Norwegian Tunnel Safety Conference 2018
«Connecting Tunnels and Communities»

Quantitative risk assessment and risk-based decision making




Bernhard KOHL, ILF– 18.06.2018

OUTLINE

- Background
- Tools for risk-based decision making
- Safety measures
- Case studies

BACKGROUND

Traditional approach to tunnel safety –
prescriptive approach

- 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**

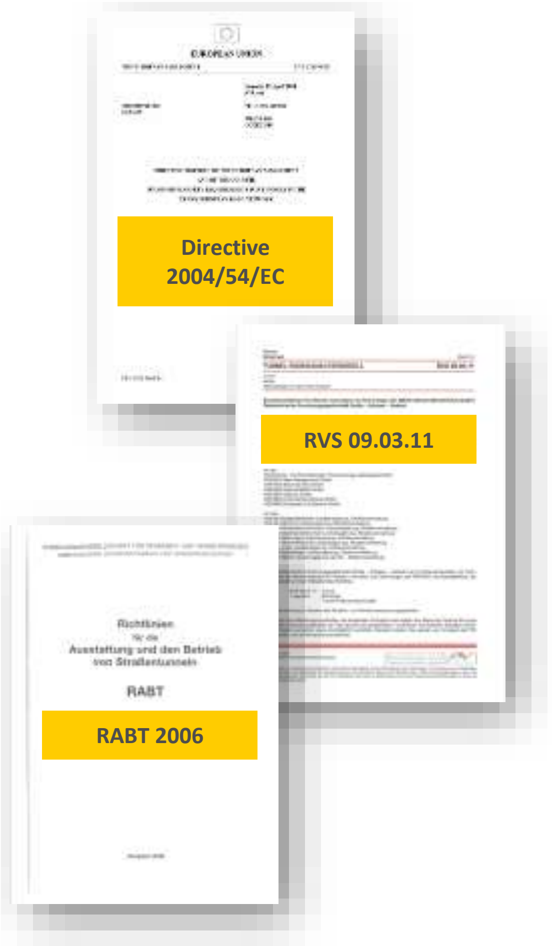

Tunnel du Lioran; Quelle: CETU


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



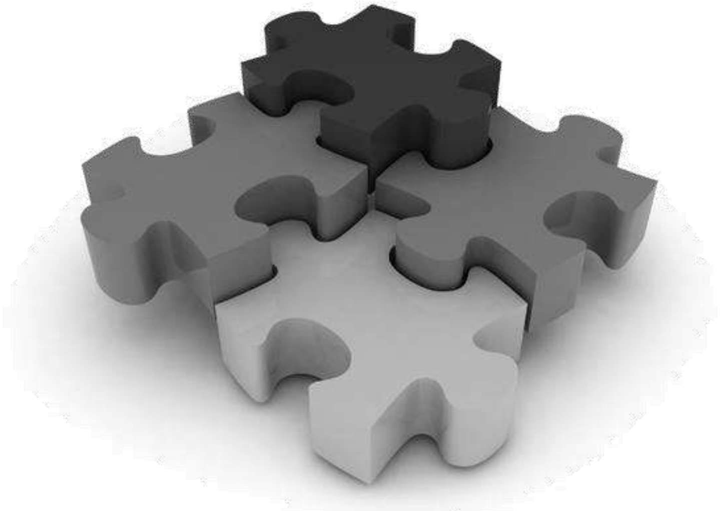
BACKGROUND

Basic principles of a risk-based approach

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”)



TOOLS FOR RISK-BASED DECISION MAKING

Types of risk assessment methodologies

System based approach	Scenario based approach

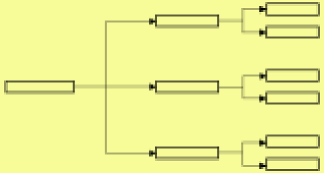
System based approach

Input: Influencing factors

Tunnel length | Traffic volume | Portion of heavy vehicles | . . .

Logical tree

initial event → accident scenarios



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Modelling of Consequences

→ RISK

Results

Expected risk value (fatalities/year)

R

Risk distribution (F-N-Curve)

Scenario based approach

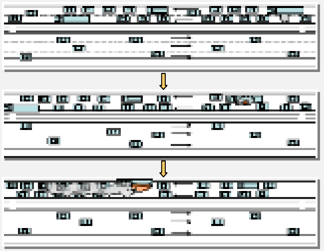
Select relevant scenarios → Analyse development of scenarios → Investigate effects and consequences of scenarios → optimize design

