# Effectiveness of Risk Mitigation Measures for Road Tunnels

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**Many countries, in particular those with a long tradition in operating road tunnels, have developed a framework of guidelines and regulations for the design, the construction and the operation of road tunnels. Although safety has always been an important issue, guidelines often focus on technical design specifications in order to establish a certain level of standardization and to guarantee an adequate performance of the various technical systems. However, this traditional prescriptive approach does not take into account the effectiveness of prescribed measures in a particular tunnel. Hence the resulting safety level might differ from tunnel to tunnel. Furthermore, even if a tunnel fulfils all regulatory requirements, there are residual risks which in the traditional prescriptive approach to safety are not obvious and not specifically addressed *[1]*.**

Therefore modern safety standards also take into account the evaluation of the effectiveness of safety measures. In the European Union, for instance, the EC Directive 2004/54/EC on minimum safety requirements for road tunnels has been enforced. This Directive contains three elements related to the notion of tunnel safety measure effectiveness.

- Annex I includes a list of minimum safety measures distinguishing between infrastructure measures and measures concerning operations; thus a minimum safety level is defined, which can be taken as reference for a qualitative or quantitative safety assessment
- In article 13, risk assessment is introduced as a practical tool for the evaluation of tunnel safety; thus a risk-based approach is established in addition to the traditional prescriptive approach
- Annex I also introduces the principle of equivalence. When there are justifiable reasons not to apply the measures required by the Directive (restrictive conditions, disproportional cost, etc.), alternative measures are allowed, as long as it can be demonstrated that the same (or a higher) safety level can be achieved. This has to be supported by risk assessment.

This highlights the need to assess the effectiveness of risk mitigation measures for road tunnels.

Alternative or additional measures may be required for various reasons, for instance:

- to counterbalance the influence of specific risk increasing factors, like frequent congestion in an urban tunnel or a high gradient exceeding a defined reference value;
- to compensate shortcomings in the construction or the equipment of an existing tunnel, for instance in the course of an upgrading process.

The ability to assess the effectiveness of risk mitigation measures is crucial for decision making – in the design phase of a new tunnel as well as for the upgrading of an existing tunnel – if several alternative solutions to increase safety are available and an optimized solution (e.g. in terms of cost-effectiveness) has to be found.

## RISK MITIGATION MEASURES FOR ROAD TUNNELS

A key basic principle of road tunnel safety planning is the holistic approach *[2]*: A safe tunnel environment can only be achieved by an optimized and balanced interaction of all aspects influencing safety, including infrastructure, equipment, user behaviour, operational practices and emergency response procedures *(illustration 1)*. Any additional safety measure needs to be integrated into this complex system in the best possible way, taking all relevant interaction effects into account.

An illustrative example for such interdependencies are lay-bys: in long tunnels lay-bys are located at defined distances in order to provide a safe place for vehicles which are not able to continue their ride through the tunnel. Drivers can leave their cars without being exposed to the traffic on the driving lanes and a broken-down vehicle does not impede the traffic, thus reducing the risk of a subsequent incident such as a collision. However, the end wall of such a lay-by could severely aggravate a collision, if a vehicle unluckily crashes into it. Hence additional measures like a crash cushion are required to mitigate this effect. On the other hand, under specific conditions it could be beneficial to replace lay-bys by other measures, for instance a continuous emergency lane. This could also be an interesting alternative from an operational

