RISK ASSESSMENT AS A TOOL FOR DECISION MAKING TO IMPROVE TUNNEL SAFETY

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1 BACKGROUND OF RISK-BASED DECISION MAKING

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. Guidelines typically include a set of prescribed safety measures for tunnel categories and they also often focus on technical design specifications in order to establish a certain level of standardization and to guarantee an adequate performance of various technical systems. Although guidelines pretend to provide a unified safety level, in reality 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].

Although guidelines sometimes seem to provide a rigid framework, practical experience shows, that there are a lot of options to optimize tunnel safety measures e.g. from a cost-effectiveness perspective. However, this requires a tool, which is able to quantify the effects of risk-mitigation measures on tunnel safety, because the traditional prescriptive approach does not take into account the effectiveness of prescribed measures in a specific case.

Therefore, modern safety standards also take into account the evaluation of the effectiveness of safety measures. The EC-Directive 2004/54/EC on minimum safety requirement for road tunnels contains three elements related to the notion of tunnel safety measure effectiveness [10]:

- 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 defines the framework for assessing the effectiveness of risk mitigation measures for road tunnels by applying a risk based approach.

Risk-based approaches make it possible to identify and evaluate relevant additional safety measures for the purpose of risk mitigation. 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. To guarantee an adequate performance of the ventilation, design procedures and design parameters (e.g. the design fire size) have to be defined in order to establish a unified design approach, which typically is done in a technical design guideline. Therefore the prescriptive approach and the performance-based approach are to be considered as complementary elements of the safety assessment process [1].

2 TOOLS FOR RISK-BASED DECISION MAKING

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 has to be found (e.g. in terms of cost-effectiveness).

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.

2.1 General Approach

In a risk-based approach, an integrated approach to tunnel safety is provided by systematically analysing emergencies, 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 [1], [9]. 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-based approach may also focus on specific questions or specific scenarios without investigating the complete range of possible incidents. Therefore, different methods have been developed 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.

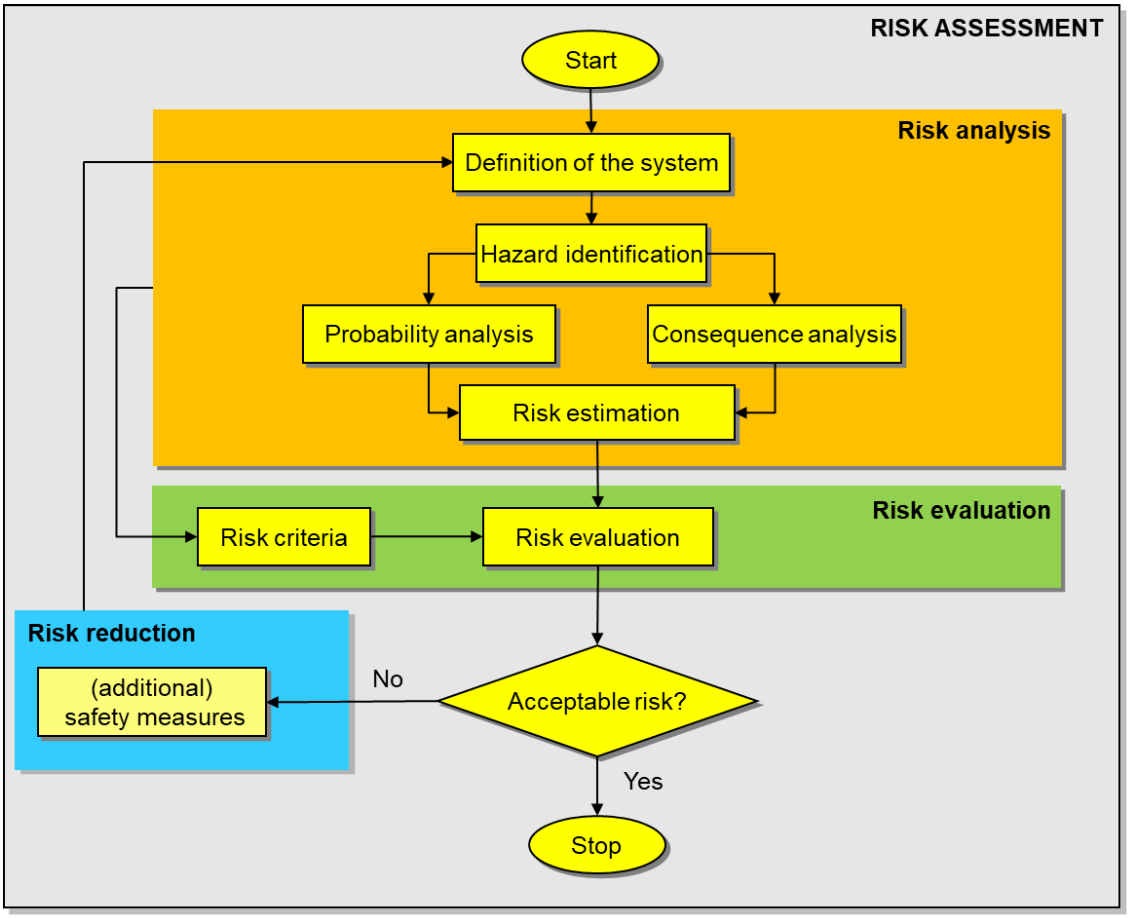

Fig. 1: Risk assessment process [1]

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. The most common quantitative risk indicator is casualties (fatalities / injuries) referring to the group of tunnel users.

As there are various tools which can be applied in practice, it is crucial to select the best methodology available for a specific problem. To be able to assess a specific effect of an individual risk mitigation measure, the methodology applied must be sensitive to the modifications of the functionality of the tunnel safety features influenced by this specific measure. Effective risk mitigation measures are able to intervene at several points in the chain of events of a specific incident type. To quantify the overall effect the methodology applied must be able to model all these effects in a realistic manner. Furthermore, in some cases specific input data at a detailed level is required for a consistent modelling.

Fig. 2: Effective tunnel closure enforced by barriers, Lioran Tunnel (France) © CETU

For instance, if the measure “fast and efficient tunnel closure in case of a fire incident” needs to be assessed, there are several aspects which need to be taken into account:

- To implement fast incident detection in a risk assessment the approach must be able to model the influence of time on emergency response (the activation of tunnel closure, activation of emergency mode of the ventilation etc.); additionally, quantitative information is required to which extent an enhanced detection system is able to reduce the (average) detection time
- A traffic model is required which is capable of representing a change in traffic configuration (less vehicles queuing close to the incident location, more vehicles stopping at places farther away or outside the tunnel)
- A fire and smoke propagation model which is able to simulate smoke propagation throughout the tunnel in dependence of time. In the best case this is a transient model which is able to take the effect of variable influences on the longitudinal airflow into account (like vehicle movements in the first phase of incident; the start-up and control of the ventilation system during the fire incident, the buoyancy effect of the fire etc.)

In many cases this requires a risk model providing an integrated set of various simulation tools

Over the past decade, different risk analysis methods have been elaborated and implemented in guidelines on a national level. A documentation of the most common methods can be found in two PIARC Reports, “Risk Analysis for Road Tunnels” [2] and “Current Practice for Risk Evaluation for Road Tunnels” [1].

A continuous improvement of some of these tools has enlarged their applicability for decision making a lot. However, the example provided makes also clear that the quality of the results depends on two key parameters:

- The suitability of the applied risk assessment tool for a specific problem
- The availability and quality of input data for a specific topic

2.2 Concept for the assessment of the effectiveness of risk mitigation measures

The process for the assessment of the effectiveness of risk mitigation measures typically consist of 4 steps [10]:

- In a **first step**, the specific problems of an individual tunnel with respect to user safety must be identified and analysed. In a first approach this is typically done by a qualitative safety analysis.
- 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.
- 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. At first this step must be performed qualitatively on a detailed level. The quantification of the effects can be based on data (measurements, statistics), on theoretical considerations, on practical experience or on expert judgement.
  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.
- 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 the effect of the measure 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 incident scenarios.

For an efficient and consistent implementation of this concept the application of a well-proven system-based risk assessment tool is highly recommendable [1], [2], [3], [5], [6]. All the effects can be quantified in such a model, thus providing information on the overall effectiveness of a specific risk mitigation measure. Further, a systematic quantitative study of the safety effects of all measures in question can be performed, thus providing input for other studies, like a cost-benefit-analysis for the risk mitigation measures in question. 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.

3 PRACTICAL EXAMPLE FOR RISK-BASED DECISION MAKING

3.1 Description of the problem

The case study presented in this paper is dealing with a specific problem in the operation of an unidirectional tunnel which is exposed to extreme wind during seasons with specific weather conditions.

The unidirectional tunnel is equipped with a longitudinal ventilation system which has been designed taking the meteorological conditions into account – as far as possible. But previous studies demonstrated that the ventilation is not able to reach the design objectives in extreme wind situations. Consequently, if a fire incident occurs in such a situation, it may happen that smoke is propagating against the driving direction and against the direction of the ventilation, thus endangering people in vehicles queueing behind the fire site.

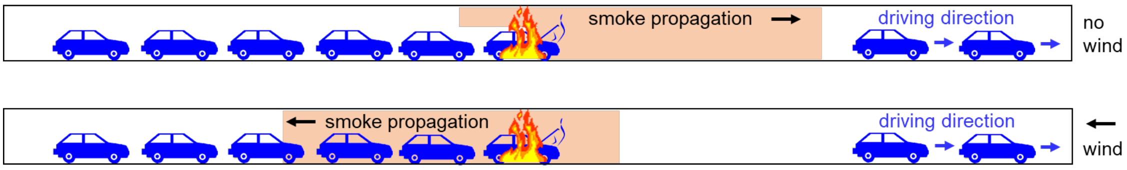

Fig. 3: Change of smoke propagation direction in case of extreme wind on the tunnel portal

As all options for upgrading the ventilation system had apparently been exhausted already, the idea came up to study alternative risk mitigation measures with a risk assessment model to cope with this situation. In particular, some decision criteria should be provided to the operator, as a basis for a decision on operational measures which could even be a temporary closure of the tunnel. These decision criteria should be based on measurable parameters.