scenario 1

scenario 2

scenario 3

…



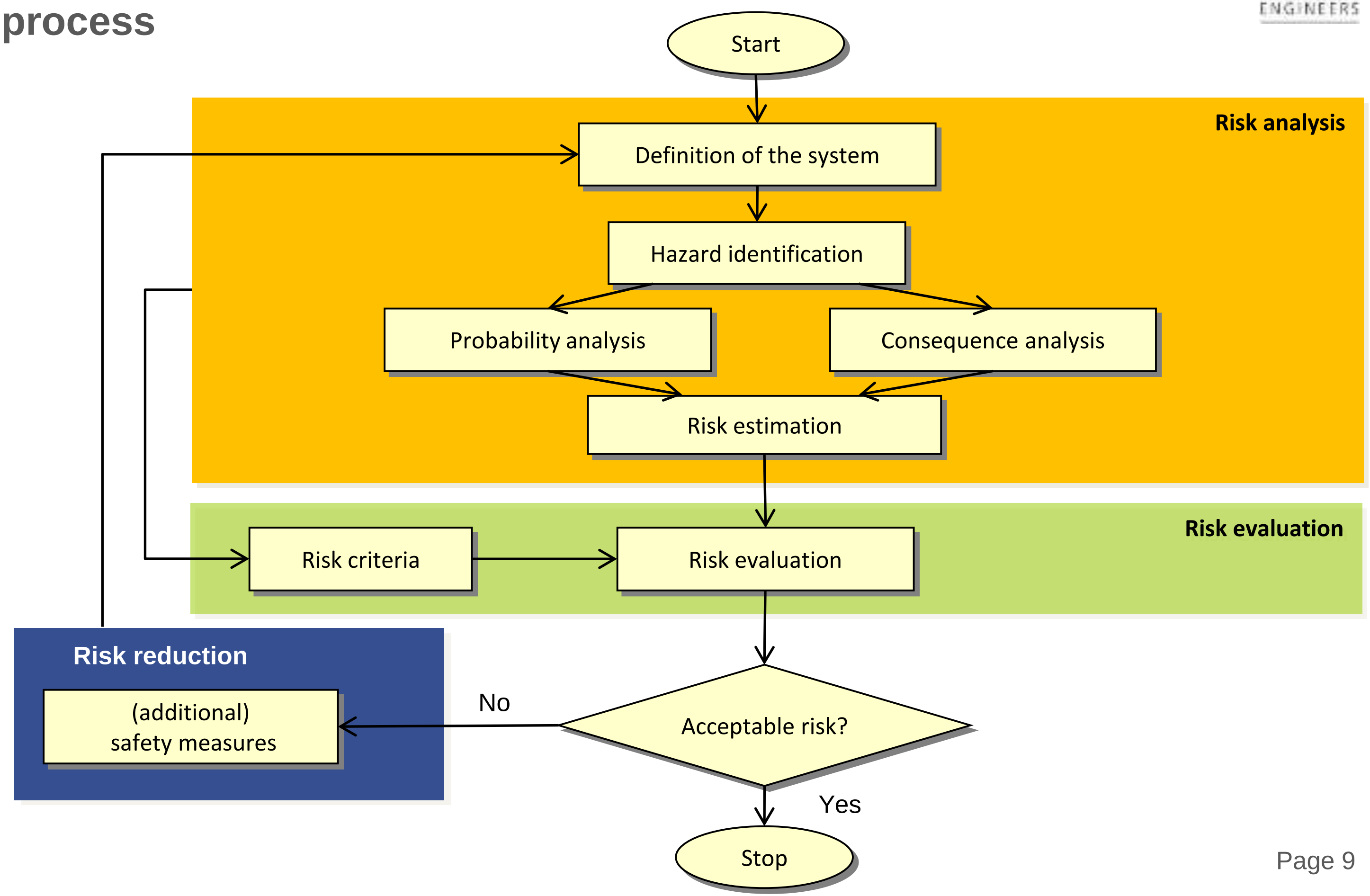
eg. evacuation

- Investigation of the overall system in an integrated process
- Assessment of risk values for the whole system

- Analysis of relevant scenarios
- Obtaining information on frequency / consequences for each individual scenario

TOOLS FOR RISK-BASED DECISION MAKING

Risk assessment process

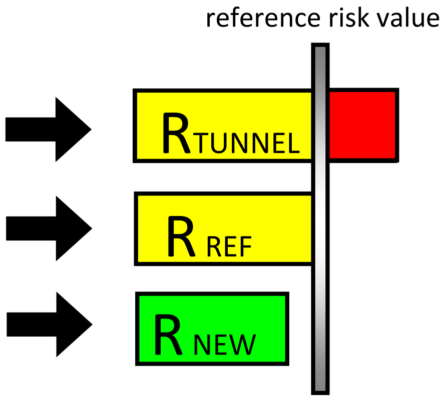


TOOLS FOR RISK-BASED DECISION MAKING

Principle of risk evaluation

RELATIVE APPROACH

- The assessed tunnel is **compared to a “reference tunnel”**
- This “reference tunnel” **defines the acceptable risk level** (because it meets all prescriptive requirements, represents acceptable conditions etc.)
  - In Europe: tunnel of same geometry and traffic fulfilling EC-Directive requirements
- **Additional risk** of the assessed tunnel to be **compensated** by alternative risk mitigation measures



TOOLS FOR RISK-BASED DECISION MAKING

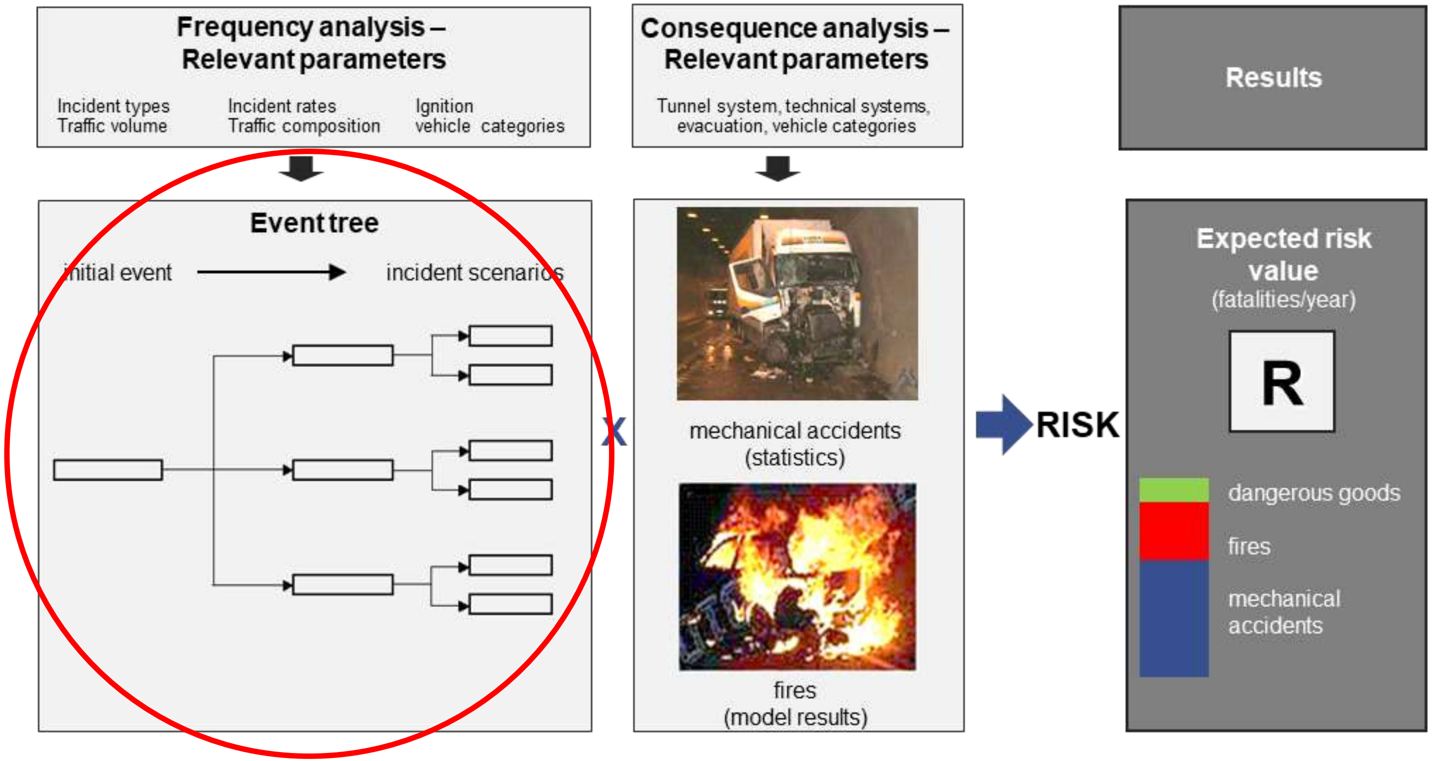
Typical application of quantitative risk assessment

