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Risk Analysis Methodology for Road Tunnels and Alternative Routes

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The work includes an overview of road tunnel risk analysis methodologies that have been developed in Europe as a consequence of several major accidents and subsequent Directive on minimum safety requirements for road tunnels. In our analysis, we used PIARC - OECD quantitative risk assessment model (QRAM), which includes the largest choice of different scenarios, tunnel types and traffic parameters. On the other hand, it does not include several risk reduction measures, which we managed to assess in our methodology by combining the QRAM with scenario based analysis in which we used 1D ventilation model, CFD fire model simulation and evacuation model. Apart from this, we present a calculation of risk acceptability criteria for Slovenia. There is also a description of risk assessment procedure and an example case study in which risk assessment of bidirectional and unidirectional traffic through a tunnel is carried out.

Keywords: risk analysis, quantitative risk analysis, road tunnel, tunnel fire, tunnel ventilation, traffic, risk acceptability criteria

0 INTRODUCTION

Risk analysis of road and other tunnels is becoming widely conducted as certain past accidents caused a large number of fatalities and enormous economical damage. Among the most disastrous accidents were the Mont Blanc and Tauern tunnels. The first one killed 39 people and the second one 12, with 50 injured [1]. There was also significant material damage – a large number of vehicles was destroyed and tunnels with their equipment were severely damaged and thus, inoperable. These two events caused major disturbances to the traffic connections in the area as in such mountainous areas alternative routes usually do not provide sufficient backup. Moreover, an unplanned major reconstruction of the tunnels was a costly and demanding task.

The idea of quantitative risk analysis is to calculate the probability for events with a large number of fatalities or material damage to occur in a tunnel. Usually statistical data would provide answers to such questions. However, the data are too uncertain as such events are very rare in tunnels. Therefore, every single major tunnel accident will have a significant effect on statistical data. Also, tunnels are similar only at a first sight, but if they are analyzed in detail, it can be observed that they have different geometry and consist of different construction materials, electrical and mechanical equipment, especially ventilation systems. Meteorological conditions are different in tunnel surroundings as well. Therefore, each tunnel is unique and has to be analyzed separately.

The answer to this problem lies in risk analysis methodologies, which rely on statistical data of frequent events (such as traffic accidents and vehicle fires) and the modeling of less frequent emergency events such as large tunnel fires, including an operation of ventilation and other equipment. The modeling of tunnel ventilation, fire, traffic and evacuation can be a difficult and computationally demanding task. However, considering a random nature of such events and a number of factors that influence them, it is reasonable to simplify the models. For example, ventilation and fire models are implemented either by using 1D, zonal models or simply by the estimation of the affected area, which is based on real data or simulations. Simplification is of great importance as the list of analyzed scenarios is usually long and every scenario can occur in many different ways. For example – a tunnel fire can occur close to the portals or somewhere in the middle. Each case will yield different temperature and smoke distributions inside the tunnel and will, therefore, give tunnel users different chances of self-rescue and survival. Thus, the number of tunnel accident

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victims will depend on the severity of the accident, the number of people caught inside the tunnel and the chances for rescue and self-rescue, among other factors.

The tunnel risk assessment methodologies originate from nuclear and chemical industry, where such an approach has been used for decades. Accidents in this field are rare, but can have major consequences. Therefore, risk assessment methodologies have been applied to identify and minimize the risk for the population and environment.

Widespread development and application of road tunnel risk assessment methodologies has begun after the EU issued a Directive on minimum safety requirements for road tunnels 2004/54/EC [2], also known as the "Road tunnel directive". Along with minimum safety requirements, it also prescribes conditions when it is mandatory to carry out a risk assessment of a tunnel. Consequently, the PIARC – OECD QRA model [3] and [4], Austrian model TuRisMo, the Dutch RWQRA [9] and [6] methodologies were developed among others. The most widely used is the PIARC – OECD model, which can be used to assess risk in currently operating tunnels and alternative routes.

The aim of our work was to determinate the risk acceptability criteria and risk analysis of two road tunnels in Slovenia, where temporary traffic regime was introduced due to reconstruction. The problem arose as there were a lot of factors which influence the risk, but were not included in the methodology.

1 THEORY AND METHODS USED

1.1 Risk Calculation Overview

Several different types of risk can be assessed: individual, societal and impact-based. The individual risk is the probability for an individual to be involved in an accident if they are located in a hazardous area. Societal risk deals with the number of people involved in an accident and frequency of such an accident. Impact based treatment of risk is based on the strength of the impacts that occur (such as increase in temperature, pressure or toxic gas concentrations).

