Paper title:
Safety in road tunnels – state of the art

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ABSTRACT: In the past decade – as a consequence of the big tunnel fires in Mont Blanc, Frejus or Tauern Tunnel – an intensive development took place regarding tunnel safety guidelines as well as methods for a performance-based evaluation of tunnel risks. Furthermore the EC-Directive 2004/54/EC on minimum safety requirements for tunnels in The Trans-European Road Network established a framework for road tunnel design, equipment and operation and initiated a certain harmonization of tunnel safety standards in Europe.
The paper introduces the two different approaches to tunnel safety
- the prescriptive approach – based on guidelines and
- the performance based approach – based on risk assessment.

It presents important aspects of both approaches – referring to current PIARC publications and ongoing activities and research work in various countries. In this context the need for harmonization of regulations defined in design guidelines (which are based on experience and expert judgement) and new findings (based on systematic application of risk assessment) is addressed.

1 TWO APPROACHES TO ROAD TUNNEL SAFETY

The operation of complex technical systems like road tunnels always induces associated risks. Technical failures, malfunction, failures in operation or misuse may cause different kinds of incidents (breakdowns, accidents, etc.) with adverse effects for safety of people, property, or environment. The development of a technical system is always combined with efforts to avoid or reduce these risks. In principle this can be achieved by two different approaches:
- by practical experience
- by systematically investigating potential hazards and resulting threats in advance, trying to eliminate their causes and / or reduce their consequences

In the past in many countries the safety design of road tunnels to a great extent was based upon regulations and guidelines: if the applicable prescriptions of relevant guidelines were fulfilled the tunnel was regarded as safe. These guidelines had been developed over decades and were mainly based on the experience of everyday operation, including incidents and accidents.
However, this prescriptive approach has some shortcomings which are particularly evident in accidents exceeding the range of existing operational experience:
- Even if a tunnel fulfills all regulative requirements it has a residual risk which is not obvious and not specifically addressed
- A prescriptive approach defines a certain standard of tunnel equipment etc. but is not suited to take the specific conditions of an individual tunnel into account. Furthermore, in a major accident the situation is completely different to normal operation and a great range of different situations exceeding existing operational experience may occur.

Hence, in addition to the prescriptive approach, especially for complex systems a supplement is needed which specifically addresses emergency situations: a risk-based approach. Risk-based approaches allow a structured, harmonised and transparent assessment of risks for an individual tunnel, including the consideration of local conditions in terms of relevant influence factors, their interrelations and possible consequences of incidents. Moreover, risk-based approaches make it possible to propose relevant additional safety measures for the purpose of risk mitigation and can be the basis for decision-making considering cost-effectiveness in order to assure the optimum use of limited financial resources.

However, a risk-based approach cannot replace technical design specifications. For example, the results of a risk analysis can help to define functional requirements for a ventilation system of a tunnel, but to guarantee an adequate performance of the ventilation a set of technical parameters has to be defined which for example can be done in a technical design guideline; hence the prescriptive approach and the performance based approach are indispensable supplementary elements of a state of the art for safety planning of a road tunnel. Consequently, new international (such as the EC Directive 2004/54/EC, [1]) and national tunnel regulations are addressing risk assessment to an increasing extent.

2 THE PRESCRIPTIVE APPROACH

The prescriptive approach is the traditional approach to tunnel safety. Many countries developed design guidelines for their road tunnels.
Well-known examples are:

- RABT 2006, Germany
- NFPA 502, USA
- RVS standards, Austria
- Technical Instructions for Safety Dispositions in New Road Tunnels, France
- SIA 197, Switzerland

Although the main focus of these design guidelines is to specify technical requirements for tunnel construction and equipment in order to assist tunnel designers and to achieve to a certain extent a uniform tunnel standard, safety had always been an integrated element of tunneling guidelines. However, safety issues are often not addressed in an explicit and systematic manner in these guidelines. Furthermore the more and more common use of new, more systematic approaches to tunnel safety (like the risk-based approach) revealed gaps and shortcomings in existing guidelines.
Hence, in some countries discussions are coming up, intending to modify certain definitions in existing guidelines in order to improve the harmonization of the prescriptive and the risk-based approach. This process is often based on results of systematic risk studies carried out for model tunnels, aiming to systematically investigate the influence on risk of certain parameters.

