RISK EVALUATION IN ROAD TUNNELS BASED ON CFD RESULTS

by

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Original scientific paper
https://doi.org/10.2298/TSCI201108174V

Approaches to risk assessment in tunnelling and underground spaces were introduced in 2004 as a result of several serious accidents in tunnels such as Mont Blanc and Tauern Tunnel in 1999. The EU has published the minimum safety requirements for tunnels over 500 m on Trans-European Road Network. The risk assessment is mandatory and should cover all components of the system, i.e. infrastructure, operation, users and vehicles. The professional community has started using the quantitative risk assessment approach, where the crucial issue is the consequence analysis of fire scenarios in a tunnel. Fire development is a complex physical phenomenon and its calculation is time consuming, therefore, complex models have rarely been used in quantitative risk assessment approaches. This paper presents the methodology of integrating fast-processing risk assessment methods with time-consuming CFD methods for fire consequence analysis in the process of tunnel safety assessment. The main variables are soot density and temperature, which are analyzed in one-minute time steps during the fire. Human behavior is considered with the evacuation model, which is needed to evaluate fatalities during the fire process. The application of the methodology is presented based on the evaluation of the national tolerable risk for tunnel transport and compared with referenced EU risk criteria. Furthermore, the presented methodology links CFD simulation results and the quantitative risk assessment approach, still representing the collective risk with F-N curves.

Key words: *tunnel safety, fire safety, risk assessment, CFD, F-N curves, quantitative risk assessment*

Introduction

Risk assessment studies and specifically fire consequence analyzes usually apply fast computation models [1]. A risk assessment is a multicriteria process that requires a network approach for process and hazards identification. The followed events are systematically analyzed with a Bayesian network, events tree, faults tree, and other well-known approaches [2, 3]. The gap in most risk assessment approaches is the connection between a systematic risk identification and a precise calculation of fire consequences. The main reason for that is the incompatibility of approaches.

After the entering in force of EU directive 2004/54/EC on minimum safety requirements for tunnels the risk assessment methods were proposed by PIARC [4] with the quantitative risk assessment model (QRAM). Other tools and methodologies for risk assessment in

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road tunnels were developed: the Dutch RWQRA model [5] and the Austrian RVS 09.03.11-TuRisMo methodology. The fire consequence calculations, as a main part of risk evaluation, are done with a simple 1-D flow model or at most with the zone models approach. These models cannot cover a specific flow dynamic, smoke stratification, influence of different ventilation systems, vorticity, cross-flow. Effects like backlayering are modelled directly in 1-D models, but its reliability is scenario dependent and is not reliable, or in other scenarios overestimated [6]. A methodology for fire safety evaluation, which improves existing methodologies based on a deterministic approach is more reliable, as the approach to integrate CFD consequence results in a statistical QRA method.

The presented paper explains the upgrade of authors' work on fire modelling applying CFD models [7, 8] for different standard fire scenarios and includes basic human behavior during evacuation. These consequences are further multiplied with the probability (likelihood) of the same events and the result is the individual risk for fatalities or injuries for fire events in tunnels. Vidmar and Petelin [8] has presented the systematic approach on preparation of the tunnel numerical models, their processing and validation. The summarized process of numerous scenarios was presented in a large risk matrix, presented here in section *Consequences of tunnel fire*, which provides the perspective of risk variation as a function of fire source, different types of ventilation, and human behavior during evacuation. The conclusion that a larger fire leads to more severe consequences is obvious and increases with the time of evacuation. The consequences are even more uncertain when ventilation is different, natural, and forced. Natural and cross ventilation are less efficient compared to longitudinal ventilation; therefore, when conducting risk assessments, the focus should be on reliable consequence models, as it could be CFD. The next step after obtaining reliable consequence results is to incorporate them into the risk assessment model using risk criteria and limit the risk to acceptable unacceptable limits. The approach is presented in the following sections.

Methodological approach regarding tunnel safety

The risk evaluation is here divided into two approaches. The first is the assessment of events that lead to a fire accident and the second is the evaluation of fire consequences obtained from CFD. Road tunnels are designed to be controlled systems, and thus more reliable than *natural* ones. Similarly, to an industrial process, where safety risk assessment has been introduced first, a traffic flow in a tunnel is a controlled process. The structure of the tunnel, the control of the traffic and safety systems, are intended to maintain control of all events that could happened in operational and emergency situations. Hazards that lead to the tunnel accident and fire are widely described in [4, 9] and in the description of the PIARC-QRAM [10] and are not a not repeated in the paper. The event tree for a gasoline spill from QRAM is used in this paper as a reference to present the possibility of implementation of CFD results for scenarios risk evaluation.