The societal risk R is defined as a product between event frequency F and consequences C [7]:

$$R = F \cdot C\,. \tag{1}$$

The consequences are either fatalities or fatalities plus injuries together. If the economical risk is assessed, the consequence is the cost of the damage caused by the accident.

SR is usually represented by using F-N curves, which are charts with consequences on abscissa and frequencies on ordinate axis. The charts are drawn in the logarithmic scale. Such a chart represents a scale of the accident, which means that it is possible to determine what kind of an accident is expected to occur: a single accident causing 100 fatalities or 100 small accidents causing a single fatality.

Societal risk can also be represented by using the expected value (EV), which is the expected amount of consequences (accident victims) in a certain time period. EV can be calculated from F-N curve by using the following equation

$$EV_s = \sum_{N=0}^{\infty} f_{s,N} N \tag{2}$$

where $f_{s,N}$ is the frequency of an accident with N fatalities. The subscript s indicates the number of the scenario as F-N curves are often drawn for several scenarios (Fig. 1).

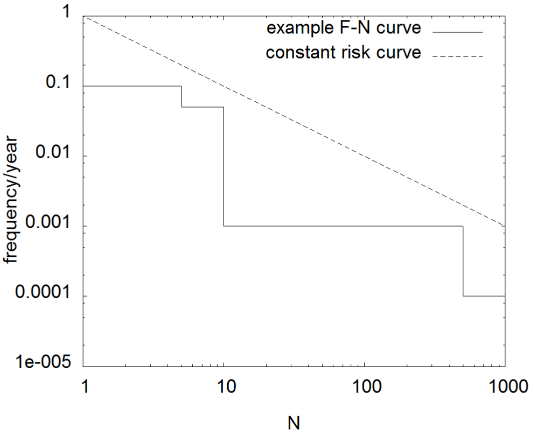

Fig. 1. *An example of F-N curve and a line, representing constant risk*

As the F-N charts are drawn in the logarithmic scale, a line representing constant risk is straight, with an inclination coefficient -1. This property can be shown by calculating the logarithm on both sides of the Eq. 1.

The societal risk is assessed by using the combination of statistical data and the models of events that lead towards the final accident. Such a combination is used as there is usually no sufficient statistical data about the most disastrous accidents because they rarely occur. In other words, there is data on the frequency of traffic accidents, but there is hardly any statistical data on accidents which involve 50 fatalities in tunnels. By combining accident frequency and the probability of a fire that follows an accident and fire simulation, it is possible to tell how often an accident taking a large number of lives can be expected.

1.2 General Risk Assessment Procedure

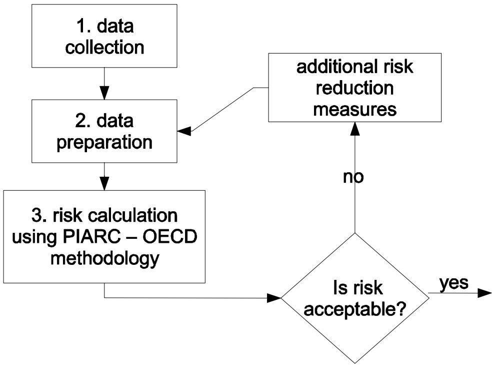

Fig. 2. *Typical risk assessment procedure using PIARC – OECD QRAM model. The risk is recalculated until risk reduction measures are sufficient*

The risk assessment procedure consists of data collection, data preparation (calculation, verification) and risk calculation. In case of a road tunnel risk assessment, the data on traffic, accident frequencies, tunnel equipment and meteorological conditions have to be collected.

The risk calculation is carried out using simplified models, which estimate expected consequences and display results in the form of F-N charts or expected values.

Afterwards it has to be decided whether the risk is acceptable. This is done by comparing it against the prescribed limit. The comparison can also be made against the risk of another tunnel or an alternative route that has been obtained with the same methodology.

1.3 Overview Of Road Tunnel Risk Analysis Methodologies and Tools

The EU Road Tunnel directive [2] only prescribes the conditions when risk analysis should be carried out, but it does not define what kind of methodology should be used. Consequently, several methodologies have been developed. They provide tools for the calculation (quantification) of risk using predefined, simplified models of several accident scenarios. The choices of scenarios are different in each model as it has not been prescribed by the directive, therefore, the calculated risk will depend on the methodology.

During the risk calculation the same fire scenario is simulated several times in different sections of the tunnel. Each of those simulations gives a different result. Usually the final result is the average value of those results, calculated from the frequency of each scenario.

Road tunnel risk calculation output is the expected number of fatalities and injuries.

Different risk assessment methodologies not only consider different scenarios, but are also adopted for different types of routes and tunnels. For example, the Dutch RWQRA has been designed only for unidirectional, longitudinally ventilated tunnels, as there are no tunnels of other types in the Netherlands. On the other hand, Austrian model TuRisMo includes unidirectional and other types of the tunnels. PIARC – OECD QRAM model is the only one supporting open road sections (see Tables 1 and 2).