3 THE RISK-BASED APPROACH

Two recent PIARC publications are discussing the risk based approach and the current state of its practical application: The report "Risk analysis for road tunnels" ([2] published in 2008) and the new report "Current practice of risk evaluation for road tunnels" ([3] to be published in 2013).

3.1 *Introduction and definitions*

In a risk-based approach emergencies are systematically analysed, typically by applying scenario techniques; both the probabilities of scenarios as well as their consequences are addressed. A quantification of risks can be achieved by combining probability and consequences of each scenario. By summarising the partial risks of all scenarios the overall risk of a tunnel can be calculated. This approach also includes scenarios which may not yet have happened (and consequently are not covered by experience) but which may happen and may have major consequences.
However, not all effects can be quantified and a risk analysis may also focus on specific questions or specific scenarios without investigating the complete range of possible accidents. Therefore different methods have been developed [2] [3] and are practically applied and the selection of the most suitable method to investigate given issues has to match the specific problem, the required depth of assessment and the available resources [2].
In a risk analysis different types of risk can be investigated [3]:

- Harm to a specific group of people (fatalities and/or injuries): the most common risk indicator is fatalities referring to the group of tunnel users.
- Loss of property/economical loss: typical examples are damage to the tunnel structure (resulting in repair costs) and longer periods of tunnel closure due to damage caused by an accident (resulting e.g. in loss of toll income).
- Damage to immaterial values: e.g. damage to the reputation of a company, region or a country as a consequence of the reaction of media to an accident with major consequences.

Furthermore, results of a risk analysis can be used as a basis for further investigations, such as evaluation of socio-economic consequences.
Risks can be addressed in a quantitative or in a qualitative way. Qualitative methods typically focus on the functional analysis of the sequence of events and the interaction of people, systems and procedures. With quantitative methods, characteristic risk values for the whole tunnel can be calculated.
If risks are quantified, this can be done for individuals or for specific groups of people. The individual risk is the risk to an individual person who uses a tunnel, or lives near the tunnel. It is not only determined by the hazards (which provoke the risk) but also by the exposure of the individual person to these hazards. The risk to a defined group of people is called societal risk. The societal risk to tunnel users/neighbours is the most

common quantitative risk indicator for the risk assessment of road tunnels.
The societal risk can expressed in two different ways:

- As expected risk value (EV): represents long-term average number of statistically expected fatalities per year
- As FN diagram: shows magnitude of consequences in relationship to the (cumulated) frequency of a hazard

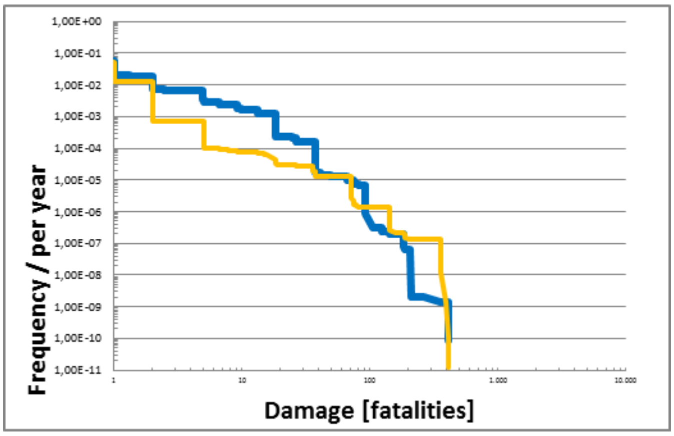

Figure 1. Societal risk-expressed as FN-diagram

3.2 *The risk assessment process*

Risk analysis is embedded in the risk assessment process [2] which includes the following three elements:

- **Risk analysis:** Risk analysis is a systematic approach to analyse sequences and interrelations in potential incidents or accidents, hereby identifying weak points in the system and recognising possible improvement measures.
- **Risk evaluation:** Risk evaluation is directed towards the question of acceptability of the identified risks to answer the question "Is the estimated risk acceptable?" For a systematic and operable risk evaluation, risk criteria have to be defined and it has to be determined whether a given risk level is acceptable or not [3].
- **Risk reduction:** If the estimated risk is considered as not acceptable, additional safety measures have to be proposed to reduce risk.

The procedure for a risk analysis can be divided into the following 4 steps:

- Definition of the system.
- Hazard identification: Systematic process to identify and structure all relevant hazards, and to analyse their correlating effects.
- Probability analysis: Determination of the probabilities of relevant events/scenarios.
- Consequence analysis: Investigation of consequences of relevant scenarios.