Although the CFD model set-up and processing is more time consuming than hazards identification, the results are more reliable than from any other fire model. This is why all the events following the fire, like evacuation, emergency ventilation, and intervention, become meaningful and could be organized in a better way, reducing the risk. The paper is therefore focused mainly on fire events and the risk to people during the evacuation time. Fire development and spread is a complex phenomenon and CFD programs are reliable and useful for simulations [11]. The authors [12-15] have conducted a large number of validation tests archiving the reliability of results in a range of 20% to 30% compared to experimental tests.

Also, the authors conducted validation tests of the tunnel models applying the program fire dynamic simulator (FDS) with Memorial Tunnel experiment results. Validated models are further used on a simulated tunnel including fire source characteristics, ventilation system protocol, tunnel geometry and others as well as their reciprocal interactions. Results from these simulations are used in the research as the input for consequence evaluation and risk assessment, improving the reliability of the QRA model.

Risk criteria evaluation

Risk acceptance criteria are the limits above which a tunnel operator will not tolerate risk on the installation. Authors like Trbojevic [16] and Lohansen [17] have emphasized the individual risk criteria based on national standards and EU community guidelines. The harmonization of risk acceptance criteria for the transport of dangerous goods is described in the final report of a DG-MOVE project in the Risk Analysis for Road Tunnels report of [10, 18]. Harmonised estimations of fatalities and injuries have been proposed, based on a common value of € 1.5 million depending on proportion per capita income, but this is only a proposed value. No national regulation (law) exists with a defined fatality value to be used for risk acceptance criteria definitions, rather national guidelines are used, but studies often refer to reports like those of the EC or PIARC. A fully harmonised value of preventing a fatality (VPF) in EU has not been adopted because it would fail to take account of their ability to invest in risk control options. The VPF per fatality is used to indicate where risk prevention measures are applicable or practicable. The introduction of the VPF is understood as the value itself, and how it could be calculated, but the use of VPF as risk criteria is essentially misguided. The risk criteria are better when based on the economic value of the business. The value of 1.5 million per fatality (fat.)is about equivalent to an average sum of income of a person in 40 years of worktime. The valuation of human life on this basis would not be socially appropriate, because it is assigning a price to a human life [19]. It could only be the measure of the low acceptance criteria. The upper should always be based on the economic value of the business. Through this the potential annual loss of lives is calculated as:

$$PLL_{\mathrm{A}} = rEV \tag{1}$$

where r is the number of fatalities in tunnels divided by the financial contribution of the traffic transport. The financial contribution is in our case the share of the transport activity of the national GDP. The EV is the economic value of the business and represents the overall economic savings of tunnels as opposed to alternative roads. Based on this approach values change yearly depending on general national economic activity. Deriving from the equation of the collective risk, $PLL_{\mathrm{A}} = \Sigma_{N=1}^{N_{\mathrm{u}}} N f_N$ the potential loss of lives is based on cumulative risk, obtained as a sum of all individual risks. Here N and N_{u} represents the number of fatalities and the maximum number of fatalities in tunnel accidents, respectively and f_N is the occurrence probability obtained from accident statistics.

Values for consideration are taken from Slovenian publicly available information evidence where the transport contribution represents about 10% of GDP and is $4.5 \cdot 10^3$ million €. The economic savings of tunnels are calculated in cost benefit analysis like by Ayalon [20] and includes time savings, fuel savings, air pollution savings and noise savings benefits. The savings estimation used in this analysis is about 5.7 million €/km per year. The overall EV savings for our nation's tunnels is about 270 million € per year. For the year 2017, r is calculated to 0.667 fat./1000 million €. Converting this ($1/r$) to risk acceptable cost per fatality yields 1.5 1000 million €/fat. As the values are high the costs are measured in 1000 million €, what means 1 billion €. Compared to open road transport the risk level acceptance criterion is about 20 million €/fat., for cruise shipping about 1.5 fat./billion € and so on. The PLL_A is calculated from eq. (1) and results in 0.18 fat. per year for all tunnel length in 2017.

$$F = \frac{PLL_\text{A}}{\sum_{N=1}^{N_\text{u}} \frac{1}{N}} \tag{2}$$

where F is the frequency of accidents involving one or many fatalities, N_u – the upper limit of fatalities in one accident (50 for a bus), and PLL_A annual potential loss of lives.