Basically all of the above mentioned models are meant to be used in iterative process of risk assessment, which includes the steps described in the previous section. A different approach towards risk treatment – risk optimization is described by Holicky [8] and [9].

Table 1. *Overview of the methodologies*

Model	Unidirectional tunnels	Bidirectional tunnels	Alternative routes (open road)
RWQRA	YES	NO	NO
PIARC – OECD	YES	YES	YES
TuRisMo	YES	YES	NO

Table 2. *Model implementations and features*

Model	Type of ventilation supported	Accident-affected area	Implementation	Risk representation
RWQRA	longitudinal	estimated during the calculation execution	stand-alone application	F-N curve, *EV*
PIARC – OECD	longitudinal, transverse	estimated during the calculation execution	Excel application	F-N curve, *EV*
TuRiSmo	longitudinal, transverse	pre-estimated	prescribed procedure (manual calculation)	quantified into classes

It assumes that the tunnel is modeled using Bayesian networks and the optimum risk is found by calculating function minima. The methodology allows the inclusion of risk reduction and consequence costs and optimizes both of them in terms of overall cost.

The most suitable model to be used for our study was PIARC – OECD QRA, as it was the only one supporting open roads and bi-directional tunnels. This was needed as proposed temporary traffic regime was bidirectional.

The above listed methodologies do not include several measures and properties that we intended to assess. The properties required by us were natural ventilation, the effect of driving speed on accident frequency and the relationship between safety barriers and the ability of successful evacuation. To sum up, none of the methodologies include the efficiency of rescue and extinguishing operations.

1.4 The Combination of QRAM Model and Scenario Based Analysis

We have decided to use a combination of PIARC – OECD QRAM and scenario-based analysis, which is shown in Fig. 2. Such an approach enabled us to identify the most dangerous scenarios using QRAM model and to assess a large variety of safety reduction measures using scenario analysis.

The procedure is very useful, when there are one or two scenarios, which give the most significant contribution to the overall risk. In such a case it is convenient to simulate those scenarios in detail in order to define risk reduction measures. To summarize, quantitative risk assessment had been used to identify the most dangerous scenarios, which were afterwards analyzed in detail (Fig. 3).

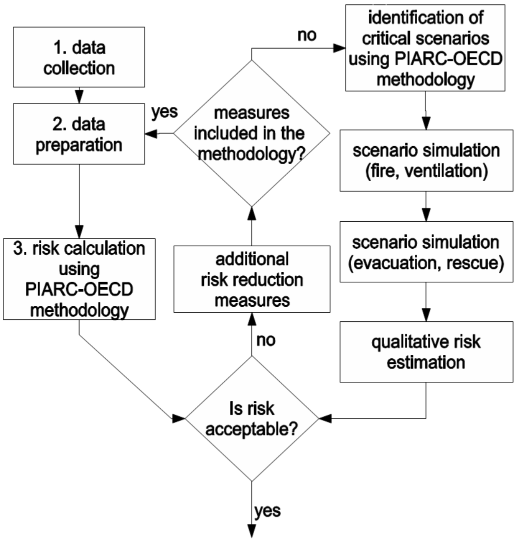

Fig. 3. *Improved approach combines quantitative risk assessment and qualitative critical scenario analysis*

Fire scenario simulation has been performed using a combination of CFD and evacuation model [10] and [11]. The CFD simulation provides the possibility to analyze temperature and smoke distributions inside the tunnel in detail.

The output of this model is a risk table, representing quantified risk for tunnel users during the evacuation.