- **To support 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 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
  - Demonstrating compensation of specific characteristics by alternative measures
  - In construction phase of upgrading of existing tunnels
- **To select the best suitable combination of risk mitigation measures**
  - By combining results of risk assessment with cost-effectiveness analysis for safety measures

TOOLS FOR RISK-BASED DECISION MAKING

Methodical approach – Austrian Tunnel Risk Model TuRisMo

Methodical components of TuRisMo (system-based risk model)



TOOLS FOR RISK-BASED DECISION MAKING

Methodical approach – Austrian Tunnel Risk Model TuRisMo

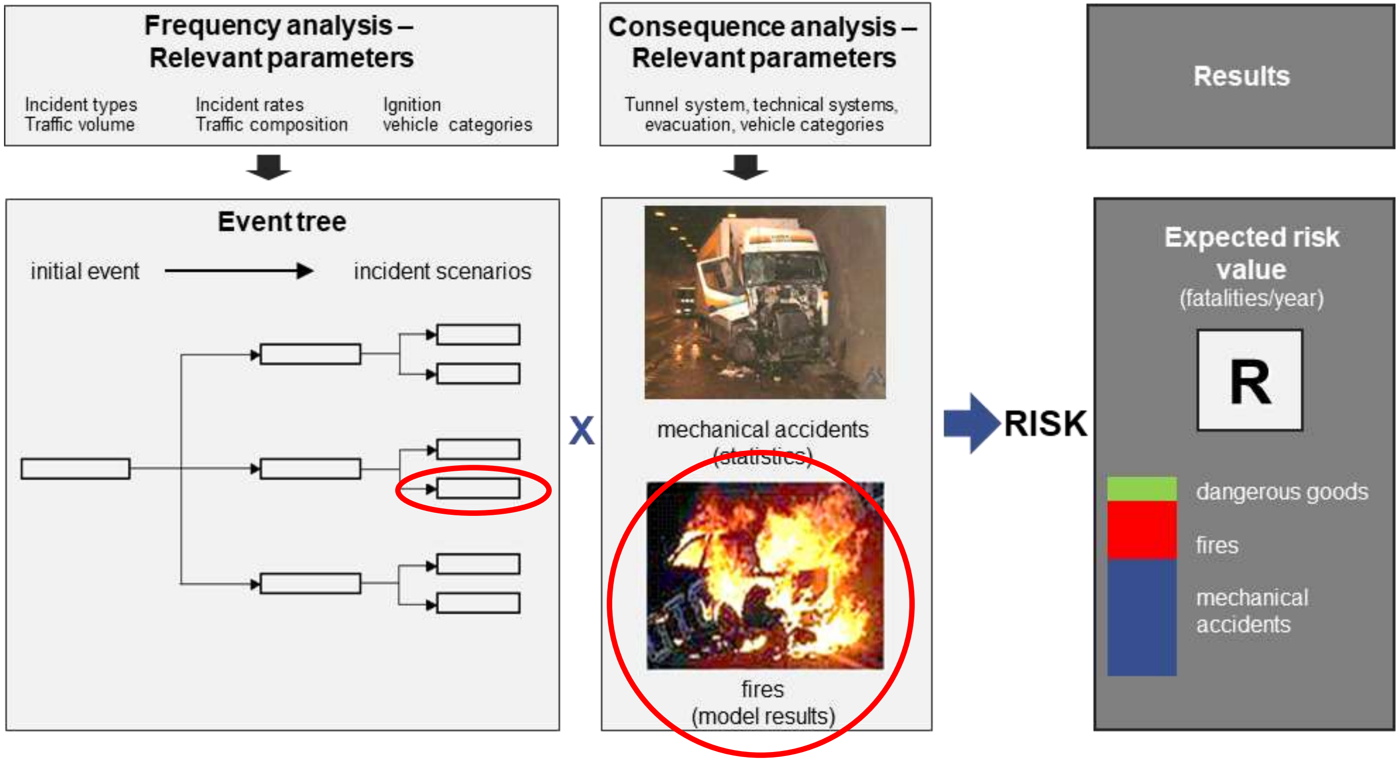
Frequency analysis – basic incident scenarios

- Breakdown or malfunction of a vehicle causing a fire
- Breakdown or malfunction of a vehicle causing a collision *(with or without fire as a follow-up event)*
- Single-vehicle collision *(with or without fire as a follow-up event)*
- Collision between vehicles driving in the same direction *(with or without fire as a follow-up event)*
- Head-on collision *(with or without fire as a follow-up event)*