3.2 Assessment methodology

As a suitable risk assessment methodology the Austrian Tunnel Risk Model “TuRisMo” [6] was selected. The Austrian methodology uses a fully integrated approach that allows for the detailed analysis of many kinds of safety measures and for interactions between different safety measures. Factors such as the installed safety equipment and boundary conditions such as traffic conditions are taken into account rigorously. The method combines a quantitative frequency analysis based on statistical evaluations and a quantitative consequence analysis that includes (i) a (mechanical) collision-only part and (ii) a distinct fire consequence model. Figure 1 shows a schematic representation of the overall structure of the method. Details of the various sub-models of the overall method have been given elsewhere [4], [5] and [6] and are not reproduced herein.

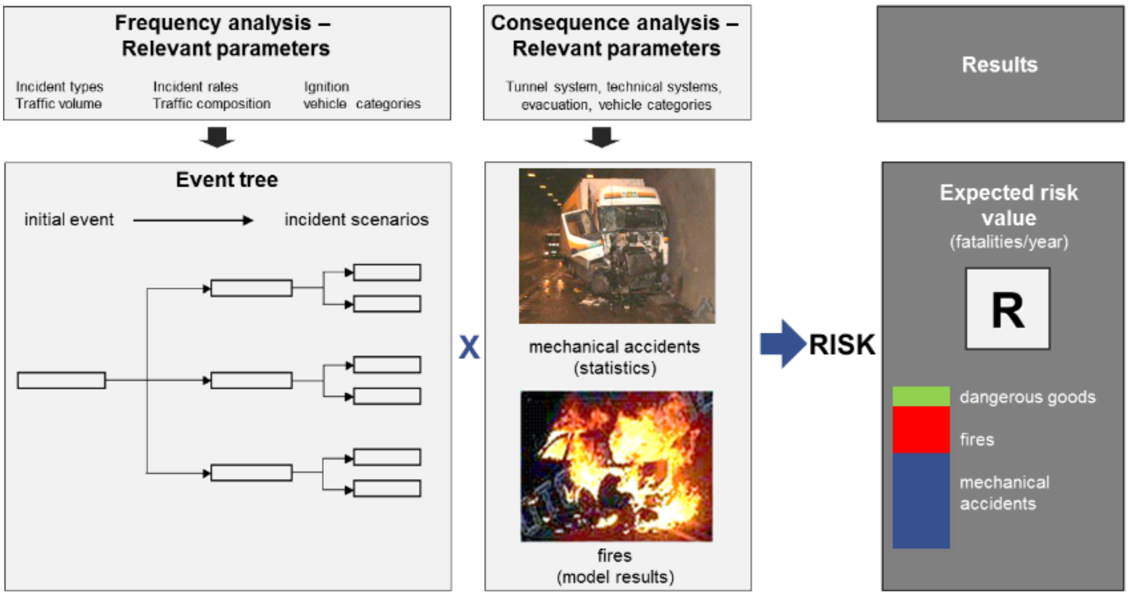

Fig. 4: Schematic representation of the TuRisMo methodology

The fire consequence model used in the investigation of emergency ventilation strategies can be summarized as follows [7]:

- Each distinct fire scenario is considered explicitly in an event tree and a set of detailed scenarios with varying local parameters is generated based on the probability distribution of the influencing parameters;
- For each of these detailed fire scenarios, a transient one-dimensional airflow simulation is performed, taking into account all important influencing factors such as traffic volume, fire location, ventilation design and meteorological boundary conditions;
- The predicted development of the longitudinal airflow velocities is then used as boundary condition in a three-dimensional CFD simulation (FDS) in which local effects such as back-layering and smoke stratification are examined;
- Visibility-, heat- and toxic-gas concentrations generated in the three-dimensional CFD simulation are then combined with person-exposure distributions dependent upon the traffic configuration after the incident;
- Based on this superposition and using an accumulation and intoxication model describing the effects of fire hazards on evacuation speed and survivability of persons [6], the expected total number of fatalities is computed. The whole process is then repeated for the next detailed scenario.

3.3 Risk-based approach for the development of decision criteria

This case study has been chosen because it is very well suited to demonstrate the challenges of risk-based decision making in an illustrative manner:

- For risk-based decision making some well-argued, practically applicable risk reference criteria are needed

- A way must be found to quantify the influence of specific characteristics of a tunnel on tunnel user risk – in this case the strong wind
- The approach must be practically applicable – in this case the tunnel operator needs a tool which is based on measurable real-time parameters which are available to him

3.3.1 Risk reference criteria

It is difficult to give general advice how to select adequate risk reference criteria, but it can be well explained, how it can be done in this specific case.

This tunnel has been subject of a risk assessment study already earlier – without specifically addressing the wind problem. The result was that this tunnel is sufficiently safe taking the tunnel configuration, the equipment, the traffic situation and the operational aspects into account. Hence, there is already a quantitative risk value for this tunnel which is acceptable.

However, this risk value is an average risk value for one year, based on the AADT for the tunnel and other average conditions. At a closer look, it becomes clear, that from a time perspective the risk is not constant, but varying over time: there are periods of time when it falls below the average value and other periods when the average value is exceeded. Given that a certain risk value is regarded as acceptable as an average value for one year, a corresponding higher risk level would also be acceptable, but only for a limited time. Traffic being the key parameter for this variation, it would be possible to derive an acceptable risk level for a defined high traffic period [11].

Assuming that the period with critical wind situation lasts for instance 30 days, the risk level of a traffic volume which is exceeded on 30 days of the year could be chosen as reference value. Of course, also the average risk value could be taken as reference, but this would be a much stricter requirement.

Defining a proper reference risk value is crucial for the whole process and must therefore be discussed and agreed with the responsible people of the tunnel operator and maybe although with authorities.

3.3.2 Practical implementation

In discussions with the tunnel operators it was found, that there a 2 key parameters

- which are measurable in real time and
- which have a significant influence on the risk level.

These parameters are the real-time traffic volume (vehicles/h) and the real time longitudinal airflow velocity inside the tunnel. Using these parameters, a matrix can be elaborated by calculating a hourly risk value for every relevant combination of traffic volume and airflow velocity. This can be done by repeatedly applying the risk model.

By comparing the resulting risk value to the reference risk value defined before, distinction can be made between situations which are sufficiently safe (risk level below reference risk level) and situations which require additional operational measures (risk level above reference risk level). This approach separates the matrix into two parts: a set of combination of parameters which are safe (green part in Fig. 5) and a combination of parameters which is critical.

An example of such a matrix is shown in Fig. 5 for illustration. The numbers in this matrix represent the fire risk of the tunnel tube affected by strong wind. In this example the reference value (red number on top of the grey column) has been calculated based on the AADT, thus representing the average hourly fire risk value of this tunnel.

current airflow velocity in tunnel tube [m/s]	current traffic volume in tunnel tube [vehicles/h]							
	100	200	300	400	500	504	600	700
3,1								
3,0								
2,5								
2,0								
1,5								
1,0								
0,5								
0,0								
-0,5								
-1,0								
-1,5								
-2,0								
-2,5								
-3,0								
-3,5								
-4,0								
	2.400	4.800	7.200	9.600	12.000	12.105	14.400	16.800
	traffic volume in tunnel tube per day [vehicles/24h]							

current airflow velocity in tunnel tube [m/s]	current traffic volume in tunnel tube [vehicles/h]							
	100	200	300	400	500	504	600	700
3,1						0,0028		
3,0				0,0019				
2,5				0,0022	0,0026			
2,0				0,0020	0,0027			
1,5				0,0026	0,0035			
1,0				0,0034				
0,5	0,0009	0,0025	0,0047	0,0078	0,0109			
0,0	0,0014	0,0054	0,0120	0,0182	0,0258			
-0,5	0,0031	0,0147	0,0404	0,0719	0,0961			
-1,0		0,0209		0,0816				
-1,5		0,0283		0,1036				
-2,0	0,0084	0,0305		0,1167				
-2,5				0,1148				
-3,0	0,0078			0,1049				
-3,5				0,0889				
-4,0				0,0734				
	2.400	4.800	7.200	9.600	12.000	12.105	14.400	16.800
	traffic volume in tunnel tube per day [vehicles/24h]							

Fig. 5: Structure of matrix for decision making with reference line based on fire risk

Fig. 6 shows the relation between fire risk and longitudinal airflow velocity for a traffic value of 400 veh./hour (left side) and the longitudinal smoke propagation of one corresponding airflow velocity (-0,5 m/s).