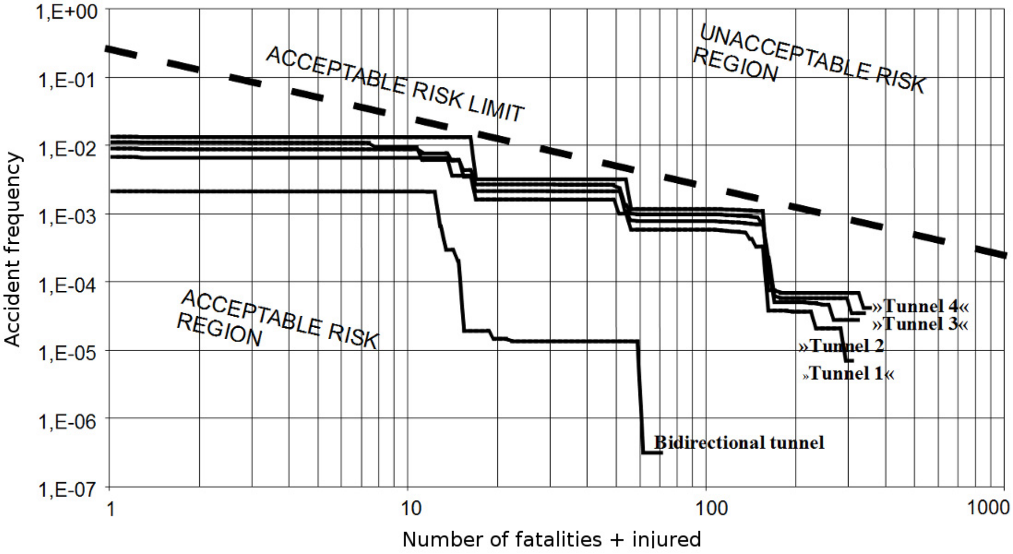

Fig. 4. *Determination of acceptable risk limit; the limit of constant risk is above all the calculated F-N curves*

2 DETERMINATION OF ACCEPTABLE SOCIAL RISK LIMIT

The limit of acceptable risk greatly depends on the environment and the country. In Slovenia, the acceptable risk due to road tunnel accidents has not yet been defined. Our aim was to set an upper margin of acceptable risk to be used in our risk analysis. The approach that we have taken assumes a calculating risk of the worst possible situation that is still permitted by national regulations and the EU directive:

- minimum tunnel width and height (cross section),
- maximum gradient,
- maximum distance between safe havens and cross passages,
- minimum ventilation performance,
- minimum monitoring equipment,
- no restrictions on dangerous goods transport,
- maximum traffic volume, possible for such type of a road.

We repeated the risk calculation on tunnels with different lengths: 1.5, 2, 2.5 and 3 km unidirectional and 3.6 km bidirectional in order to determine the highest still permitted risk. Afterwards, a straight line above the calculated F-N curve was fitted, representing constant risk. The fitted line is represented by the equation:

$$k = F \cdot N^a \tag{3}$$

If drawn in the logarithmic scale, k represents line inclination and a angle. The risk is constant when $a = 1$ (Fig. 4).

The estimated maximum acceptable risk limit is comparable to the Austrian limit, presented in [12]. Considering similar traffic and geographical conditions in both countries, our estimate seems reasonable.

The above risk limit is set as an absolute limit. In some cases the risk is normalized per unit of route length (usually km). This approach is justified by the fact that driving longer distances normally results in a higher risk of an accident. However, risk normalization is not an appropriate approach, when two routes between the same source and destination are compared. Driving between the same source and destination on route which is longer than the optimum should not be favored in comparison to shorter routes.

3 DATA COLLECTION AND ESTIMATION

The required data for risk analysis are traffic data, tunnel geometry and tunnel equipment specification. The tunnel geometry and equipment data only involves listing the installed equipment and tunnel construction description. For this reason it will not be explained in detail.

3.1. Traffic Data and Accident Frequency

The traffic data needed is often either incomplete or not available at all. In such cases it is necessary to either estimate the needed data or to interpolate it using some other similar case - either from another area or country.

Traffic parameters that have major impact on the risk are:

- traffic volume and distribution (personal cars, heavy vehicles),
- dangerous goods transported and
- accident frequency.

The traffic volume can easily be measured or estimated on the basis of historical data. It is usually comprised of the yearly trend and seasonal and daily variations. When estimating values, it is sensible to use a pessimistic estimation of the trend with high traffic volume.

The traffic counters provide information about different vehicle types that pass through counting point. This is required by the risk analysis as vehicle types have a great impact on the risk. If there are only personal vehicles in the tunnel, there is a small risk of major fire. On the other hand if there are many heavy goods vehicles in the tunnel, the risk of fire increases.

The percentage of dangerous goods vehicles and dangerous goods types are more difficult to determine if the tunnel does not have any limitations on dangerous goods traffic. The inductive loops and common traffic surveillance cameras cannot tell if there are dangerous goods transported. There are mandatory marks – ADR tables on trucks, but they are not always placed on the same location (sometimes they are at the front and sometimes on the side of the trailer). There were unsuccessful attempts of automatic detection and reading of ADR tables. Therefore, nowadays it is only possible to tell dangerous goods distribution if it is mandatory to report dangerous goods transport to the authorities. Fuel types that are used have a major impact on accident consequences as well. Recently new types of fuels are being introduced, such as alcohol and hydrogen, which is highly explosive [13].

An estimation of accident frequencies has to be done using traffic data from the same type of road from the same country as the analyzed road. Among road parameters that have impact on the accident frequency are road geometry and surface pavement, which has an impact on braking distance [14]. Motorways, for example, have different accident frequencies than ordinary extra urban or city roads. Also, accident frequencies and consequences vary greatly among countries. The accident frequencies should be expressed in accidents per vehicle km. Sometimes they can be calculated for different vehicle types separately (personal cars, HGVs, coaches).