The simplified flowchart in Figure 2 illustrates the main steps of the risk assessment process.

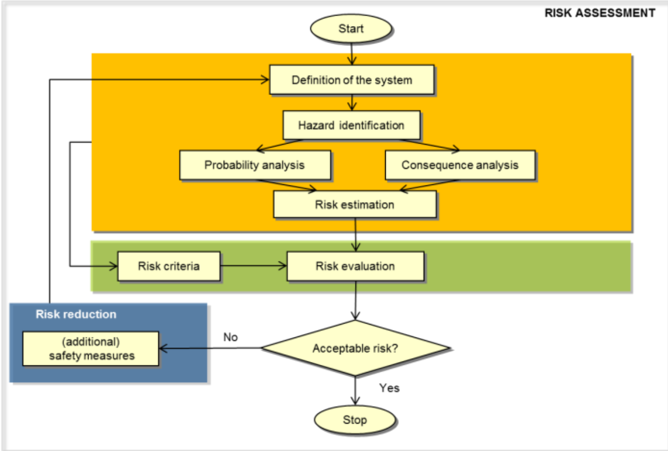

Figure 2. flowchart of the procedure for risk assessment [2]

3.3 *Current practice of risk analysis for road tunnels*

A broad spectrum of qualitative or quantitative methodological components exists for each step of the risk assessment process. For a risk analysis, different components are often combined to a more complex methodological approach. For example, in practical applications it is usually necessary to combine qualitative and quantitative components because of lack of data.

A complete procedure for risk assessment can be developed by combining the methods for risk analysis, risk evaluation and risk reduction. However, the different components are not arbitrarily combinable; rather certain evaluation methods need certain analysis components.
Risk-based approaches can be partitioned into the following two types [2]:

- **Scenario-based approach:** A set of relevant scenarios is defined, the probability of each scenario can be estimated and the possible resulting consequences are analysed (in some scenario-based approaches the estimation of the probabilities is not applied). The risk assessment is done separately for each single scenario on the basis of its characteristic indicators

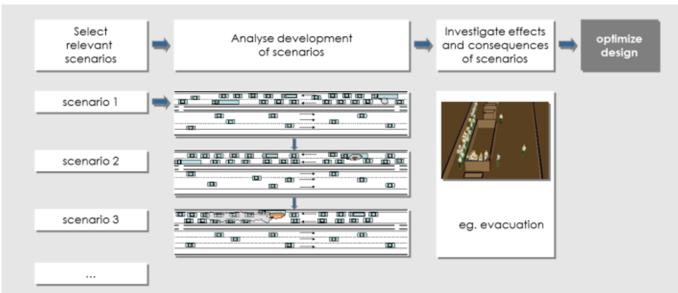

Figure 3. risk analysis – example of scenario-based approach

- **System-based approach:** By applying a system-based approach, risk values for an overall system are estimated. Thus all relevant events/scenarios which can affect persons in the system considered are taken into account. The risk assessment is done for the whole tunnel system investigated on the basis of the risk values of the system.

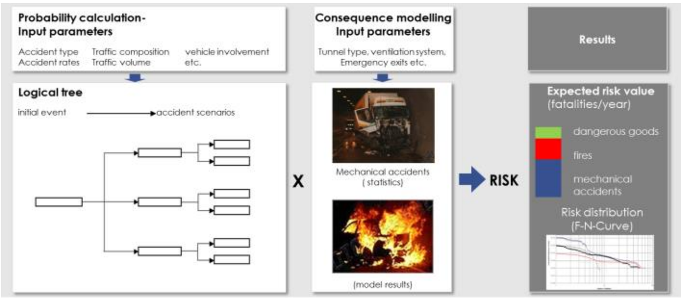

Figure 4. risk analysis – example of system-based approach

In the PIARC Report "Risk Analysis for Road Tunnels" [2] the following recommendations are given for the practical use of risk analysis:

- Select the best method available for a specific problem.
- Be aware that whatever method you choose, you are always using a model which is a more or less major simplification of the real conditions. The method can never predict the course of a real event but helps you to make decisions on a sound and comparable basis.
- Whenever possible, use specific data for quantitative methods. If specific data are unavailable, at least check the origin of the data you intend to use (are the conditions relating to infrastructure, traffic, etc., similar to your situation?). Be aware that specific features may be included in risk models that are not valid for your tunnel.
- For these reasons, risk analysis should only be performed by experts with sufficient experience and understanding of the methods they use.
- Be aware that the result of a quantitative risk analysis must be interpreted as an order of magnitude and not as precise number due to the influence of uncertainties.
- When selecting a method for a risk analysis, you should also consider how to evaluate the results since the method of risk analysis and the strategy of risk evaluation are not independent.