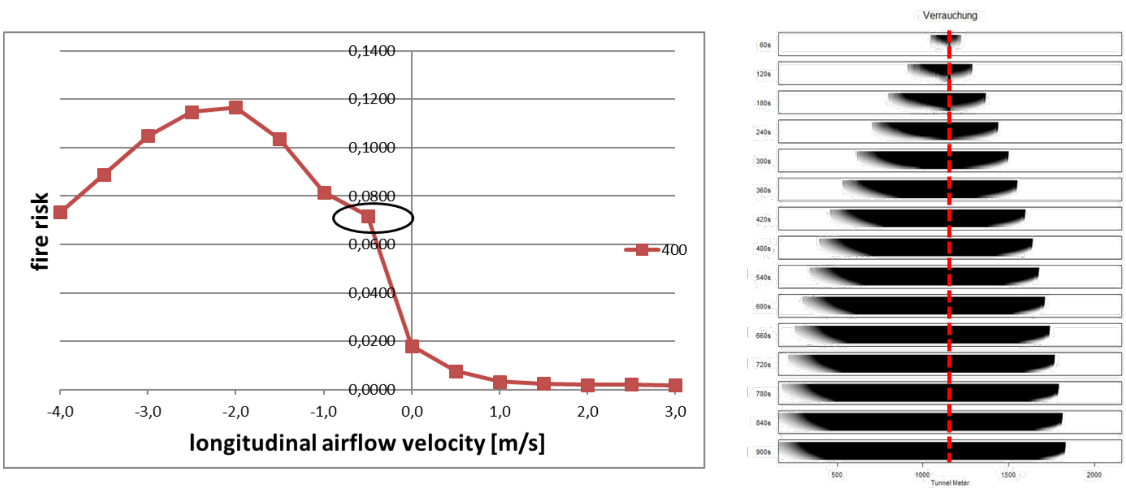

Fig. 6: Detailed results: fire risk (traffic volume 400veh/h) in dependence of longitudinal airflow velocity and smoke propagation for a longitudinal airflow of -0,5 m/s

This example demonstrates the principles of the approach. In reality the situation is more complex. For a proper understanding it is explained, that – as an additional measure – in case of expected strong wind conditions the ventilation is operated at full speed. Hence, the effect of ventilation is already included in the resulting longitudinal airflow velocity (like all other effects like vehicle movements, wind etc.). For the risk calculation in this specific application, the airflow velocity is assumed as constant and the interaction of wind with all the other parameters is not modelled. This significant simplification is possible because only the resulting airflow velocity is relevant for the risk and this value is measured in real time and therefore does not need to be simulated.

Naturally it is also possible to include additional measures into this approach which could either influence the reference line in the matrix or – if not taken into account for decision making – reduce the resulting risk in all cases.

4 SUMMARY AND CONCLUSIONS

This paper presents the background and the principles of risk-based decision making, applying modern risk assessment tools. It outlines the process to be followed for assessing the effects of additional risk mitigation measures in a quantitative way and it explains how this approach can be used in practice. To illustrate the principles, the example of a tunnel is presented which periodically is exposed to extreme wind. In case of a fire incident the effect of fire ventilation can be considerably impaired by these influences.

The case study explains the development of a simple decision making tool for tunnel operation which is elaborated by applying an advanced risk model. Applying this tool, the tunnel operator can decide on the activation of operational measures in critical situations, based on measurable parameters. The example also demonstrates the high flexibility of such a risk-based approach which can be adapted to a wide range of different questions relevant for decision making in the context of road tunnel safety.

5 REFERENCES

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VII SIMPOSIO TÚNELES DE CARRETERA

TÚNELES: ACORTAN DISTANCIAS, UNEN PERSONAS
PANORAMA ACTUAL Y BUENAS PRÁCTICAS

VII SIMPOSIO DE TÚNELES DE CARRETERA

Promueve: GOBIERNO DE ESPAÑA MINISTERIO DE FOMENTO

Organiza: asociación técnica de carreteras, comité nacional español de la asociación mundial de la carretera; WORLD ROAD ASSOCIATION MONDIALE DE LA ROUTE

Colaboran: Generalitat de Catalunya; Ajuntament de Barcelona; BIM/SA Barcelona d´Infraestructures Municipals; AMB Àrea Metropolitana de Barcelona; CCOC CAMBRA OFICIAL CONTRACTISTES OBRES CATALUNYA

Risk assessment as a tool for decision making to improve tunnel safety

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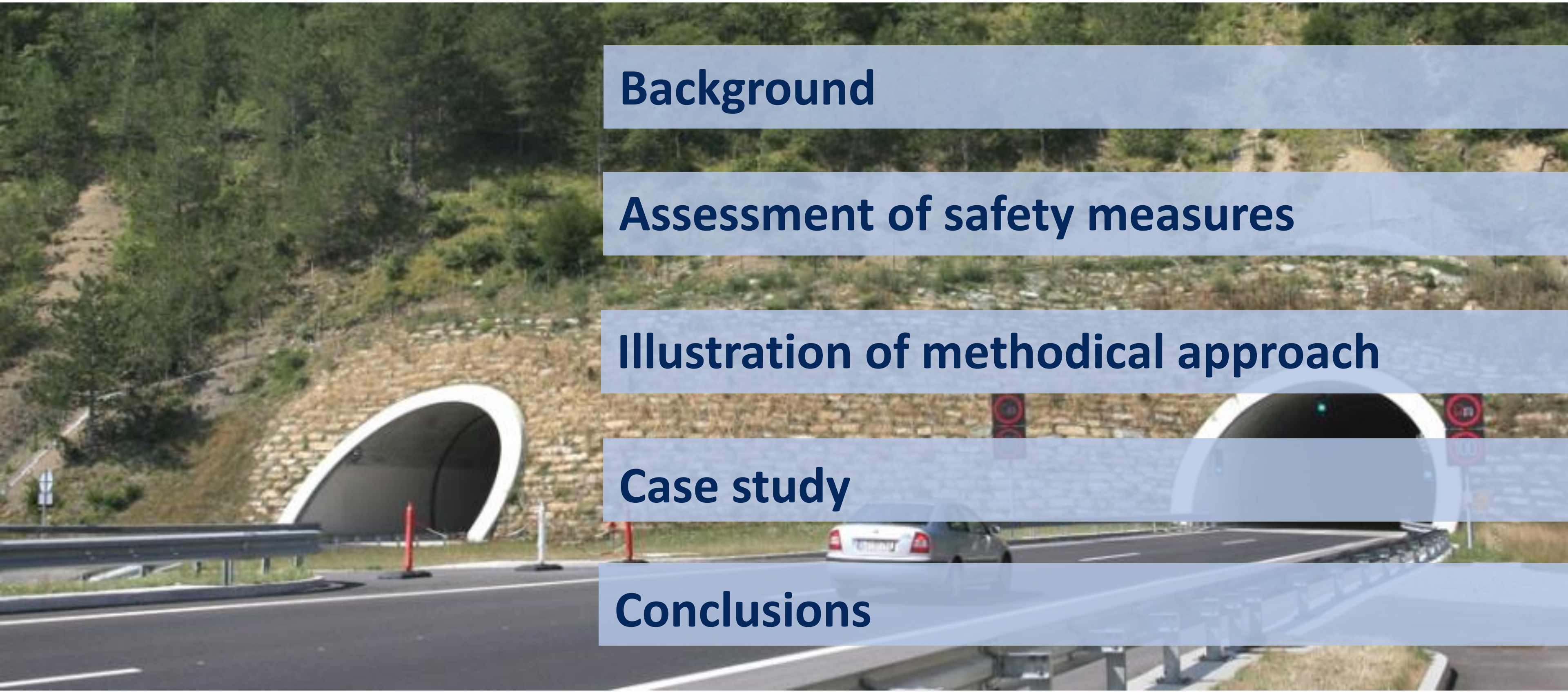
Content



- Background
- Assessment of safety measures
- Illustration of methodical approach
- Case study
- Conclusions

Background

Prescriptive approach – traditional approach to tunnel safety

- Framework of **guidelines and regulations** for design, construction and operation of road tunnels
- **Focus on technical design specifications** to establish a certain level of standardization and guarantee an adequate performance of technical systems
- The resulting **safety level might differ** from tunnel to tunnel
- Does not take into account **effectiveness of safety measures** in a particular tunnel
- Does not address the **residual risk**

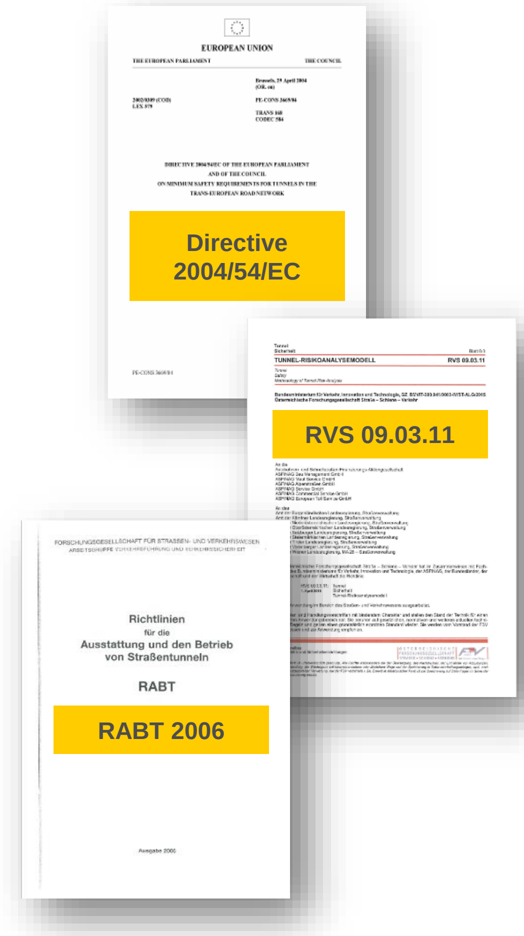
Tunnel du Lioran; Quelle: CETU

Source ASFiNAG

Background

Modern safety standards take into account the **evaluation of effectiveness** of safety measures

- **EC Directive 2004/54/EC**
  - **Introduces risk assessment** as practical tool for the evaluation of tunnel safety
  - Includes a **list of safety measures**, thus defining a minimum safety level
  - Introduces the **principle of equivalence**: alternative measures allowed if they provide the same or higher safety level