TOOLS FOR RISK-BASED DECISION MAKING

Methodical approach – Austrian Tunnel Risk Model TuRisMo

Methodical components of TuRisMo (system-based risk model)



TOOLS FOR RISK-BASED DECISION MAKING

Methodical approach – Austrian Tunnel Risk Model TuRisMo

Consequence analysis – workflow for individual fire scenarios

- **Linear fire model** defining fire growth up to maximum HRR
  (3 different model fires – 5 MW / 30 MW / 100 MW)
- **1D airflow simulation:**
  Longitudinal velocity; defines boundary conditions for 3D model
- **3D airflow simulation:**
  Temperature, Concentration of flue gases at walking level (1.6m)
- **Egress simulation:**
  Distances that can be walked
- **Exposure projection:**
  Fatality rate for assessed scenario

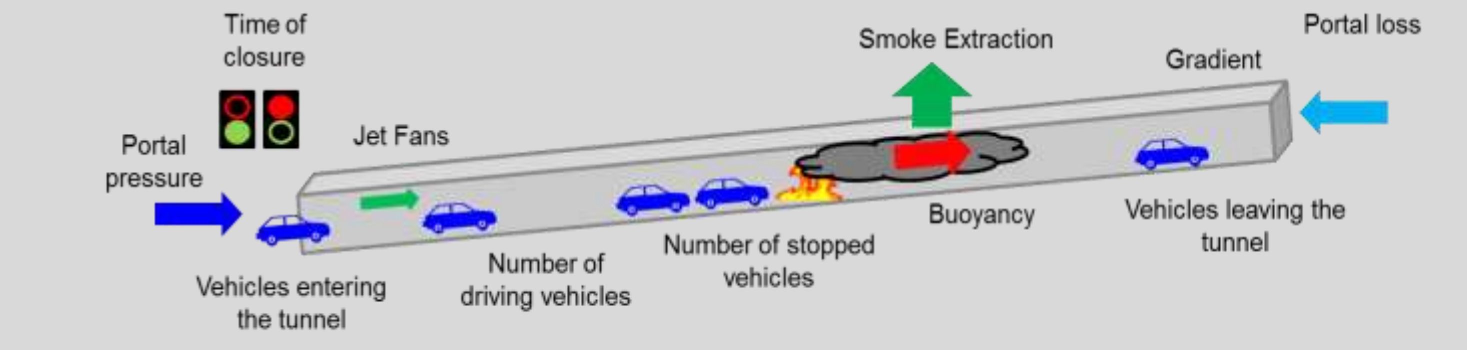
TOOLS FOR RISK-BASED DECISION MAKING

Methodical approach – Austrian Tunnel Risk Model TuRisMo

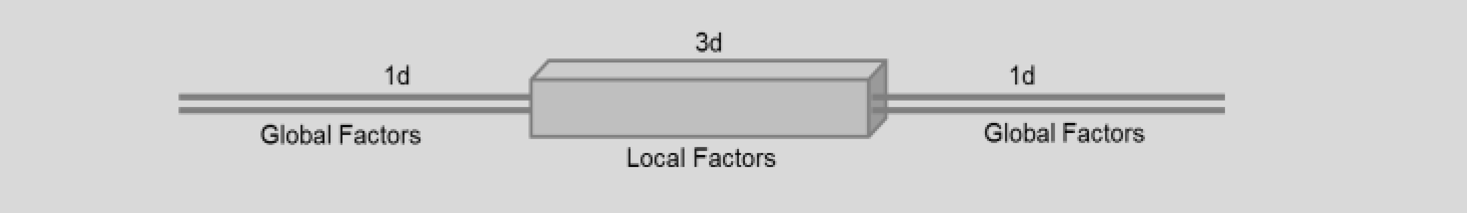
Consequence analysis – fire development and smoke propagation

Parameters covered by smoke propagation model

- Combined transient 1D/3D simulations



- Implementation



TOOLS FOR RISK-BASED DECISION MAKING

Methodical approach – Austrian Tunnel Risk Model TuRisMo

Consequence analysis – egress simulation

Processing of results of smoke propagation simulation

- **Output:** temperature, flue gas concentrations, extinction co-efficient at a height of 1,6m
- **Transferred** directly **into egress model**, influencing the movements of people during evacuation
- **Accumulation-based intoxication model** applied (Purser model): visibility influences walking speed, accumulated physiological effects may cause immobility
- Different types of occupants with different walking speeds are assessed, maximum distance is computed after which a certain type of occupant is incapacitated

TOOLS FOR RISK-BASED DECISION MAKING

Methodical approach – Austrian Tunnel Risk Model TuRisMo

Consequence analysis – exposure projection

- Zones with stopped vehicles are computed
- Distribution function of emergency exits is computed for every point of the domain
- Distribution density of emergency exits combined with distances that can be covered gives the “mortality rate” (people not able to reach a safe zone = emergency exit on their own are counted as “fatalities”)
- Mortality rate and people density give the **fatality rate of one basic scenario**
- This **procedure** is **repeated for all basic scenarios** investigated, covering different fire sizes, different fire locations and different traffic scenarios

TOOLS FOR RISK-BASED DECISION MAKING

Austrian Tunnel Risk Model TuRisMo - application

Examples of tunnel features which can be assessed in the risk model

- **Tunnel geometry**
  - Unconventional or changing tunnel cross sections
  - Gradient with special characteristics
  - Varying emergency exit distances
  - Continuous emergency lane / distance of lay-byes
- **Tunnel safety systems**
  - Special characteristics of individual ventilation system (e.g. varying or insufficient capacity, leakages etc.)
  - Influence of ventilation control over time (e.g. different ventilation strategies)
  - Specific meteorological conditions (e.g. big pressure differences at portals)