The tolerable risk, from eq. (2) is calculated for the year 2017 and is $4.7\cdot10^{-2}$ fat. per year. The upper tolerable limit is obtained by multiplying the value of the tolerable risk by a factor of 10, obtaining $F_\text{upper} = 4.7\cdot10^{-1}$, and the lower limit by multiplying by a factor of 0.1, obtaining $F_\text{lower} = 4.7\cdot10^{-3}$. The range between the tolerable limits is the as low as reasonably practicable (ALARP) region. The final risk acceptance criteria could still be based on national safety policy with lower limits. Tables and 2 show the calculated value and the procedure of evaluating how the risk criteria are based on the economic share of the tunnel transport.

Table 1. Risk criteria evaluation

Input values	Parameter	Value	Denotation
To establish risk evaluation criteria for drivers	r	0.667	fat./1000 million €
Economic value	EV	269.182	[million €]
Maximum fatalities	N	50*	Fatality
Calculated values	Parameter	Value	Denomination
Sum 1/N	1/N	4.41	[1-50]
Potential loss of lives	PLL_A	$1.79\cdot10^{-1}$	fat. per year
Tolerable one or many fatalities	F	$4.07\cdot10^{-2}$	fat. per year
Upper border ALARP	F_upper	$4.07\cdot10^{-1}$	fat. per year
Lower border ALARP	F_lower	$4.07\cdot10^{-3}$	fat. per year

* Author choice

Comparing the calculated tolerable risk for one fatality with PIARC, we can see the differences. The calculated tolerable risk is $4.07\cdot10^{-2}$ fat. per year and PIARC uses $1\cdot10^{-3}$ fat. per year. According to the above model this risk could be obtained if the statistics of fatalities in tunnels would be 0.2 fat. per year or one fatality every five years.

We can realize here that the current benefit of tunnel transport allows the risk that is actually higher than the consolidated risk in the EU. In practice this is understandable as the social acceptability of risk is not only a matter of a particular risk calculation but also a matter of policy decision counting different aspects of social level of a country and a wider community.

Consequences of tunnel fire

As the consequences represent the second part of the risk calculation the idea of the study is to investigate how the differences of results between a simple fire model and CFD

Table 2. Economic value of tunnel transport

Input values	Value	Denotation
Savings for the tunnel per year*	$3.15 \cdot 10^1$	[million €]
Tunnel length	5.5	[km]
GDP**	$4.5 \cdot 10^4$	[million €]
Transport share (10%)	$4.50 \cdot 10^3$	[million €]
Number of fatalities per year in tunnels	3	[fat. per year]
Overall tunnels	47	[km]
Calculated values		
Savings for one km tunnel	5.727	[million €/km]
Overall savings on tunnels	269.2	[million €]

* Ayalon, O., *et al.*, *Evaluating Market Benefits of Transportation Tunnels – The Carmel Tunnels as a Case Study*. Journal of Environmental Protection, 2016. **7**: p. 1259-1272, ** Official notice, 2018

model influence the calculation of the risk. The CFD model is applied for fire development in the tunnel and smoke propagation. Vidmar and Petelin [8] have already conducted deep research on fire dynamics in tunnels applying CFD methods. The program used for CFD modelling is FDS that has been validated by the authors for their specific scenarios, and has also been widely validated by other researchers [12-15].