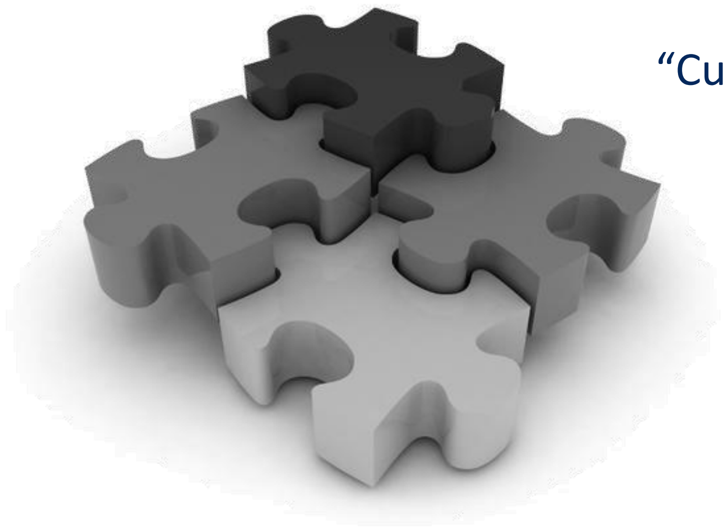


Background

Prescriptive versus risk-based approach

"Prescriptive based approach and risk based approach have to be used as complementary elements of the safety assessment process."

(Recommendation, PIARC Report
"Current Practice for Risk Evaluation for Road tunnels")



Background

Why do we need risk-based decision-making?

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

- To **counterbalance** the influence of specific **risk-increasing factors**
- To **compensate shortcomings** in construction or equipment of existing tunnels

- In many cases several alternative solutions are available and an **optimized solution** has to be found
- Risk assessment helps to **identify safety measures** and to **assess their effectiveness** (quantitatively)

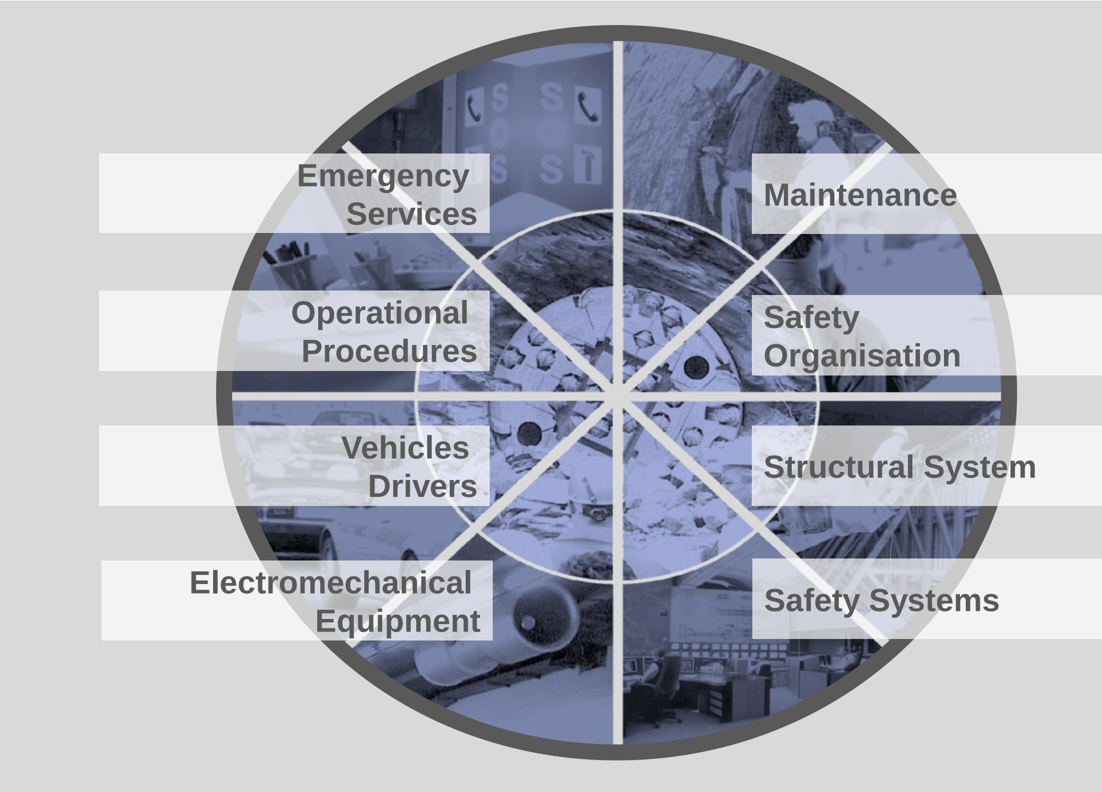
Background

Typical application of risk-based decision-making

- For design decisions in planning phase (tunnel structure & equipment)
- For decisions on additional risk mitigation measures (in case of deviation from prescriptive requirements, to compensate specific characteristics etc.)
- To select the best suitable combination of risk mitigation measures by combining results of risk assessment with cost-effectiveness analysis
- To decide on operational strategies for emergencies (operation of ventilation, traffic management etc.)
- To decide on safety requirements for upgrading of existing tunnels
- To demonstrate a sufficient level of safety
  - In case of deviation from prescriptive requirements
  - In construction phase of upgrading of existing tunnels

Assessment of safety measures

Holistic approach

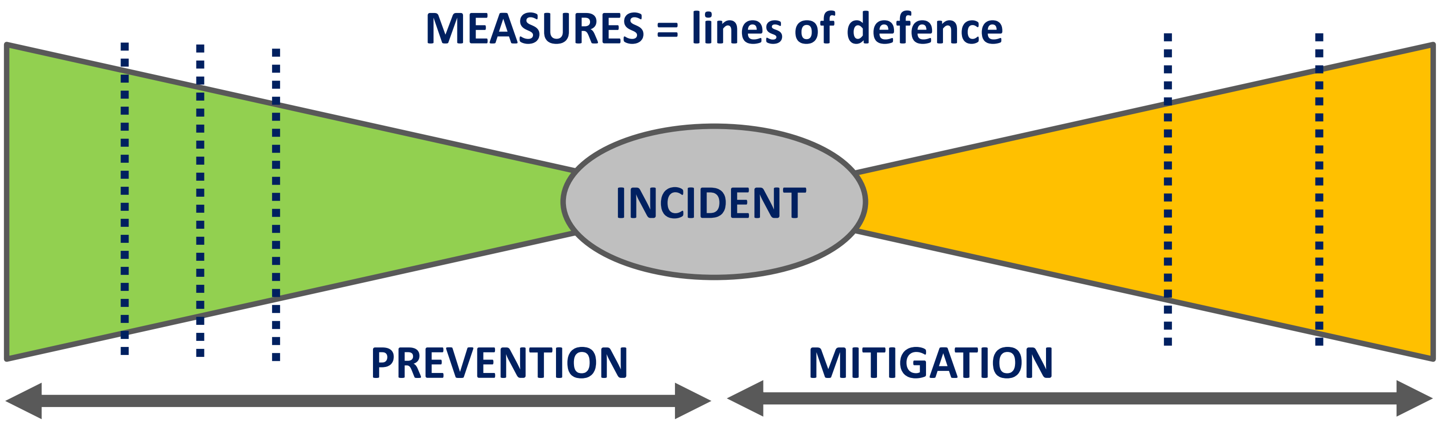


- A safe tunnel environment requires a optimized and balanced **interaction of all aspects** influencing safety
- **Additional safety measures** need to be **integrated** into this complex system – taking **interaction effects** into account

Assessment of safety measures

Tools for risk-based decision making

- **Risk model** must be capable of **quantifying the effects of risk-mitigation** measures on tunnel safety
  - by **modelling the influence** of a specific measure on the functionality of a specific tunnel safety feature
  - at each **individual influence point** in the chain of events



- The **quality of a tool** depends on
  - The **suitability for a specific problem**
  - The availability and **quality of input data**

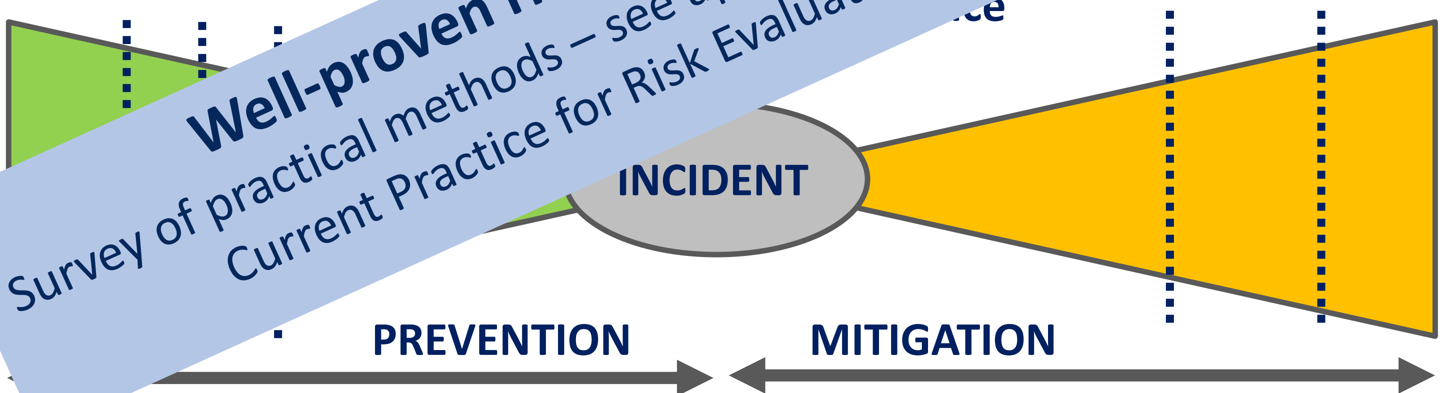
Assessment of safety measures

Tools for risk-based decision making

- **Risk model** must be capable of **quantifying the effects** … **ation** measures on tunnel safety
  - by **modelling the influence** of a specific … y of a specific tunnel safety feature
  - at each **individual influen**… …ts