TOOLS FOR RISK-BASED DECISION MAKING

Austrian Tunnel Risk Model TuRisMo - application

Examples of tunnel features which can be assessed in the risk model

- **Tunnel safety systems**
  - Effects of fixed fire fighting systems (FFFS)
  - Influence of time delays of incident detection systems
- **Traffic and operation**
  - Specific traffic characteristics variation (specific traffic composition, over time, congestion)
  - Influence of vehicle movements and all measures influencing traffic movements
  - Speed regulation and speed control
  - Type / location of facilities for tunnel closure (e.g. barriers at tunnel entrance, traffic signals inside tunnel)

SAFETY MEASURES

Hierarchy of tunnel safety measures

PREVENTION

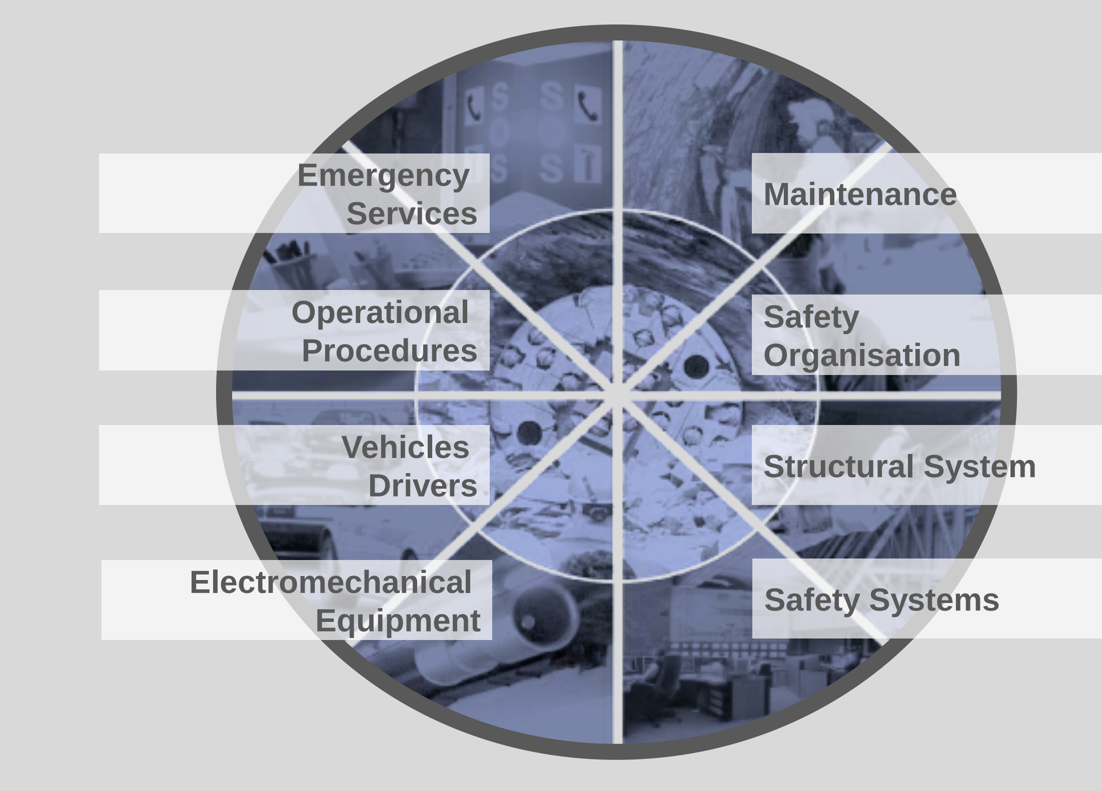
MITIGATION

SELF-RESCUE

EMERGENCY RESPONSE

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

SAFETY MEASURES

Practical example: Lay-Bye

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

- (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)

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

CASE STUDY

Upgrading of existing tunnel - scope

- Tunnel 1.5 km long,
- Bidirectional traffic (13,000 veh/day; 5% HGV traffic)
- Longitudinal ventilation
- No emergency exits

Tunnel does not fulfil minimum safety requirements
emergency exits not feasible due to extreme topographical conditions

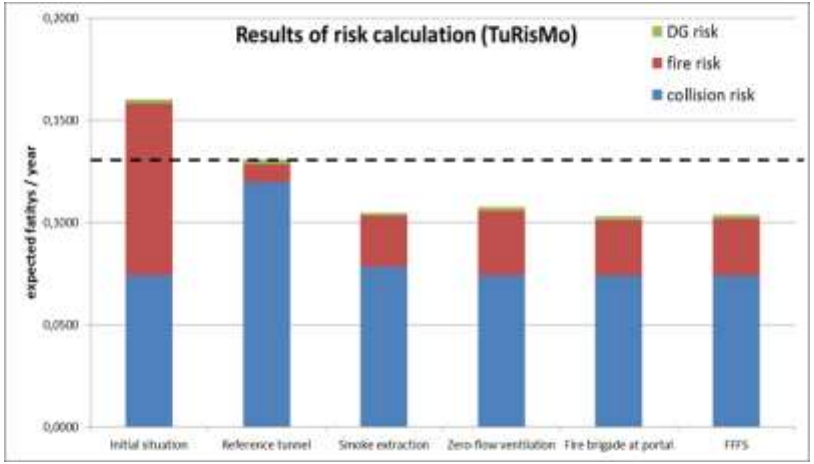
Compensation by alternative measures required

Alternative measures investigated:

a) semi-transversal ventilation with smoke extraction
b) Alternative smoke management (zero-flow ventilation)
c) Implementation of FFFS
d) 24/7 fire brigade located close to tunnel portal

CASE STUDY

Upgrading of existing tunnel - results



Decision on alternative measures based on:

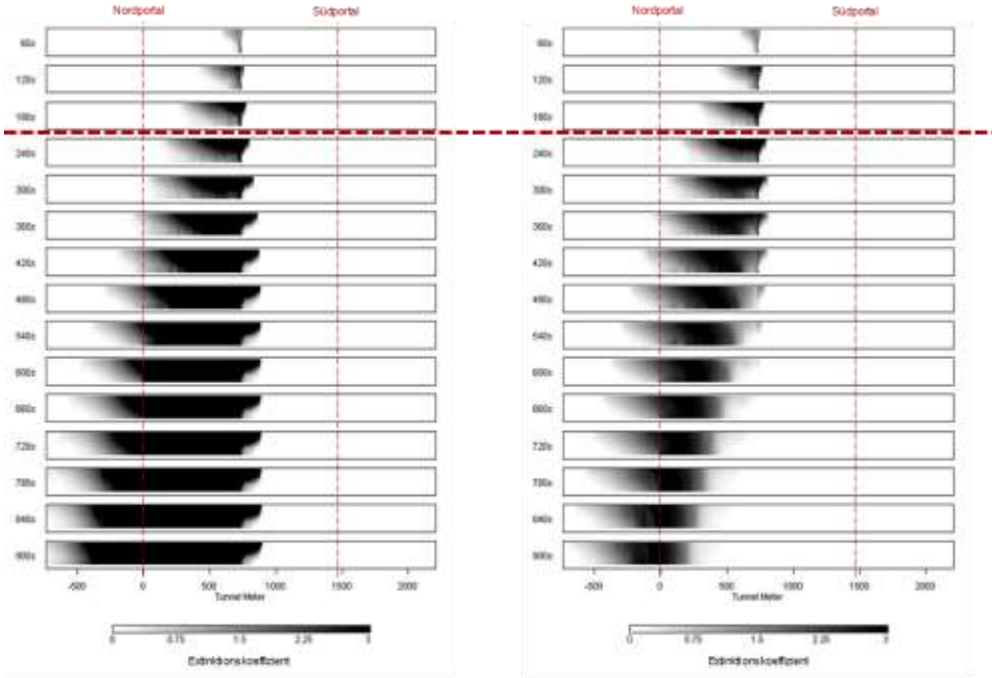
- Results of QRA
- Results of cost-effectiveness analysis of measures
- Qualitative Assessment of additional aspects (like compatibility with fire fighting activities)

Decision in favor of implementation of FFFS

CASE STUDY

Upgrading of existing tunnel - illustration

Measure: fire brigade located close to tunnel portal
Smoke propagation in time steps of 1 minute –
with / without intervention of fire brigade

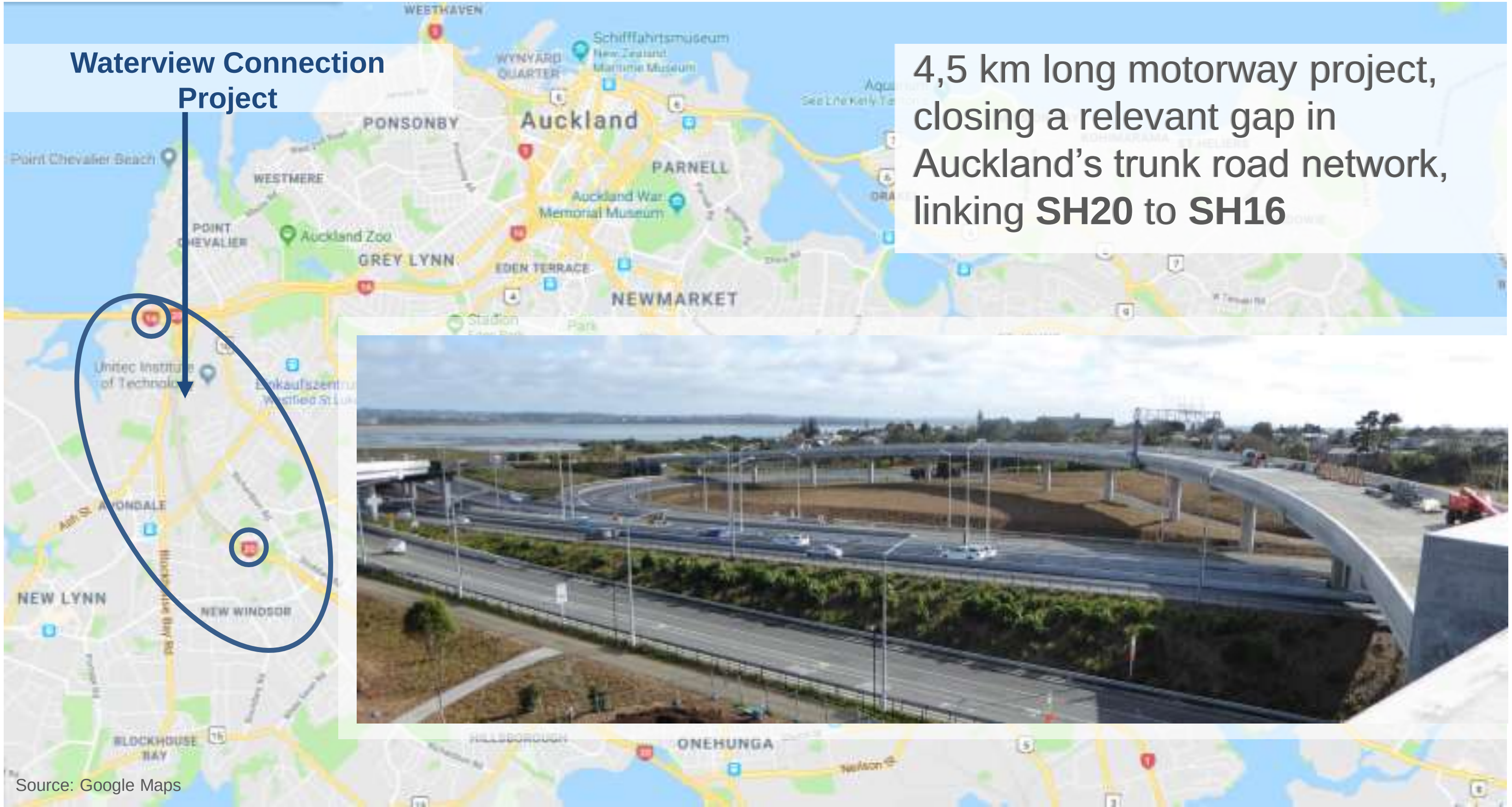


180 seconds

Fire brigade starts fire fighting within 3-5 minutes

CASE STUDY

Commissioning of new tunnel – Waterview Tunnel (NZL)