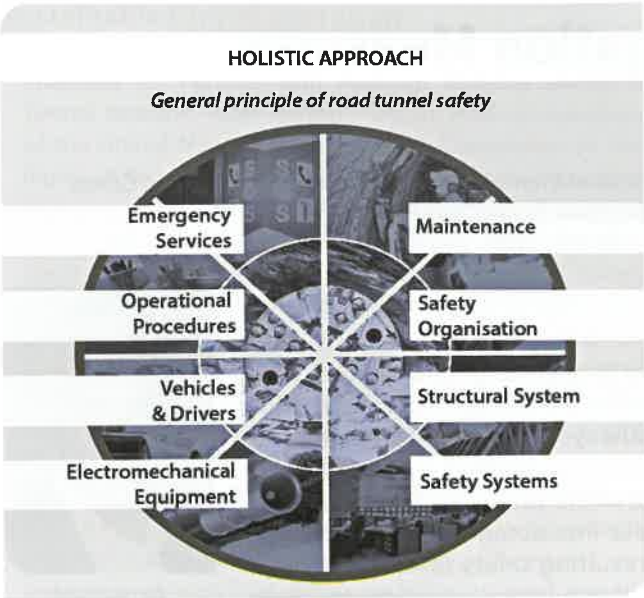


*Illustration 1 - Holistic approach*

*Illustration 2 - Lay-by in an Austrian motorway tunnel © ASFiNAG*

point of view, in particular in tunnels with a high traffic load, although at a considerably increased cost.

This simple example highlights the importance of a proper assessment of all potential positive or negative effects of a safety measure within a specific tunnel, whilst taking into account other aspects like operation or cost. This also explains why it is not possible to give globally applicable recommendations for specific risk mitigation measures and why a specific approach for the assessment of their effectiveness is required (see section *General concept for the assessment of the effectiveness of risk mitigation measures*).

Safety measures can be grouped into 4 categories, according to their mode of action and their main effects on risk:

1. Measures preventing the occurrence of significant incidents – thus reducing their frequency;
2. Measures mitigating the consequences of significant incidents;
3. Measures supporting self-rescue;
4. Measures supporting emergency response.

Measures can act on collisions or fires or both types of incidents. For instance, a measure reducing the frequency of collisions also reduces the frequency of fires being generated as a consequence of collisions.

Quite often a well-thought out combination of measures is required to be effective. This is typically the case for measures acting on fire risk, like tunnel ventilation. For a proper operation of the fire mode of tunnel ventilation, a fire must be detected quickly and its location must be identified correctly. Real-time airflow measurements in the tunnel tube provide input to the proper operation of the ventilation fans. Even if the fire ventilation for smoke management is controlled automatically, there may be the option for the operator to interfere in specific situations. Moreover, smoke management interacts with self-evacuation of tunnel users facing a fire incident. As can be seen in this example, effective smoke management requires an optimised interaction of several safety systems, in addition to procedures, human actions and the behaviour of tunnel users. This example demonstrates that the effectiveness of this complex chain of interacting measures cannot be assessed by simple means, but requires complex simulation tools to model the sequence of events.

Improvements by additional measures can be made at several levels, for instance by accelerating fire detection, thus gaining time for further actions, or by providing adequate information to people, thus initiating a faster and more efficient self-evacuation. As self-rescue is a crucial element of safety in the event of a tunnel fire, a better understanding of human behaviour in fire emergencies in a tunnel environment is very important *[3]*. Finding ways to influence human behaviour in a positive way would contribute considerably to enhancing the benefits of existing infrastructure and equipment.

Whereas for measures acting on fire risks the focus is more on mitigation and self-rescue, measures acting on collision risks focus on prevention and mitigation.

In the current working cycle, working group *Tunnel Safety* of Technical Committee D.5 *Road Tunnel Operations* is specifically studying measures for tunnel collisions. Based on a detailed analysis of a representative sample of internationally collected case studies, measures acting on collision risks will be recommended, describing their effects in relation to specific conditions and discussing other relevant aspects like cost-effectiveness. The results of these activities will be published in a report titled *"Prevention and Mitigation of Tunnel-Related Collisions"*.

## GENERAL CONCEPT FOR THE ASSESSMENT OF THE EFFECTIVENESS OF RISK MITIGATION MEASURES

The example of lay-bys described in the previous section demonstrates that deciding on safety measures is not straightforward and often requires a trade-off of various, sometimes contradictory effects. It also becomes clear, that in such a situation a clear picture of all safety relevant effects of such a measure is required, and a quantification of these effects would be highly beneficial.