Well-proven risk analyses methodologies

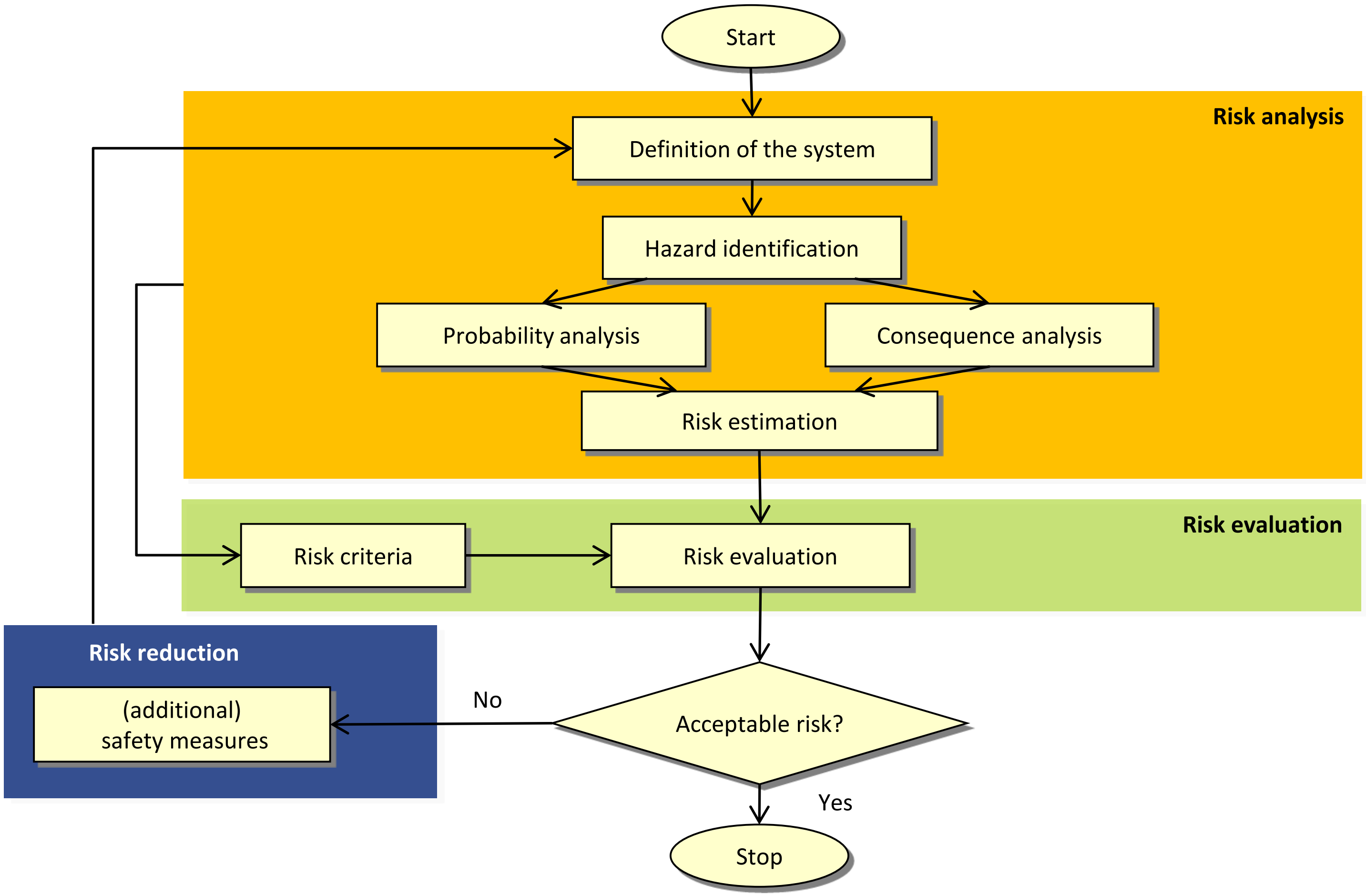
Survey of practical methods – see appendix A of PIARC report 2012/R23 Current Practice for Risk Evaluation for Road Tunnels



- The **quality of a tool** depends on
  - The **suitability for a specific problem**
  - The availability and **quality of input data**

Assessment of safety measures

Risk assessment process



Assessment of safety measures

Assessment process for tunnel safety measures

1. **Specific safety problems** of an individual tunnel must be defined
2. **Suitable measures** need to be **found** which are able to mitigate or compensate the problems identified
3. For the tunnel in question it is necessary to **analyze how the measure acts on the risk** caused by the specific problems, including interaction effects
   - This step must be performed **qualitatively**, but quantification is highly beneficial
   - 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 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
4. After having assessed the effectiveness of a risk mitigation measure on a detailed level, **the effect of the measure on the overall safety level** of the tunnel is studied (e.g. by application of **professional risk assessment tools**)

Assessment of safety measures

Practical example: Lay-Bye – qualitative analysis of effects

- (intended) positive effects:
  - Safe place for vehicles not able to continue
  - Drivers can leave their car without being exposed to traffic
  - Broken down vehicle does not impede traffic
  - Risk of subsequent incident (collision) reduced
- (unintended) negative effects:
  - End wall could aggravate consequences of collision, if a vehicle crashes into it
  - Hence additional mitigation measures required (e.g. crash cushion)

Necessity of **proper assessment of all positive and negative effects** of measure on safety within a specific tunnel, together with **other aspects** like operation or cost

Illustration of methodical approach

Example: Austrian Tunnel Risk Model TuRisMo

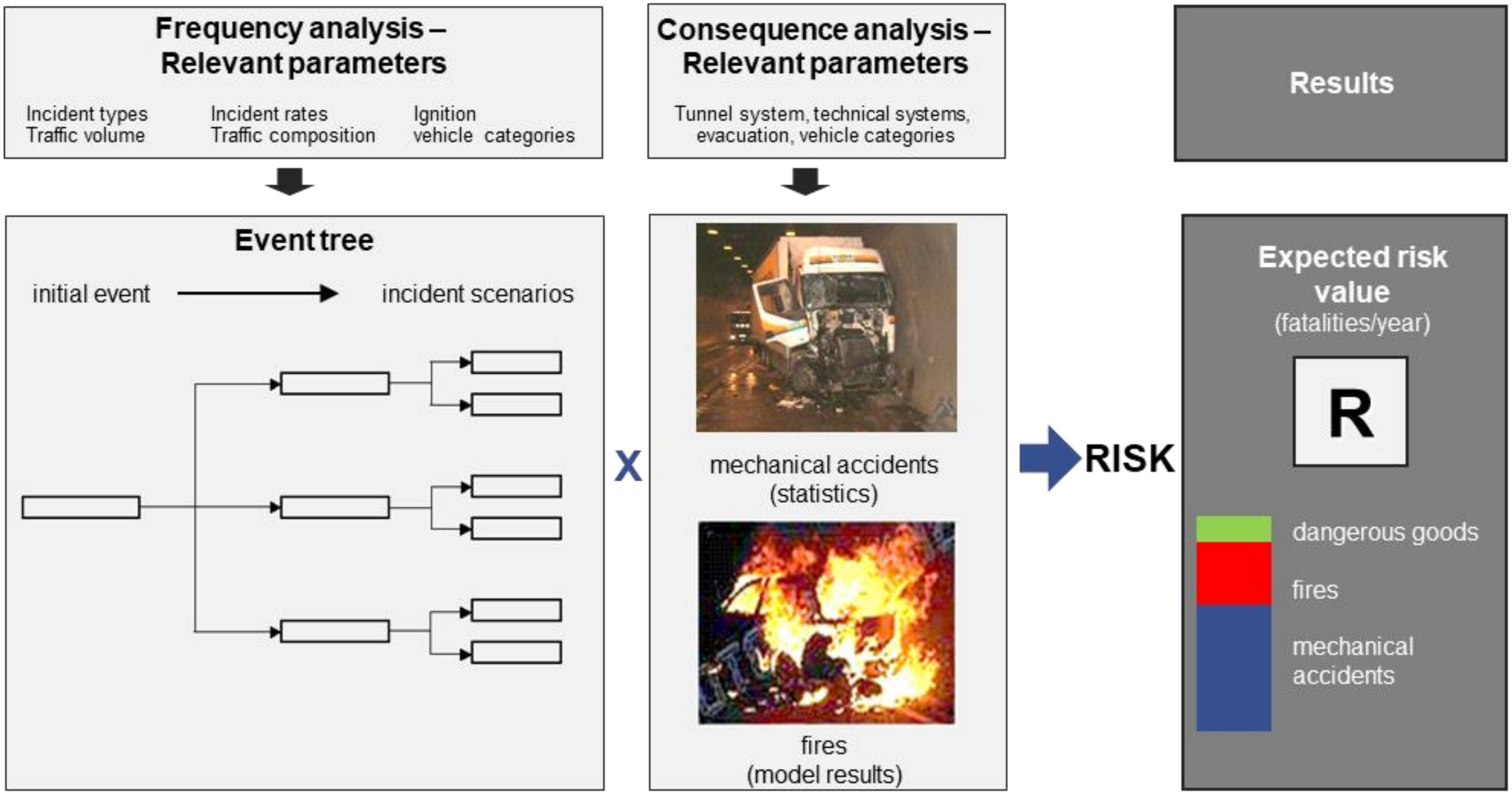
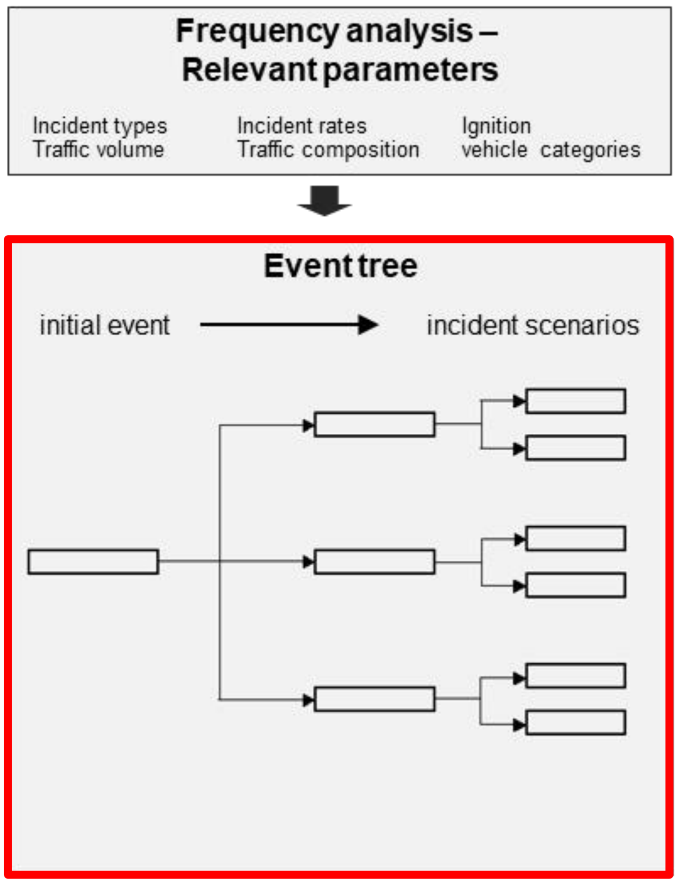