This report [2] also presents a description of several practical methods.

3.4 *Current practice of risk evaluation for road tunnels*

Risk evaluation is a fundamental part of the risk assessment process. It is the procedure by which consideration is given to the tolerability of risk, usually by measuring the calculated risk against pre-defined risk acceptance criteria. The definition of these criteria is not universal but is embedded in a specific legal, social and cultural environment and is influenced by many aspects. Although there are no universally accepted risk criteria for road tunnels, there are established criteria in use in some countries for certain applications.

Risk evaluation [3] can take many forms, including qualitative approaches (such as the evaluation of the outcome of risk scoring systems and the evaluation following implementation of prescriptive design guidelines) and quantitative approaches where risk analysis has been used to derive risk in terms of expected values or FN curves.

Societal risk for a particular tunnel may be evaluated against absolute or relative criteria; or both as is often the case in practice. Evaluation against absolute criteria requires an agreed threshold or target risk to be established for the project. The calculated risk for the tunnel must then fall below this target to be acceptable. Evaluation against relative criteria typically requires the establishment of a reference risk profile that represents an equivalent tunnel that is deemed to have an acceptable level of risk, typically because it complies with all the relevant standards and guidelines. The calculated risk for the tunnel must then fall sufficiently below that of the reference tunnel to be acceptable.

For risk expressed as the expected value (EV) the evaluation is fairly straight forward. This approach is easy to apply but does not take into account the distribution of consequences because accidents with very low probability/very high consequences only contribute to a minor extent to the expected value. If appropriate, a risk aversion factor may be included to offset this so that incidents with high numbers of fatalities are made less acceptable than the more frequent incidents with fewer fatalities.

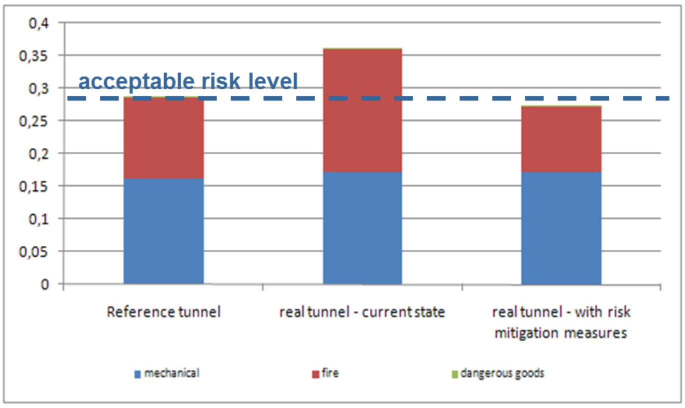

Figure 5. Application of relative criteria – risk expressed as EV

For risk expressed in the form of an FN curve, graphical information is provided about the frequency of incidents and the distribution of the numbers of fatalities in those incidents. Absolute evaluation criteria can be defined in the form of acceptance lines in the FN diagram and these reference lines are typically strictly linked to a specific analysis method or risk model. Acceptance lines in the FN diagram often have upper and lower limits between which an ALARP (As Low As Reasonably Practicable) zone is defined, where risks should be reduced to as low as reasonably practicable. Risks in this zone should typically be reduced as long as the cost of the risk reduction is not disproportionate to the monetary benefit.

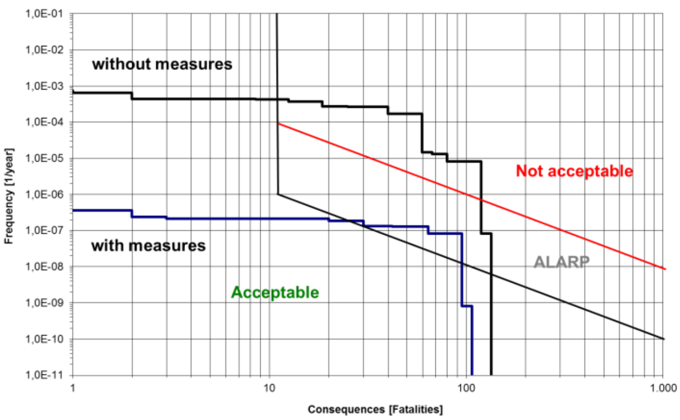

Figure 6. FN diagram including absolute criteria of acceptability

As with the absolute criteria for risk in terms of EV, the definition of the acceptability curves/boundaries in the FN diagram is not straightforward and is often a long-term process in which all stakeholders are involved.
Some Countries defined absolute risk criteria [3] which in most cases are limited to specific methods and specific applications. The comparative approach with FN curves is very useful for the risk-based comparison of alternatives but FN graphs can be difficult to interpret and need to be read very carefully, particularly where curves intersect.