The assessment process typically requires 4 steps:

1. **in a first step**, the specific problems of an individual tunnel with respect to user safety must be identified and analysed. This can be done by performing a qualitative safety analysis and/or applying a professional risk analysis tool *[1]*;
2. **in the second step**, suitable measures need to be found which are able to mitigate or compensate the problems identified in the first step under the specific conditions of the tunnel under investigation, taking design factors, traffic conditions and traffic characteristics as well as operational conditions into account;
3. **in the third step**, for the tunnel in question it is necessary to analyse how the measure acts on the risk caused by the specific problems, including all relevant interaction effects, as explained in the example of lay-bys. In any case, this step must be performed qualitatively, but of course any possible quantification is highly beneficial in the further process. The quantification of the effects on a detailed level can be based on data (measurements, statistics), on theoretical considerations, on practical experience or on expert judgement. For instance, coming back to the example of lay-bys, operators can normally provide a reasonable guess for the percentage of vehicles which are not able to reach a lay-by within a particular tunnel, even if statistical data is not available. This information can be taken as a basis for the assessment of the effects of removing or adding additional lay-bys or replacing them by an emergency lane.
   For more complex problems – like the response to a fire incident – the use of complex simulation tools like CFD smoke propagation simulation or egress simulation may be indispensable. In this case it is necessary to model the whole chain of events with sufficient accuracy. The effectiveness of additional measures can be assessed by modifying the parameters in the model which are influenced by the measure;

*Illustration 3 - A modern control centre at Arlberg Tunnel (Austria) – The brain behind operational measures © ASFiNAG*

**TABLE 1 - EXAMPLES FOR EFFECTIVE RISK MITIGATION MEASURES (NON-EXHAUSTIVE LIST) FOCUSSING ON EQUIPMENT AND OPERATIONAL MEASURES**

| MEASURE | DESCRIPTION OF MEASURE | INCIDENT TYPE | EFFECT DESCRIPTION | PREVENTION | MITIGATION | SELF RESCUE | EMERG. RESP. |
|---|---|---|---|---|---|---|---|
| Enforced speed control (section control) | Measurement of average speed on a defined road section; consequent punishment of violation | c | Prevention of speeding / reduction of average speed / speed difference between vehicles | X | X | | |
| Speed limit | Permanent or temporary (imposed by traffic management system) | c | Reduction of speed, more effective if combined with enforced speed control | X | X | | |
| Rumble strips | Edge of driving lane marked by *"rumble"* strips | c | Rises awareness of driver if vehicle is getting off driving lane | X | | | |
| Real time information on congestion | Traffic management system informs driver on congestion in front of him | c | Speed reduction and increase of awareness; more effective together with speed limit | X | X | | |
| Discourage lane changing | Adequate road marking in critical sections together with early routing information – for complex tunnels, with several lanes | c | Reduces lane changing manoeuvres in critical sections | X | | | |
| Traffic guidance barriers at tunnel walls/transition points of tunnel cross section | Traffic guidance barriers (e.g. jersey profile) are fixed on tunnel wall or located at critical points | c | Softens the impact of a collision with tunnel wall and guiding the vehicle back to driving lane | | X | | |
| Crash cushion | Construction absorbing energy by deformation, to protect critical points (like edge of separation wall between two tunnel tubes) | c | Mitigates consequences of crash against hard obstacles by controlled absorption of energy | | X | | |
| Immediate lane closure in case of incident | Affected lane is closed by traffic management system (red cross) – requires reliable incident detection | c | Protects stopped vehicles on driving lane (breakdown) prevents uncontrolled evasive manoeuvers and secondary collisions | X | X | | |
| Effective tunnel closure enforced by barriers | Traffic lights at tunnel portal / inside tunnels are respected with delay only; enforcement by barriers accelerates interruption of traffic flow | c/f | Reduction of exposure to effects of a fire by reducing number of vehicles inside the tunnel / keeping vehicles away from fire location; reduction of secondary collisions | X | X | | |
| Improved incident detection | Various systems available (video detection, inductive loops in road surface, acoustic detection system) acting on different incident types | c/f | Enhance speed and / or reliability of incident detection thus accelerating any further action; effective in combination with other measures (e.g. tunnel closure / lane closure) | X | X | X | X |
| Avoid/ reduce congestion inside tunnel | Control traffic flow by traffic management measures or stop traffic before tunnel to avoid a queue inside; limited applicability in networks with high traffic load | c/f | The risks caused by congestion are shifted to outside | X | X | | X |
| Thermo-scanner | System which is able to identify lorries with a critical temperature pattern, when passing by (infrared cameras combined with specific evaluation software) | f | System detects and separates lorries which might be the cause of a fire due to any kind of overheating; for tunnels with high fire rates | X | | | |
| Fixed fire-fighting system | Fire fighting system installed in a tunnel and integrated in tunnel control system; different technologies available (water-mist, deluge, compressed air foam) | f | Assists with the early suppression and the subsequent management of tunnel fires (details depend on system installed *[4]*) | | X | | X |
| Public address system | Loudspeaker system installed in the tunnel | f | Helps to initiate / accelerate self-evacuation and allows to provide instructions to people on site, thus guiding their behaviour | | | X | |
| Fast intervention unit | Mobile unit of specifically educated staff with professional fire fighting equipment | f | Fast intervention allows fire fighting at an early stage of fire development; supports self-rescue on site | | X | X | X |