The accident frequency per kilometer f_{acc} can be calculated as:

$$f_{acc} = \frac{N_{inv}}{N_{all} l} = \frac{N_a \overline{N_{va}}}{N_{all} l} \qquad (4)$$

where N_{inv} is the number of vehicles involved in accidents, N_{all} is the number of vehicles driven through the route and l is the length of the route. The N_{inv} can also be expressed using the number of accidents and the average number of vehicles involved in an accident. When there is no data, a reasonable estimate of $\overline{N_{va}}$ would be 2.

Imposing speed limit as a risk reduction measure is often questioned. Unfortunately, the PIARC – OECD model does not consider speed reduction effect on accident rate. The accident rate is considered constant regardless of driving speed.

For this reason we used the statistical model described in [15], which represents a relation between the change in driving speed and accident rate:

$$\Delta f_{\%} = \left[\frac{53.4}{1+e^{-0.35\Delta v}}\right] - 26.7 \qquad (5)$$

where $\Delta f_{\%}$ is change in accident frequency in % and Δv reduction in driving speed in km/h. The model was obtained using statistical data. The effect of reduced driving speed on accident frequency can, therefore, be calculated as

$$f_{acc,\,l} = \frac{(100+\Delta f_{\%})}{100} f_{acc} \qquad (6)$$

where $f_{acc,l}$ is the accident frequency that has been decreased due to driving speed reduction.

3.2. Ventilation Performance Estimation

The ventilation specification and meteorological data must be collected to calculate the ventilation performance. The PIARC – OECD model requires data on volumetric air flow along the tunnel section $\overset{o}{V}$ for an analysis of a longitudinally ventilated tunnel. In case the tunnel has transverse ventilation, it is also required to determine the air flow extracted from and blown into the section. This data can be collected from tunnel documentation or measured if the tunnel is equipped with calibrated air speed meters. The naturally ventilated tunnels are not supported by the model. By calculating the ventilation performance using the following method, it is also possible to use it for tunnels without mechanical ventilation.

Otherwise it can be calculated using the modified Bernoulli equation [16], which represents pressure drops along the tunnel tube as:

$$\Delta p_{met} = \Delta p_{loc} + \Delta p_{fric} \pm \Delta p_{piston} \pm \Delta p_{fans} \qquad (7)$$

where Δp_{loc} and Δp_{fric} are pressure losses due to tunnel shape and air friction, Δp_{piston} is the change in pressure due to piston effect caused by the driving vehicles and Δp_{fans} is pressure caused by ventilation fans. If there is no mechanical ventilation, the last variable in Eq. (3) can be dropped out.

In Eq. (7),

$$\Delta p_{loc} = \frac{\rho}{2}\zeta v_{air}^2 \qquad (8)$$

are local pressure losses, where ρ is air density and ζ is loss coefficient and

$$\Delta p_{fric} = \frac{\rho\lambda l}{2d_H} v_{air}^2 \qquad (9)$$

are friction losses, where $\lambda$is coefficient, $l$is tunnel length and d_H hydraulic diameter.

The pressure due to piston effect caused by driving vehicles is calculated as:

$$\Delta p_{piston} = \frac{\rho l \gamma_{conv}}{2S_{tun}v_{veh}}(v_{veh} - v_{air})^2 \sum_i S_i \qquad (10)$$

where γ_{conv} is convoy coefficient, S_{tun} is tunnel cross section, $v_{veh}$is vehicle speed and $S_i$is the surface of vehicle i.

The increase in pressure caused by fans

$$\Delta p_{fans} = \sum_j \frac{\rho\eta P_{fan,j}}{2S_{tun}v_{fan,j}}(v_{fan,j} \pm v_{air}) \qquad (11)$$

is calculated from coefficient η, j^{th} fan air velocity $v_{fan,j}$ and fan power $P_{fan,j}$.

Eqs. (7) to (11) yield a non-linear equation for air speed v_{veh} in stable conditions along the longitudinally ventilated tunnel with and without mechanical ventilation. The equation has the following independent variables: tunnel length and cross-section, loss and friction loss coefficient, vehicle speeds, fan speeds and power. The details about the model can be found in the article by Ferkl et al [16].

The meteorological conditions yield remaining part of the Eq. 4 [17]:

$$\Delta p_{met} = \pm\frac{\rho}{2}(\zeta_w v_w^2 + \zeta_{w,t} v_w v_{air}) \qquad (12)$$

where ζ_w and $\zeta_{w,t}$are constants, depending on shape of tunnel portals and v_w is wind speed.