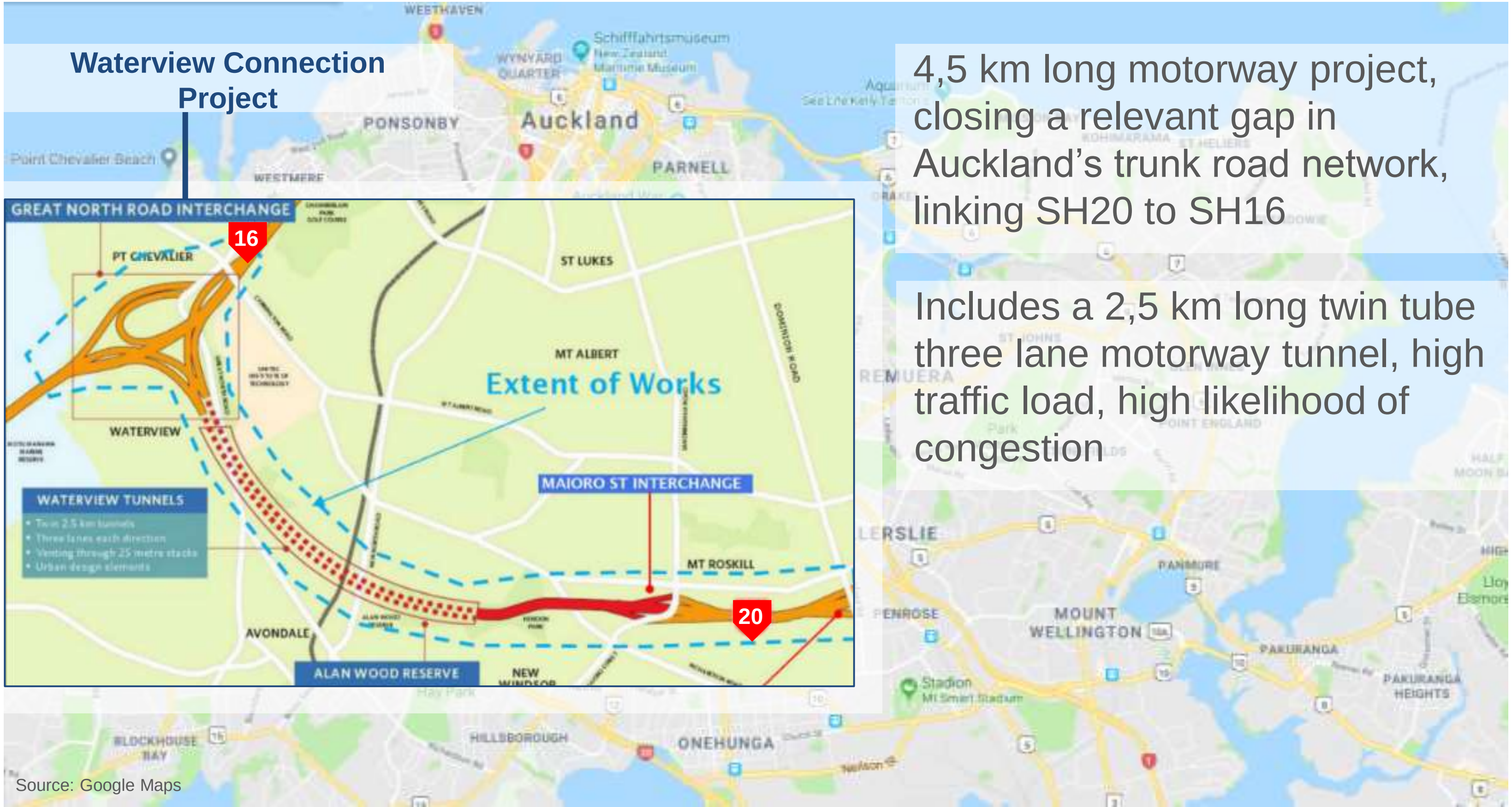
4,5 km long motorway project, closing a relevant gap in Auckland's trunk road network, linking **SH20** to **SH16**

Source: Google Maps

CASE STUDY

Commissioning of new tunnel – Waterview Tunnel (NZL)

Waterview Connection Project



4,5 km long motorway project, closing a relevant gap in Auckland's trunk road network, linking SH20 to SH16

Includes a 2,5 km long twin tube three lane motorway tunnel, high traffic load, high likelihood of congestion

Source: Google Maps

CASE STUDY

Commissioning of new tunnel – Waterview Tunnel (NZL) - scope

Basis:

- Earlier **risk study in design phase**, justifying and specifying safety-relevant tunnel configuration and equipment in detail
- resulting **risk level** was **classified as** being “**ALARP**” (as low as reasonably practicable – hence acceptable), based on a frequency of **congestion less than 1%**
- a **higher level of congestion** should be **avoided** by traffic management measures

Objectives:

- Analyze the influence of a level of congestion > 1% on the personal risk of tunnel users, applying a **system-based quantitative risk model** (Austrian tunnel Risk Model TuRisMo 2)
- as **reference case**, the risk level of the tunnel assuming a **congestion level of 1%** shall be taken – representing the situation which initially was assessed as “ALARP”
- **evaluate the differences in risk** comparing the situation with increasing level of congestion (up to 8%) to the reference case
- identify and **assess additional risk mitigation measures** – as far as required

CASE STUDY

Commissioning of new tunnel – Waterview Tunnel (NZL) - approach

Risk model includes **2 types of congestion:**

- **Congestion as a consequence of a preceding incident** represents initial phase of a congestion period (when the queue is building up), a situation which may induce secondary collisions and fires
- **Congestion due to traffic overload** represents a standing / slow moving queue caused by traffic bottlenecks inside or outside the tunnel; characterized by slow speed – collisions will most probably only cause material damage, but no casualties.