*Illustration 4 - Fixed fire fighting system in operation – Bregenz City Tunnel (Austria) © BASt*

*Illustration 5 - Tunnel cross section with lane marking by rumble strips and traffic guidance barriers on tunnel walls – Norra Länken Tunnel (Stockholm) © ILF*

4. after having assessed the effectiveness of a risk mitigation measure (or a set of such measures) on a detailed level, **the fourth step** should study what the effect of the measure is on the overall safety level of the tunnel. This can be done by analysing the functionality of the measure with respect to a representative set of potential incidents. Whereas the crash-cushion mentioned in the lay-by example is only effective for the very specific case of a vehicle running off the driving lane at the exact location of a lay-by (very low probability), a speed limit with effective enforcement (like continuous speed control) would be effective for all collisions.

By applying a professional system-based risk assessment tool *[1, 2, 5]* steps 1, 3 and 4 can be done very efficiently. All the effects can be quantified in such a model, thus providing information on the overall effectiveness of risk mitigation measures. A systematic quantitative study of the safety effects of all measures in question can be performed, thus providing input for further studies, like a cost-benefit-analysis. All this information can be used in an optimisation process aiming to increase tunnel safety to the required level, at the same time balancing cost and other relevant effects.


*Illustration 6 - Effective tunnel closure enforced by barriers, Lioran Tunnel (France) © CETU*

## APPLICATION OF THE CONCEPT AND PRACTICAL EXAMPLES

Although guidelines sometimes seem to provide a rigid framework, practical experience shows that there are a lot of options for applying the concept defined in the section *General concept for the assessment of the effectiveness of risk mitigation measures*.

This applies in particular to tunnels with specific characteristics, where risk-increasing factors need to be compensated for or for the upgrading of existing tunnels, where the requirements of modern guidelines cannot be fulfilled or only at disproportionate cost. Sometimes quite simple measures can be quite effective, like accelerating and enforcing tunnel closure in case of a fire in a bidirectional tunnel: every vehicle which does not enter the tunnel or get close to the fire site will not be exposed to the effects of the fire and will not be involved in a subsequent collision.

Based on the experience of many risk studies, some examples of potentially effective risk mitigation measures for collision or fire risks are provided in *table 1*. However, as previously mentioned, it is not possible to provide specific information on their effectiveness on a global level – this can only be done on the basis of a proper risk assessment study for an individual tunnel.#

## REFERENCES

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