The Eq. 3 has to be solved for air speed along the tunnel using Newton-Raphson or any other method. It is then possible to calculate volumetric air flow along the tunnel from the air speed as

$$\overset{o}{V} = S_{tun} \cdot v_{air} \qquad (13)$$

Therefore, PIARC – OECD QRAM can be utilized for naturally ventilated tunnels by estimating volumetric air flow along the tunnel using Eq. (7), tunnel data and meteorological data from the wind rose of the area.

4 A CASE STUDY EXAMPLE

Our analysis involved risk assessment of a temporary traffic regime due to tunnel reconstruction. The subject of assessment was a road section consisting of open sections and two unidirectional tunnels [20]. The tunnel geometry data is shown in Table 3.

To illustrate the situation, normal and suggested temporary regimes are shown in Figs. 5, 6 and 7. The planned duration of the temporary regime was about 4 months. During this time the traffic had to flow as normally as possible, including undisturbed heavy goods transport, which is important because of revenues from the road tolling.

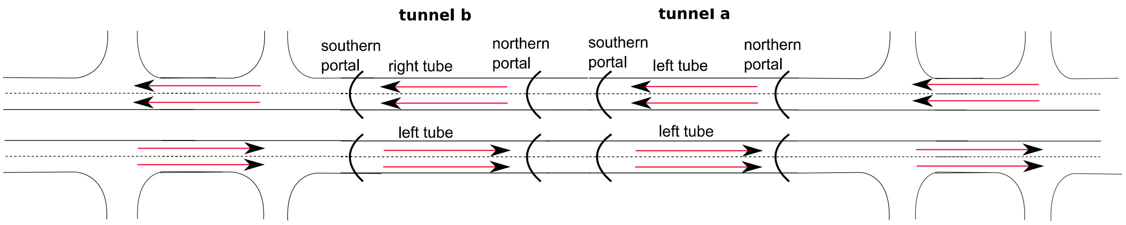

Fig. 5. *Normal traffic situation for double bore road tunnel (F-N curve in Fig. 8, situation 1)*

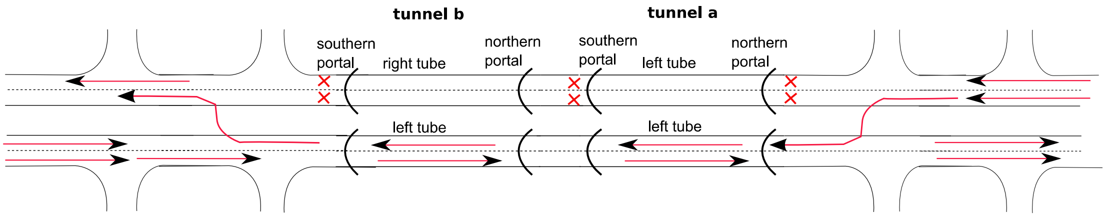

Fig. 6. *Temporary bidirectional traffic regime through single bore, when one is closed (F-N curve in Fig. 8, situation 2)*

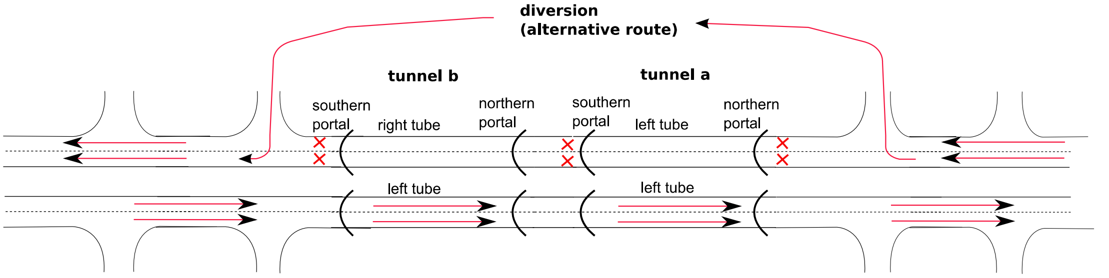

Fig. 7. *Suggested regime with a traffic diversion and one direction unaffected. (F-N curve in figure 8, situation 3)*

Table 3. *Tunnel geometry data*

Tunnel	a	a	b	b
Tube	right	left	right	left
Length [m]	788	757	708	745
Inclination Gradient [%]	2.13	1.91 to 2.62	-2.0 to 1.64	-0.9 to 1.79
Cross section [m^2]	56			
Maximum Height [m]	6.86			
Maximum Inner Width [m]	9.5			
Road Width [m]	7			
Lanes	2			

The problem arose as risk during the temporary regime increased significantly due to:

- high daily traffic volume (24000 to 30000 vehicles) and decreased road capacity
- increased risk of severe accidents in bi-directional areas
- no mechanical ventilation and emergency exits in the tunnel
- no automatic video incident detection
- CO (carbon monoxide) sensors in questionable working condition.