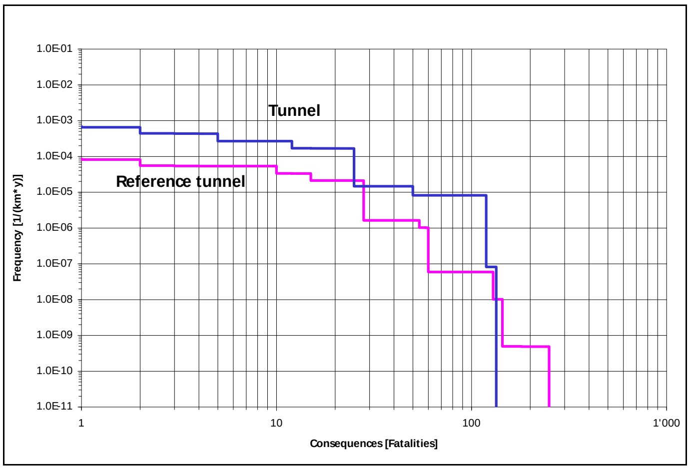

Figure 7. comparison of FN curves of "real" tunnel and "reference tunnel"

To increase the robustness of risk evaluation, the different risk evaluation strategies described are often combined with each other and with other approaches such as scenario analysis and cost-effectiveness analysis where safety measures may be prioritised to ensure that the resources are spent in such a way that the maximum risk reduction is obtained.

4 RISK ANALYSIS AS DECISION MAKING TOOL

4.1 *Current practice*

There are four main reasons, why the application of risk analysis as a decision making tool becomes more and more popular [8]:

- The safety standard of road tunnels in Europe in general is high.
- Hence further improvements in tunnel safety are cost-intensive, and – on the other hand – the financial resources available for further improvements are more and more limited.
- A focus on extreme scenarios may result in an unbalanced safety level and disproportionate cost.
- In most cases there are different options to reach a safety goal – sometimes there are low cost alternatives

Furthermore, both, the capability of risk assessment methods, as well as the availability of data required for an analysis close to reality improved a lot; at present a much more specific analysis and evaluation of individual safety parameters is possible than in the past.
Hence taking these aspects into account there is an increasing need for informed decisions supported by well-defined decision making tools and there are the methods suited to meet these requirements.

4 typical fields of application can be defined for the use of risk analysis as a support tool for decisions in tunnel design and tunnel operation:

- Upgrading of existing tunnels:
  Older tunnels often do not fulfill modern tunnel safety standards. In an upgrading process the safety standard has to be improved. In existing tunnels– other than in new ones - often severe technical, operational and financial restraints have to be taken into account, so that it may not be possible (or not adequate) to just adopt it to new standards. In such situations, it may be necessary to develop different design solutions which have to be evaluated in terms of their consequences on safety, operation and cost – a typical application of risk analysis as evaluation tool for tunnel safety [4].
- Safety relevant design decisions for new tunnels:
  Also for new tunnels, sometimes different options are available to fulfill a given safety standard or additional safety measures are required to compensate a special characteristic. In both cases risk analysis may contribute to decision making, by providing information on the effects on safety of the different design options, which can be used as input data for a cost-effectiveness assessment. The most common application in practice are decisions on the design of the ventilation system.
- Safety relevant design decisions for tunnel operation:
  Operational regulations influencing safety are an option for additional safety measures for existing as well as for new tunnels. For the transport of dangerous goods this type of measure was established on a regulative basis: every tunnel has to be allocated to one of five ADR tunnel categories (category A: all dangerous goods allowed – category E: all dangerous goods forbidden). The decision, which classes of dangerous products are allowed to be transported along the tunnel route or are to be diverted on alternative routes is typically taken on the basis of the results of a risk analysis
- Investigation of specific non-standard situations, with lack of information or unclear specifications in tunnel regulations; risk based studies on such topics may provide results and conclusions of general interest, giving input to tunnel design for comparable situations.

