ISBN	Technical Note No. 4358
Publisher	Tunnel research team, Public Works Research Institute (PWRI), Japan
City / country of publication	Tsukuba, Japan
Year of publication	March 2017
Resilience topic(s) covered by literature source	Natural hazards; damage to mountain tunnels by earthquakes.
Domain of the literature source	Assuring resilience against the damage induced by the occurrence of earthquakes in mountain areas, that are likely to impede road usage.
Nature of the content of the literature source	Results of a research project by PWRI from 2011 to 2016.
Is the literature source relevant for tunnels?	Yes, especially for mountain tunnels.
Short general description of content	Damage to road tunnels by earthquakes in Japan are described and the concept of general countermeasures is introduced.
What are the main relevant messages, lessons learned or recommendations?	The Ministry of Land, Infrastructure, Transportation and Tourism (Government of Japan) issued a technical ordinance, including the content of this technical note, to all national branches of the Ministry, and delivered it as a reference to all road manager parties in 2017.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The note deals with the concept of countermeasures against earthquakes for new and existing road tunnels and the methodology of rehabilitation for tunnels damaged by earthquakes. For example, in new tunnels the permanent lining with rebar will be installed in poor ground mandatorily, to prevent the fall of concrete blocks. Periodical inspections will also be performed and the results are recorded properly to assess the health of the tunnel. This methodology will be expected as all of the countermeasures such as preventive, mitigate and recovery.
Interesting chapters, sections or annexes for further reading	All chapters.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [106]	
Reviewing WG member	Nobuharu Isago
Date of review	January 2, 2021
Title literature source	**REPORT ON DEFECTS AND DEFORMATIONS OF ROAD TUNNELS - EXAMPLES OF DEFECTS AND CONCEPTS OF DIAGNOSIS FOR INSPECTIONS**
Author(s)	Hideto Mashimo, Nobuharu Isago, Toshiaki Ishimura, Noboru Sakamoto and Toshiyuki Sasada
Reference or ISBN	Technical Note No. 4360
Publisher	Tunnel research team, Public Works Research Institute (PWRI), Japan
City / country of publication	Tsukuba, Japan
Year of publication	March 2017
Resilience topic(s) covered by literature source	Maintenance and refurbishment, diagnosis for health assessment of tunnels.
Domain of the literature source	Assuring resilience by supporting the quality and health of road tunnels through inspection.
Nature of the content of the literature source	Results of a research project by PWRI from 2011 to 2016.
Is the literature source relevant for tunnels?	Yes, especially for mountain tunnels.
Short general description of content	Examples of defects and deformations of road tunnels constructed by conventional methods are described and the concepts of inspection and diagnosis are introduced.
What are the main relevant messages, lessons learned or recommendations?	The Ministry of Land, Infrastructure, Transportation and Tourism (Government of Japan) reissued the national guideline for periodic tunnel inspections to all road manager parties in 2019 and the Japanese Road Association published the 'Technical memorandum of road tunnel maintenance' in 2020, including the content of this technical note.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The note deals with the methodology for supporting periodical inspections of road tunnels, that are performed every five years in all road tunnels in Japan. The methodology aims for the implementation of rational inspections and diagnoses for all parties.
Interesting chapters, sections or annexes for further reading	All chapters.

Review sheet for literature study PIARC TC 4.4 WG2 on Safety and Resilience [107]	
Reviewing WG member	Toshiaki Sakaguchi
Date of review	December 28, 2020
Title literature source	**TENGUYAMA AND TENJIN SECOND TUNNEL INTRODUCED MPVC**
Author(s)	Hiroki Ueda, Kazushi Nakamura, Yasushi Takeuchi, Noriaki Noguchi
Reference or ISBN	Not available
Publisher	The Japan Society of Mechanical Engineers
City / country of publication	Tokyo, Japan
Year of publication	2019
Resilience topic(s) covered by literature source	Extreme weather conditions causing windshield fogging and a measure to avoid it.
Domain of the literature source	Resilience for a specific domain, namely extreme cold weather conditions which are likely to cause windshield fogging.
Nature of the content of the literature source	Ventilation control design of a preventive measure to avoid the windshield fogging, by incorporating temperature and humidity sensors, and the actual implementation of the operation in a real tunnel.
Is the literature source relevant for tunnels?	Yes
Short general description of content	Vehicles driving into a tunnel under the extreme cold weather conditions often experience windshield fogging, which may cause collisions. The paper describes a ventilation control method to avoid the fogging and actual operations in a real tunnel.
What are the main relevant messages, lessons learned or recommendations?	The windshield fogging under the extreme weather conditions is studied and the paper has shown that the fogging can be avoided by a model-based predictive ventilation control method ("MPVC") incorporating temperature and humidity sensor data.
If the literature source deals with resilience / availability in certain events, what are these events and what are the measures to improve resilience?	The paper deals with a preventive measure to avoid the windshield fogging under extreme cold weather conditions. The cause of the fogging is the sharp temperature change between the outside and the inside of the tunnel. The proposed MPVC-based ventilation control takes the cold air from the outside of the tunnel into the inside near the portal, making the temperature change less sharp (more gradual).
Interesting chapters, sections or annexes for further reading	All chapters.

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