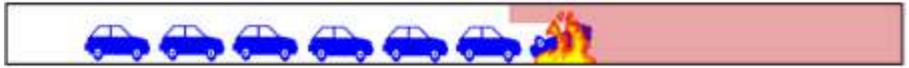
- Congestion caused by traffic bottlenecks is also characterized by a **sudden drop of driving speed at its beginning**
- Initial phase of such congestion **may induce secondary collisions** quite similar to the congestion scenario caused by preceding incidents

CASE STUDY

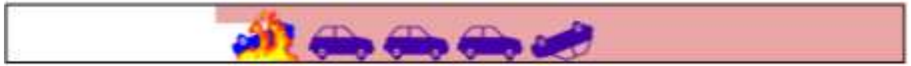
Commissioning of new tunnel – Waterview Tunnel (NZL) - approach

Risk model includes **3 basic fire scenarios**, different in terms of vehicle constellation and airflow conditions

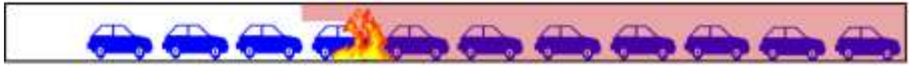
- **Primary fire scenario**: During normal traffic flow, a vehicle has a collision or a break-down and catches fire



- **Secondary fire scenario:** An incident causes a traffic jam. A vehicle hits the rear end of the queue and catches fire

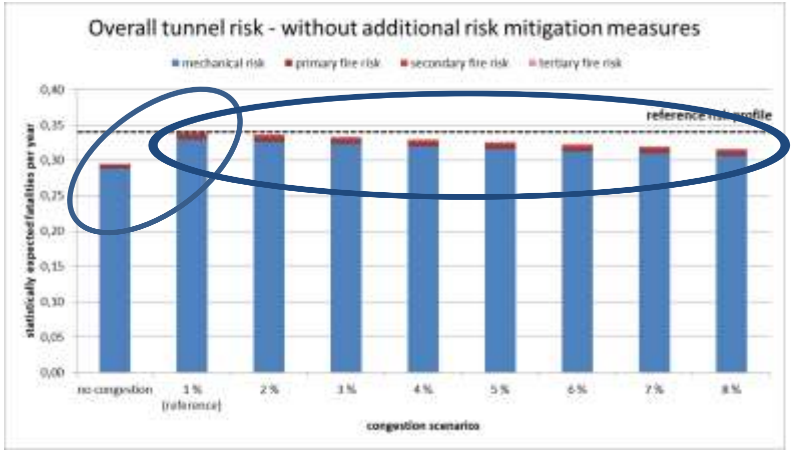


- **Tertiary fire scenario:** A vehicle in a standing / slow moving queue catches fire



CASE STUDY

Commissioning of new tunnel – Waterview Tunnel (NZL) - results



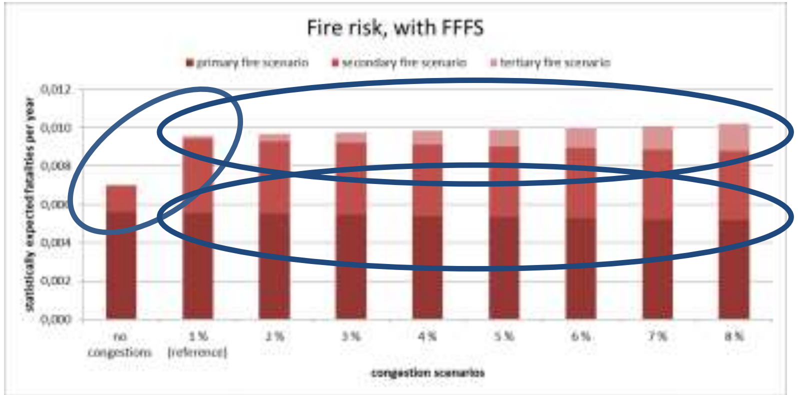
No further risk mitigation measures required to reach a safety level equal to or below the reference risk profile.

- The **collision risk dominates the overall risk** and thus as well the differences in overall risk due to the influence of congestion.

- There is a **significant increase in collision risk** from **“no congestion” to “regular congestion”** 1% of the time
  - due to secondary incidents in the initial phase of a congestion, caused by the sudden drop in velocity
- **Increasing level of congestion reduces collision risk**, because collisions in a slowly moving queue are extremely unlikely to cause casualties (drop in velocity happens just once at the beginning of congestion)
- The **fire risk is very low** – which can be explained by the low likelihood of fire incidents in general, the limited consequences of fires due to the good egress conditions and the effects of FFFS
  - the differences in fire risk due to the influence of congestion are low as well
- The fire risk increases slightly with longer-lasting congested scenarios - influence is negligible in comparison to collision risk

CASE STUDY

Commissioning of new tunnel – Waterview Tunnel (NZL) - results



- Risk related to **primary fire scenarios** (representing a traffic situation without congestion) represents **appr. 50% of the overall fire risk**
- **Risk share of the primary fire scenarios** is slightly **reduced with an increasing level of congestion** – for the same reasons as explained for the collision risk

- The **secondary fire risk** shows a **sharp increase** between a **situation without congestion in comparison to 1% regular congestion**
  - due to the increase in secondary collisions caused by the beginning of congestions
- The **tertiary fire risk** is **increased steadily by an increasing level of congestion**
  - but even in the case with 8% congestion the share in total fire risk is lower than the share of the other fire scenarios
- The three fire scenarios show quite different characteristics
  - the primary fire scenario is characterized by a high frequency but low consequences
  - the secondary and tertiary fire risk is related to incidents with very low frequency but high potential consequences

THANK YOU FOR YOUR ATTENTION!

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