Furthermore, results from risk analysis may even give input to modifications of tunnel design guidelines. Research activities on such topics are under way aiming to provide a proper basis for the discussion of such adaptions – for instance the project "Procedure for the definition of the ventilation system of road tunnels" for the German Federal Highway Research Institute or the research activities of the upgrading of the Austrian Tunnel Risk Model TuRisMo

4.2 *Practical examples*

4.2.1 *The Učka Tunnel case study*

The Učka Tunnel is a 5,062 km long tunnel in Istria with one tube and bidirectional traffic, built in 1981. It is equipped with a longitudinal ventilation system. Furthermore, the Učka Tunnel is a tunnel with very specific conditions and a series of non-standard safety measures already installed. In the next years, a second tube will be built. In the design guidelines applied (the Austrian ventilation guideline RVS 09.02.31 [5]) for the application of a longitudinal ventilation system a limit of 3 km is defined for the tunnel length. The focus of the risk assessment study is on the decision on the ventilation system of the future tunnel configuration. In the risk study it could be demonstrated that the overall risk as well as the fire risk of the real tunnel in the new configuration are below the respective values of a reference tunnel (with a transversal ventilation system) – taking the already existing, non-standard additional safety measures (mainly operational measures) into account. Hence the future tunnel (with a longitudinal ventilation system) will be sufficiently safe with respect to the requirements of RVS 09.02.31 in terms of selection of the ventilation system.

4.2.2 *Upgrading of existing motorway tunnels in Austria*

The Austrian Tunnel Safety Law [10], for instance, implements the minimum safety requirements defined in the EC Directive as minimum standard for all tunnels of the Austrian highway network; at the same time it establishes the principle for the acceptability of limited derogations under specific circumstances as general principle for exceptions for all prescriptive requirements layed down in Annex I.

Older tunnels often show different kinds of derogations from these requirements, in some cases not being very relevant in terms of effects on risk. For instance, unregular distances between emergency exits are rather common, in some cases individual distances in a tunnel (slightly) exceed the maximum distance of 500 m whereas others are shorter. In such cases it may cause disproportionate cost to solve the problem by constructive measures. By applying a up to date risk analysis approach the effects on risk of these derogations can be assessed quantitatively; if the influence on risk is acceptably low (or compensated by other – positive – effects) it may be possible to accept these derogations; if not, possible additional compensation measures can be assessed as well, thus giving input to a cost-benefit analysis.

5 NEW DEVELOPMENT IN RISK MODELLING

New developments in risk modeling are discussed taking the Austrian tunnel risk model TuRisMo as an example. TuRisMo was among the first methods published (see RVS 09.03.11 [6]) as a consequence of article 13 of the EC Directive which obliges EU member states to use, at national level, a detailed and well-defined risk analysis methodology. One objective in the evolution of the method was to develop a tool which is easy applicable to the great mayority of tunnels existing in Austria.
For fire risk, for instance, 1-dimensional smoke propagation simulations for typical model tunnels were carried out in the development phase of the risk model, thus defining a set of standardized damage values for fires for typical situation. This allows a simple and straight forward application of the risk model (on the basis of Excel – for instance) however limits its use to tunnels, which fulfill crucial prescriptive requirements and / or lie within defined limits for specific parameters (because these were taken as a basis for the calculation of the standardized damage values of the risk model).
Typical limitations refer to the tunnel cross section (vaulted cross section with 2 lanes) to the longitudinal gradient or to air flow conditions (influence of traffic movement or non-standard ventilation cannot be taken into account). Furthermore, complex tunnel systems (e.g. tunnels with changing cross sections, ramps, combined ventilation systems) cannot be investigated and specific safety measures, for instance those influencing the evaluation of an incident in the first phase (like improved incident detection measures or traffic management measures) cannot be studied properly as well. On the other hand, experience showed that such non-standard tunnels with special characteristics require special attention.
Hence the decision was taken to expand the model on the existing basis [9] in order to cover more relevant parameters in a more specific way, focusing on parameters influencing fire risk. The most relevant modifications are addressed in the following chapters.