High traffic volume increases the chances for congestion and causes a lack of ventilation due to the absence of the piston effect in the tunnel. Mechanical ventilation is not installed either. Therefore, in Eqs. (3) and (4), Δp_{fans} can be omitted. In case of balanced bi-directional traffic the piston effect almost equals zero, as contributions from both traffic directions are the same. This can be shown by inserting $v_{veh1} = -v_{veh2}$ into piston effect Eq. (10):

$$\Delta p_{piston} = \Delta p_{piston1} + \Delta p_{piston2} = \frac{\rho l \gamma_{conv}}{2 S_{tun} v_{veh}} (v_{veh1} - v_{air})^2 \sum_i S_i n_i + \frac{\rho l \gamma_{conv}}{2 S_{tun} v_{veh}} (v_{veh2} - v_{air})^2 \sum_i S_i n_i \qquad (14)$$

This yields

$$\Delta p_{piston} = \frac{-\rho l \gamma_{conv}}{S_{tun}} \sum_i S_i n_i v_{air} \qquad (15)$$

The Eq. (15) shows that there is no piston effect anymore, but instead vehicles increase air flow resistance by narrowing the tunnel cross-section area.

The air flow through the tunnel depends only on the meteorological conditions and the amount of vehicles in the tunnel, but not on their speed:

$$\Delta p_{met} = \frac{\rho}{2} \zeta v_{air}^2 + \frac{\rho \lambda l}{2 d_H} v_{air}^2 \pm \frac{\rho l \gamma_{conv}}{S_{tun}} \sum_i S_i n_i v_{air} \qquad (16)$$

The air velocity in normal conditions is lower due to a lack of the piston effect. Consequently, the chances that CO concentration inside the tunnel exceeds the allowed limits are quite high.

The CO concentrations were simulated by using the 1D model [18] and [19] and it was discovered that low wind velocity of 1 m/s or uneven traffic establishes sufficient air flow to keep CO concentration below the prescribed limit. In case of the need for ventilation, 10 minutes of uni-directional traffic would be enough to reestablish sufficient air quality.

The calculated risk (Fig. 8) exceeds the acceptable risk limit in case of temporary bidirectional traffic. It was suggested to divert one traffic direction instead of having bi-directional traffic inside the tunnels. This solution yielded a significantly lower risk (Fig. 8, situation 3). It was not favored as the capacity of an alternative route is questionable. Therefore, we had to consider alternative risk reduction measures. As seen from the F-N curves, calculated using PIARC - OECD QRAM, over 70% of the overall risk is contributed by the large fire scenario (20 to 100 MW fire heat release rate), which we analyzed in detail using CFD fire simulation combined with evacuation simulation developed by Vidmar [15]. In Table 4 risks are quantified into LR (low risk), HR (high risk) and VHR (very high risk). The results show that the risk for tunnel users of finding themselves in a life-threatening situation when there is 100 MW fire in the tunnel is significant. The only possibility of a large fire risk reduction was to lower speed limit in order to minimize the accident risk and assure fast rescue and extinction operations.

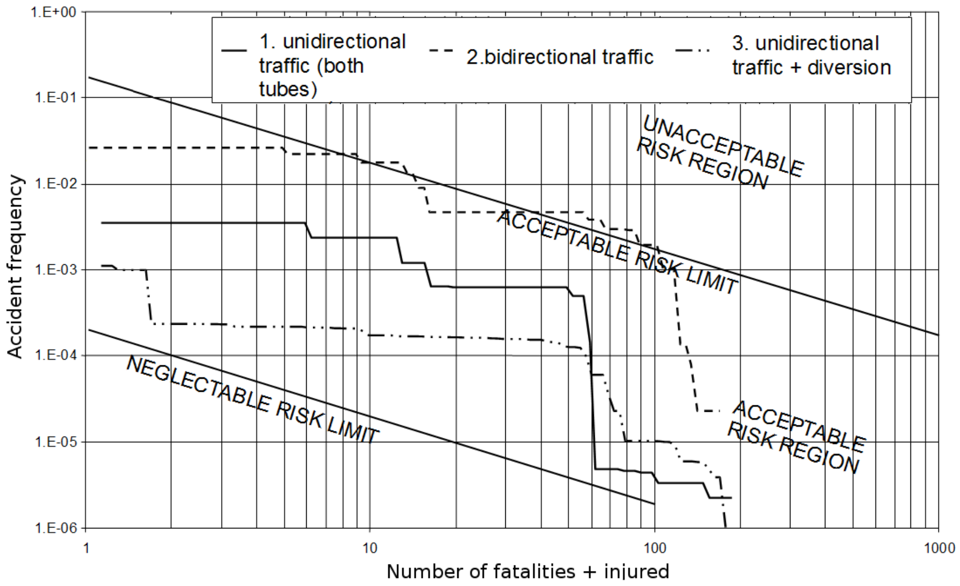

Fig. 8. *Calculated F-N curves for 3 situations: 1 – current condition with both tubes in operation (Fig. 5) 2 – increased risk in case of bidirectional traffic (Fig. 6), 3 – proposed risk lowering measure: diversion (Fig. 7)*