Illustration of methodical approach

Example: Austrian Tunnel Risk Model TuRisMo



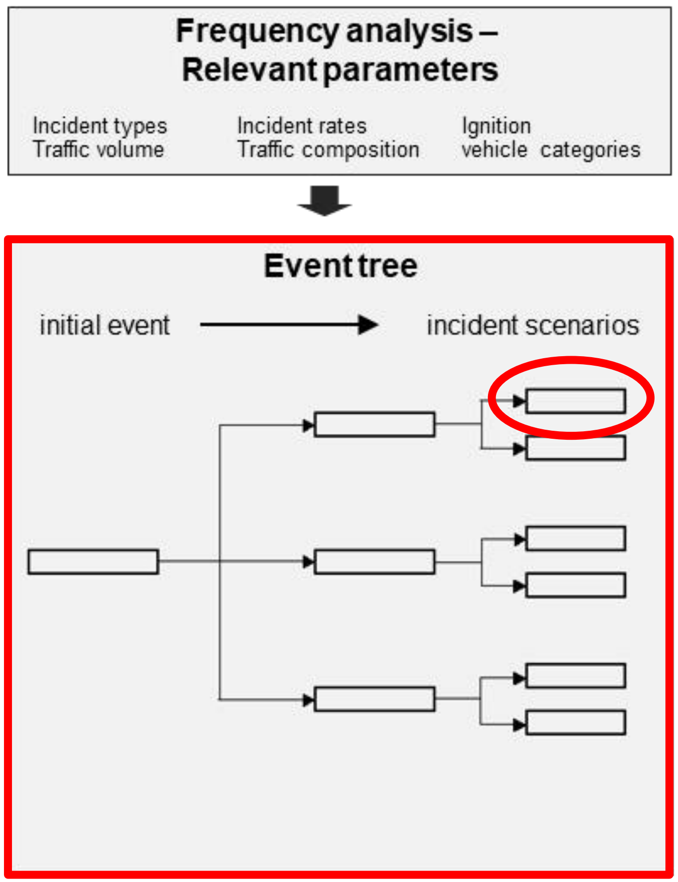
FREQUENCY ANALYSIS

Basic incident scenarios

- Breakdown of a vehicle causing a fire / a collision
- Single-vehicle collision
- Collision between vehicles driving in the same direction
- Head-on collision
- All collision types with fire as follow-up event

Illustration of methodical approach

Example: Austrian Tunnel Risk Model TuRisMo



CONSEQUENCE ANALYSIS - FIRE

Fire scenarios

- For each distinct fire scenario in the event tree
- a set of detailed scenarios with varying local parameter is generated
- based on the probability distribution of the influencing parameters

Illustration of methodical approach

TuRisMo – consequence analysis – fire risk

For each of these detailed fire scenarios, a **transient 1D airflow simulation** is performed, taking into account all important influencing factors such as

- traffic movements
- fire location
- ventilation design
- meteorological boundary conditions

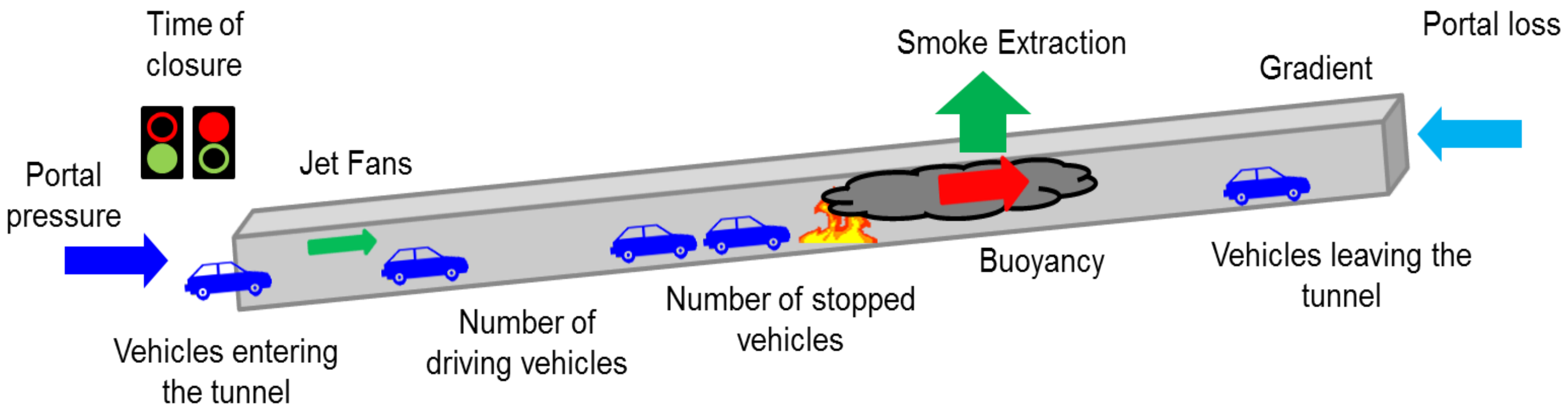
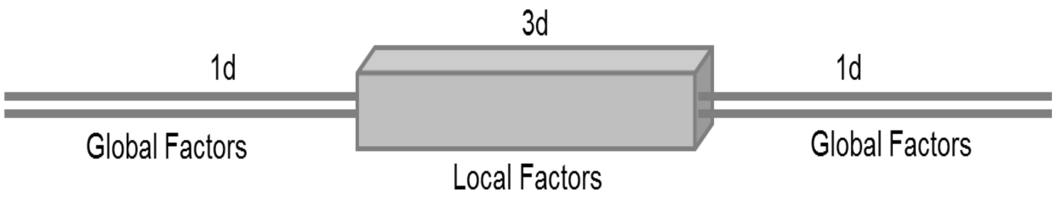


Illustration of methodical approach

TuRisMo – consequence analysis – fire risk

The predicted development of the longitudinal airflow velocities is used as boundary condition in a **3D CFD simulation** (FDS) in which local effects are examined (back-layering, smoke stratification…)



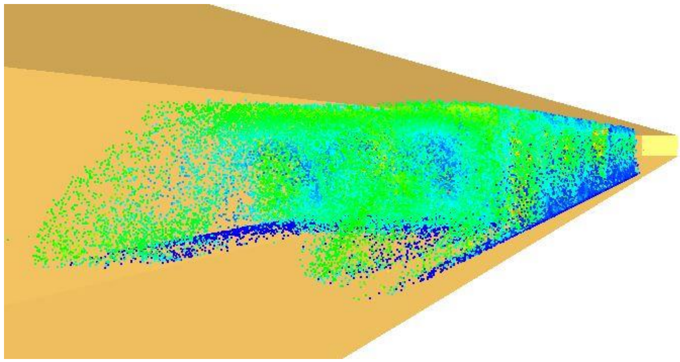


Illustration of methodical approach

TuRisMo – consequence analysis – fire risk

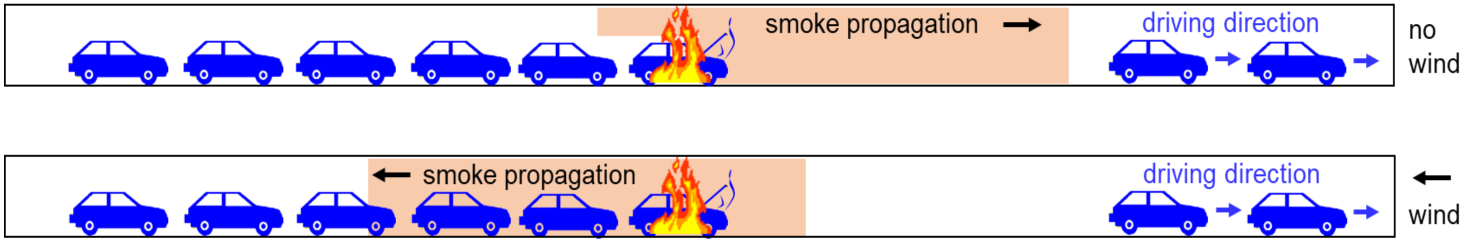
- **Visibility, heat and toxic gas concentrations** generated in the 3D CFD simulations are then combined with **person-exposure distributions** dependent upon the traffic configuration after the incident
- Using an **accumulation-based intoxication model** (Purser model) describing the effects of fire hazards on evacuation speed and survivability of persons the expected total number of fatalities is computed
- The whole **process is** then **repeated** for the next distinct scenario covering different **fire sizes**, different **fire locations** and different **traffic scenarios**