5.1 *Combined smoke propagation model*

In a 1-dimensional simulation the longitudinal airflow in the tunnel resulting of global influencing factors is simulated. The subsequent 3-dimensional simulation of smoke propagation then implements the local influencing factors based on the longitudinal velocities calculated before. The influencing factors included in the 1-dimensional and the application on the 3-dimensional model are illustrated in Figure 8.

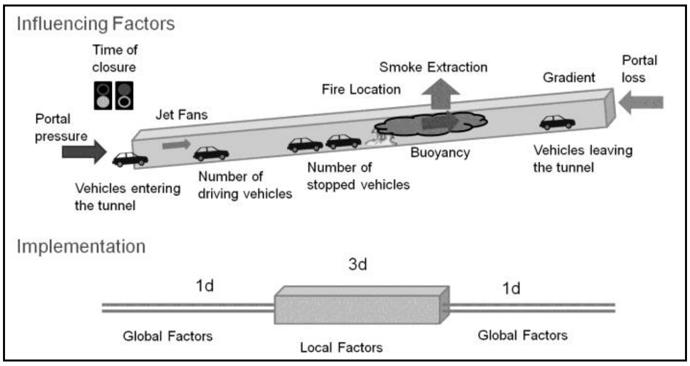

Figure 8. Influencing factors taken into account in the new 1D / 3D smoke propagation model of RVS 09.03.11 [9]

Parameters included in 1D model are:
- Drag at the tunnel walls and equipment
- Portal effects (loss of momentum at portals, wind pressure)
- Influence of moving vehicles (piston effect) and standing vehicles (drag)
- Influence of ventilation system (spin up time for jet fans and exhaust machine, position, etc.)
- Thermal forces of hot gases in the tunnel
- Heat exchange with tunnel walls (conduction effects)

Naturally the geometric properties such as overall tunnel length, cross section, circumference, inclination, ambient temperature etc. were included in the 1d model for a proper description of the resulting transport equations.
Parameters included in 3D model are:
- Exact local tunnel geometry (cross section at fire location)
- Gradient around the fire location
- Stopped vehicles in the vicinity of the fire location (causing turbulences)

The velocity development obtained in the 1-dimensional simulation is applied as boundary condition in a distance large enough to not interfere with the smoke stratification.

5.2 *Integrated evacuation simulation model*

A simplified evacuation tool was implemented in the smoke propagation model. The following features were included in this simplified evacuation tool:
- Reduction of evacuation grid to 1 dimension. This allows to reduce model complexity and computational demands while the loss of precision is minimal.
- Accumulation model by D. A. Purser [7] to calculate the accumulated dose of toxic gases and their effect on human physiology.
- Obscuration triggers start of self-rescue. This means that agents start moving as soon as the

visibility at walking level (head level of 1.6m) drops under a certain level. The time is limited by a (realistic) alert time when all people are requested to leave the tunnel.

- Direct data transfer for higher precision and optimisation of work flow

Overall the newly developed evacuation tool can achieve better precision with a reduced amount of work for each individual scenario. This allows to increase the total number of scenarios (fire locations in the tunnel, traffic scenarios) which can be covered within the risk analysis and therefore to obtain better and more representative results.

5.3 *Enhanced use of statistical traffic data*

So far the fire risk damage values were calculated on the basis of the AADT, hence for an average situation. In future it is envisaged to take at least 3 different traffic scenarios into account: one each for low, average and high traffic situations. These values shall be defined on the basis of statistical traffic data of one complete year of the investigated tunnel or of representative adjacent road sections. This approach allows to take effects into account which directly depend on the traffic situation at the time of the fire such as the resulting longitudinal velocity or the length of queuing vehicles behind the fire location. Especially in bidirectional tunnels these locations may have a large impact on the calculated number of victims.

5.4 *Implementation of additional scenarios*

According to international practice a 100 MW fire scenario was added (to implement a fire scenario which is bigger than the design-fire of the ventilation system in most cases).
In addition to the existing fire scenarios (fire in a tunnel with free traffic flow, fire in a tunnel with congested traffic) to additional scenarios were added: fire in a queue respectively accident and fire at the end of queue caused by an accident or break down inside the tunnel.

5.5 *Outlook*

The development of the new risk model is almost completed; the combined smoke propagation model and integrated evacuation simulation have been successfully tested in test calculations as well as for specific tunnels. The new model works and delivers comparable results to the existing model.
The final step will be the modification and completition of the standard damage values of the RVS and the documentation of the new model in the updated guideline. The model shall be finished by mid of 2013.

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