Table 4. *Representation of the risk that tunnel users are exposed to during 100 MW fire with natural and longitudinal mechanical ventilation using the CFD simulation; the resulted risk is shown in two lines for each safety class; the first line represents risk due to heat and second one due to smoke.*

Safety class		Consequences time [s]											
		60		120		180		240		300		360	
HRR	Venti-lation	Dist. N->S	Dist. from fire	Dist. N->S	Dist. from fire	Dist. N>S	Dist. from fire	Dist. N>S	Dist. from fire	Dist. N>S	Dist. N>S	Dist. N>S	Dist. from fire
		330	20N	350	0N	0	350N	500	150 S	50	300N	0	250N
		Starting people position	20S	ppl. pos.	20S	ppl. pos.	140S	ppl. pos.	260 S	ppl. pos.	380S	ppl. pos.	438S
		370		370		490		610		730		788	
		Selfrescue start position	20S	370	20S	Cross passage	140S	Cross passage	260 S	Cross passage	380S	Cross passage	438S
		370				490		610		730		out	
100 MW	natural	LR		HR		HR		HR		LR		LR	
		LR		VHR		VHR		HR		LR		LR	
	longitu-dinal 6 m/s	LR		LR		HR		HR		LR		LR	
		LR		VHR		VHR		VHR		LR		LR	

5 CONCLUSIONS

We have presented a risk assessment approach, which combines the standard PIARC – OECD QRA model with additional simulations in order to minimize risk in a way that it can be compared with the prescribed limits set by regulations. Our method gives the possibility of minimizing the risk by using safety measures not found in the original model. This has been achieved by combining several models, like driving speed – accident probability, ventilation and evacuation simulation. The parameters that we assessed and which are not included in the original methodology are: natural ventilation, accident rate due to speed reduction and early rescue and extinguishing intervention.

In order to determine risk acceptability, we presented a method of setting acceptable risk limit based on regulations. The results are comparable with the limit that is used in Austria, which is a country with similar traffic conditions.

6 NOMENCLATURE

List of symbols

R	risk [fatalities/year]
F	frequency [1/year]
C	consequence [fatalities]
EV_S	expected value of the risk for s-th scenario [fatalities/year]
$f_{S,N}$	number of victims
N	number of fatalities
f_{acc}	accident frequency per kilometer of a road [1/km year]
$f_{acc,\,l}$	reduced accident frequency [1/km year]
$\Delta f_{\%}$	change in accident frequency [%]
Δp_{met}	pressure due to meteorological effects at the tunnel portals [Pa]
Δp_{loc}	local pressure drop [Pa]
Δp_{fric}	pressure drop due to friction [Pa]
Δp_{piston}	pressure due to piston effect caused by the driving vehicles [Pa]
Δp_{fans}	pressure due to fans [Pa]
v_{air}	longitudinal air speed through the tunnel [m/s]
v_{veh}	vehicle driving speed [m/s]
$v_{fan\,j,}$	fan air velocity [m/s]
v_w	wind speed at the tunnel portals [m/s]
$\overset{o}{V}$	volumetric air flow along the tunnel [m^3/s]
ρ	air density [kg/m^3]
ζ	local loss coefficient
λ	friction loss coefficient
γ_{conv}	convoy coefficient
η	tunnel fan efficiency coefficient
l	tunnel length [m]
d_H	tunnel hydraulic diameter [m]
S_{tun}	surface of tunnel cross section [m^2]
S_i	frontal surface of i-th vehicle [m^2]
$P_{fan,\,j}$	fan power [W]

List of abbrevations

PIARC	World Road Organization
OECD	Organisation for Economic Co-

	operation and Development
QRA	Quantitative Risk Analysis
QRAM	Quantitative Risk Analysis Model
TuRisMo	Austrian Tunnel Risk Model
RWQRA	The Dutch Model for Quantitative Risk Assessment of Road Tunnels
EV	Expected Value
F-N	Frequency – Number
HGV	Heavy Goods Vehicle
ADR	The European Agreement concerning the International Carriage of Dangerous Goods by Road
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide

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