Case study

Operation of a tunnel exposed to strong wind

Problem

- During specific weather conditions **tunnel is exposed to strong wind** Ventilation system upgraded already, but still not able to manage airflow conditions properly – smoke propagation against driving direction possible



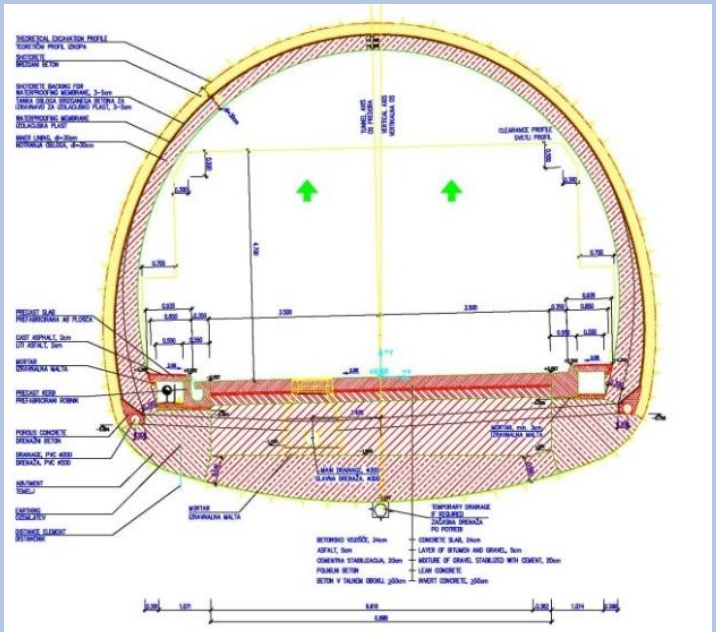
Objectives

- Development of risk-based decision-making tool, assisting the operator to decide on additional operational measures in critical wind situations

Case study

General tunnel data

- Unidirectional tunnel, 2 tunnel tubes
- Tunnel length ~ 2,3 km
- Vaulted cross section
- 2 traffic lanes per tube
- Gradient 2,5%



Tunnel safety aspects

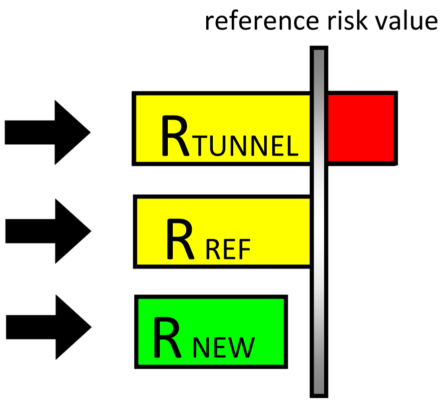
- Speed limit 100km/h
- 5 emergency exits (cross passages)
- Traffic signals at tunnel portals
- Longitudinal ventilation system
  jet fans in affected tube: 14
- Strong wind: jet fans are activated during normal operation
- Operator has to decide on operational measures

Case study

Defining risk reference criteria – example

Tunnel was subject to a risk assessment study before
Result: **tunnel** configuration, equipment **sufficiently safe**

- **Acceptable quantitative risk value** – can be used as **reference value**
  - Represents average risk for one year, based on AADT; but: risk is not constant over time
  - Given that a certain risk level is acceptable as average value for one year, a corresponding higher level would also be acceptable for a limited period
  - Traffic being the key parameter for this variation, it is possible to derive an acceptable risk level for a defined shorter traffic period
- Defining a proper reference risk value is critical for the process must be discussed and **agreed with responsible entities**



Case study

Practical implementation of the approach

- Assessment must be based on **simple and relevant decision-making parameters** available to the operator in real time
  - Traffic volume (vehicles / hour)
  - Longitudinal airflow velocity

	current traffic volume in tunnel tube [vehicles/h]							
current airflow velocity in tunnel tube [m/s]	100	200	300	400	500	504	600	700
3,1						0,0028		
3,0								
2,5								
2,0								
1,5								
1,0								
0,5								
0,0								
-0,5								
-1,0								
-1,5								
-2,0								
-2,5								
-3,0								
-3,5								
-4,0								
	2.400	4.800	7.200	9.600	12.000	12.105	14.400	16.800
	traffic volume in tunnel tube per day [vehicles/24h]							

Structure of decision matrix

Grey line:
representing critical velocity

Grey column:
representing AADT

- Calculate fire risk for relevant combinations traffic / airflow by applying the risk model

Case study

Decision matrix with **reference risk value based on AADT** (representing average hourly fire risk of the tunnel)

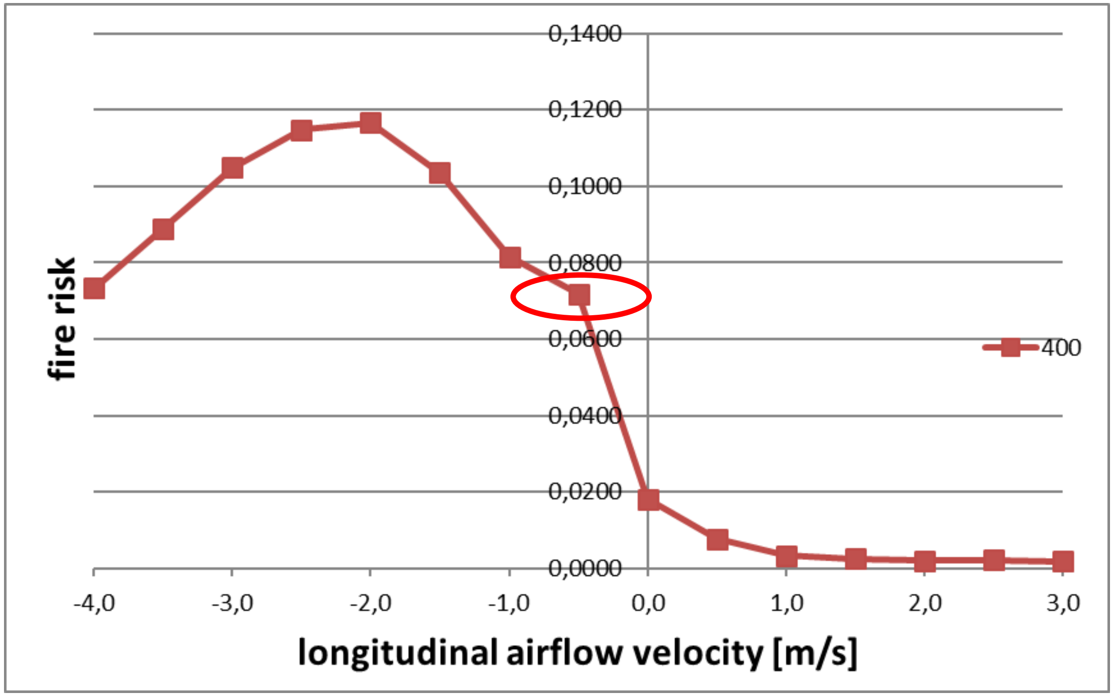
current airflow velocity in tunnel tube [m/s]	current traffic volume in tunnel tube [vehicles/h] →	100	200	300	400	500	504	600	700
	3,1						0,0028		
	3,0				0,0019				
	2,5				0,0022	0,0026			
	2,0				0,0020	0,0027			
	1,5				0,0026	0,0035			
	1,0				0,0034				
	0,5	0,0009	0,0025	0,0047	0,0078	0,0109			
	0,0	0,0014	0,0054	0,0120	0,0182	0,0258			
	-0,5	0,0031	0,0147	0,0404	0,0719	0,0961			
	-1,0		0,0209		0,0816				
	-1,5		0,0283		0,1036				
	-2,0	0,0084	0,0305		0,1167				
	-2,5				0,1148				
	-3,0	0,0078			0,1049				
	-3,5				0,0889				
	-4,0				0,0734				
	traffic volume in tunnel tube per day [vehicles/24h]	2.400	4.800	7.200	9.600	12.000	12.105	14.400	16.800

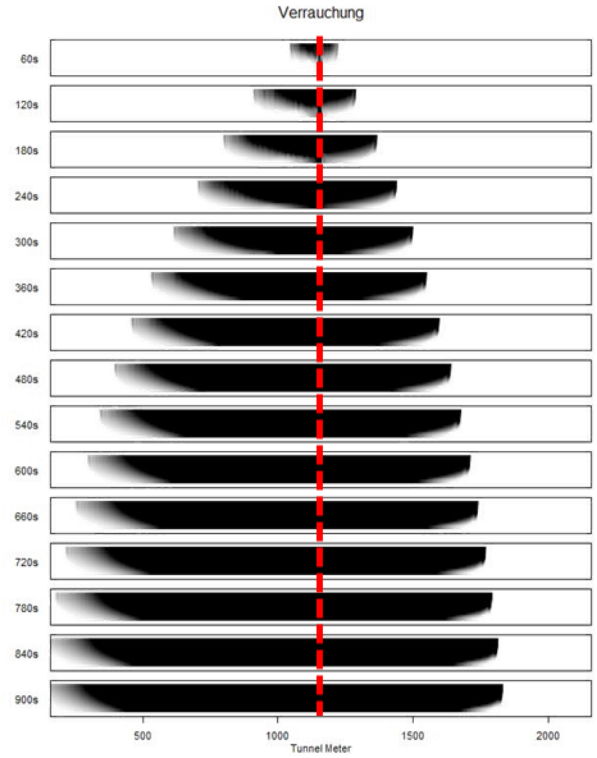
Green fields:
risk below reference value

Red fields:
risk exceeding reference value

Case study

Fire risk in dependence of airflow velocity for a traffic volume of 400 veh/h

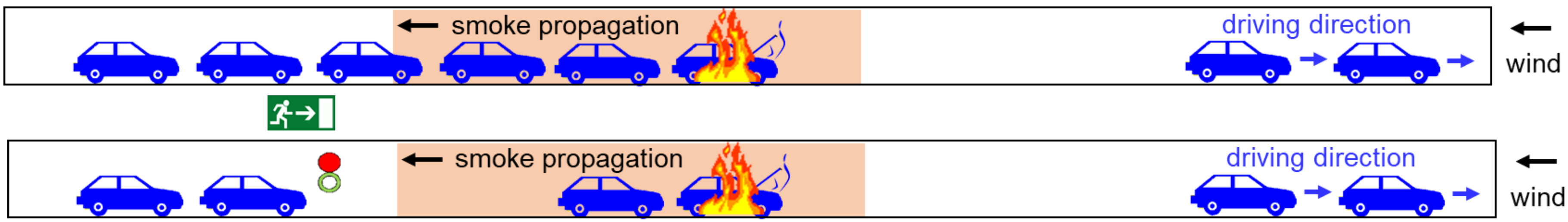


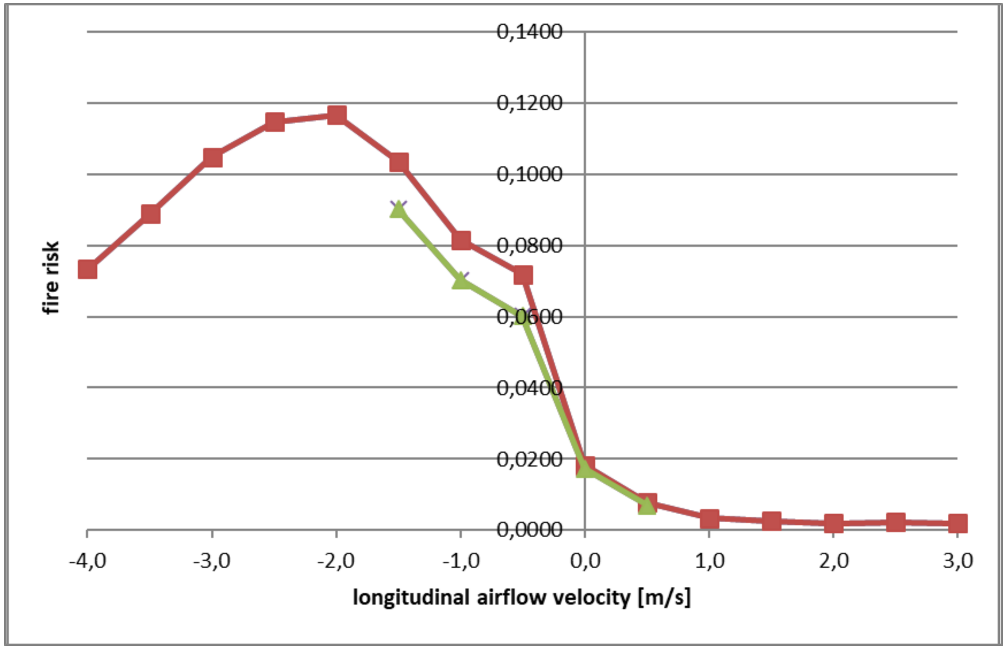


Longitudinal smoke propagation for a corresponding airflow velocity of -0,5m/sec.

Case study

Investigation of additional safety measures: additional traffic lights at emergency exits





Red line:
Fire risk without measure

Green line:
fire risk with measure

Case study

Decision matrix with **reference risk value based on AADT** (representing average hourly fire risk of the tunnel)

current airflow velocity in tunnel tube [m/s] \ current traffic volume in tunnel tube [vehicles/h]	100	200	300	400	500	504	600	700
3,1						0,0028		
3,0				0,0019				
2,5				0,0022	0,0026			
2,0				0,0020	0,0027			
1,5				0,0026	0,0035			
1,0				0,0034				
0,5	0,0009	0,0025	0,0047	0,0078	0,0109			
0,0	0,0014	0,0054	0,0120	0,0182	0,0258			
-0,5	0,0031	0,0147	0,0404	0,0719	0,0961			
-1,0		0,0209		0,0816				
-1,5		0,0283		0,1036				
-2,0	0,0084	0,0305		0,1167				
-2,5				0,1148				
-3,0	0,0078			0,1049				
-3,5				0,0889				
-4,0				0,0734				
traffic volume in tunnel tube per day [vehicles/24h]	2.400	4.800	7.200	9.600	12.000	12.105	14.400	16.800

Green fields:
risk below reference value

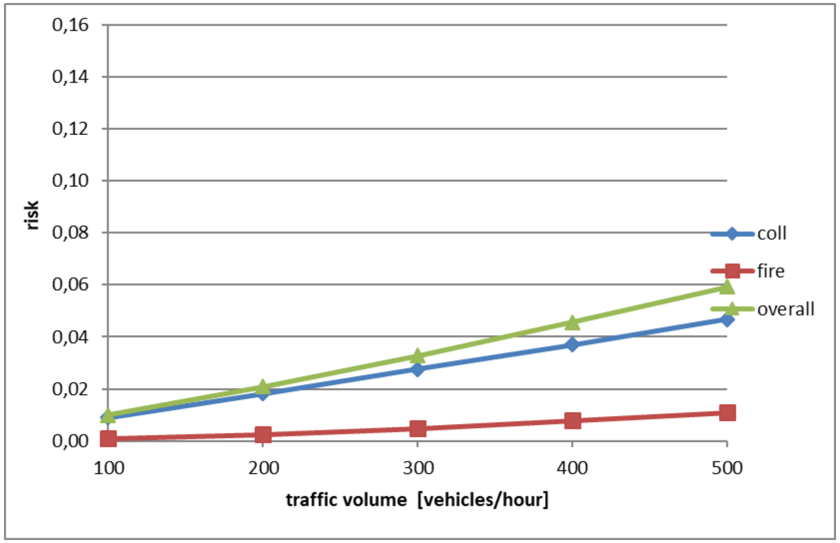
Red fields:
risk exceeding reference value

Case study

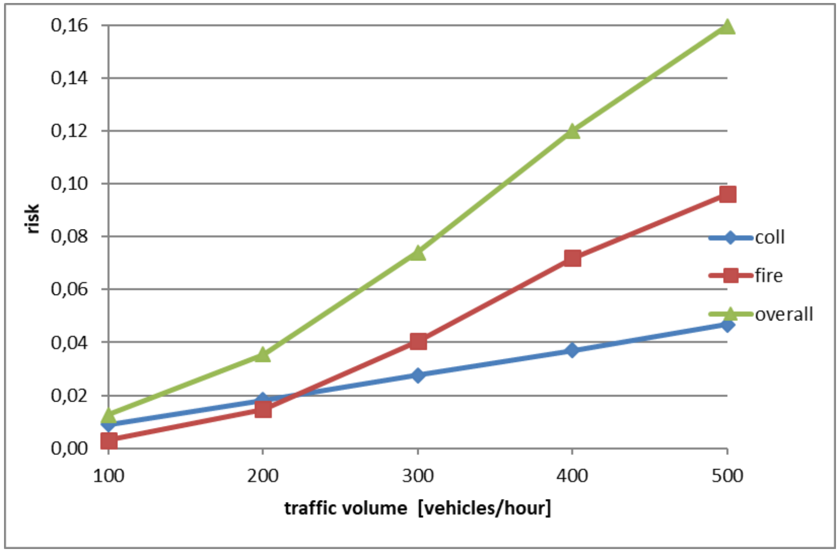
Fire risk, **collision** risk and **overall** risk

in dependance of traffic volume for airflow velocities +0,5m/s | -0,5m/s

+ 0,5m/s



- 0,5m/s



Case study

Conclusions

There is an **increasing need for informed decisions** supported by well defined risk-based decision making tools, because …

- The safety standard of road tunnels in Europe in general is high
- (Further) improvements of tunnel safety are (very) cost-intensive and the financial resources are limited
- In most cases there are different options to reach a safety goal
- Risk models provide a well balanced approach; focus on extreme scenarios may result in an unbalanced safety level and disproportionate cost
- Risk models provide a rational basis for complex decisions

Advanced risk models provide a wide range of options for new applications

Thank you for your attention!

Contact: **bernhard.kohl@ilf.com**

For more information please visit

www.ilf.com / www.tunnelriskmodel.at

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