The fluid-flow is modelled by solving the basic conservation equations. Those are conservation of mass eq. (3), conservation of momentum eq. (4), and conservation of energy eq. (5), using a form for a low Mach number [11]. The approximation involves the filtering out of acoustic waves. Additionally, the equation of preservation of the mass fraction of the component is solved eq. (6) related to the equation of state eq. (7).

$$\frac{\partial \rho}{\partial t} + \nabla(\rho u) = 0 \tag{3}$$

$$\frac{\partial(\rho Y_\alpha)}{\partial t} + \nabla(\rho Y_\alpha u) = -\nabla J_\alpha + w_\alpha \tag{4}$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla(\rho u u) = -\nabla p^* + \rho \mathrm{g} \tag{5}$$

$$\frac{\partial(\rho h)}{\partial t} + \nabla(\rho h u) = \frac{Dp_0}{Dt} + Q - \nabla q \tag{6}$$

$$p_0 = \rho \mathrm{R} T \tag{7}$$

where ρ is the density of the liquid (does not change with temperature, but only in time), ∇ – the gradient of the vector field, p^* – the pressure change due to the movement of the liquid, p_0 – the ambient pressure, R – the general gas constant, T – the ambient temperature, g – the gravitational acceleration, Q – (α) in the mixture, and Dp_0/Dt, $\partial/\partial t + u\nabla$ – a material derivation. The mass-flow due to diffusion of a liquid is defined as $J_\alpha = \rho D_\alpha \nabla Y_\alpha$ with mass diffusivity D. The heat flow is defined:

$$q = -k\nabla T - \sum_{\alpha} h_{\alpha} J_{\alpha} + q_{\rm r}$$

where k is the thermal conductivity and $q_{\rm r}$ – the surface density of the radiant heat flux. In the energy conservation equation, the enthalpy of the system is written $h = \Sigma_{\alpha} h_{\alpha} Y_{\alpha}$ where $h_{\alpha} = \int c_{p\alpha} {\rm d}t$. The previous equations are written in the form that applies to a non-viscous liquid. The special feature of FDS is that the basic equations are added to the turbulent description model, at the sub-grid level, by means of constant coefficient of the Smagorinsky model, 0.2. The standard turbulence model uses the large eddy simulation (LES) method. The combustion model is based on the assumption that combustion is mixture controlled. This implies that all species of interest can be described by the mixing fraction Z. The heat from the reaction of fuel and oxygen is released along an infinitely thin layer where Z takes its stoichiometric value determined by solving the transport equation for Z. The state relations are calculated for a stoichiometric reaction of C_7H_{16}.

The FDS uses a non-iterative pressure solver to properly couple the pressure and velocity fields and is spatially and temporally accurate to second order, so better accuracy is achieved with finer grids. Using a direct pressure solver is fast and accurate, but the limitation is that only a uniform grid is used. A numerical scheme is *consistent*. According to the Lax convergence theorem, the scheme is both consistent and stable and the numerical solution of the discretized equations will *converge* to the exact solution of the PDE when dx and dt approach 0. The lattice independence analysis for the gas dispersion and the optimal lattice density is set (which is given below for each scenario) so that the cell aspect ratio is 1×1×1 in the Cartesian co-ordinate system. The combination of the CFL, von Neumann, and divergence time-step constraints ensures stability and (assuming our numerical procedures are consistent) thus convergence.

Tunnel fire scenarios

Simulations of tunnel fires are conducted using 12 tunnel scenarios. Three levels of fire source from 20 MW, 50 MW, to 100 MW are simulated assuming four ventilation protocols from the less to the more effective: natural, longitudinal, semi transverse and transverse.

The modelled tunnel is 650 m long, 9.5 m wide, and 8.5 m in height or 6.5 m when the roof is lowered for transverse ventilation channels. The fire is located 350 m from the portal in all the models, differing only in the size of the burning area. The calculation of the 12 scenarios is done on a server computer with four eight core processors and 64 GB RAM memory. The discretization of each model is from 0.8 M to 1.5 M mesh points. The initial and boundary conditions as a numerical discretization are specific for each model, depending on fire source size, ventilators positions, air extraction openings and the conversion stability of the model. These parameters are based on findings from the validation tests that are briefly described in the following section to understand the reliability of the results. The main parameters for simulations are listed in tab. 3. Parameters for the hear release rate (HRR) of different fire source are selected according the design fires in PIARC [10], the number of ventilators and their characteristics is taken from different design project but is similarly referenced by memorial tunnel tests [21]. Similarly the HRR dynamics and the ventilators dynamics is defined according the design characteristics [12, 15].

Table 3. Boundary and initial conditions for different types of ventilation

Ventilation/Boundary and initial conditions	Longitudinal	Transverse
Portals	Open boundary condition	
Walls	$T_{\text{initial}} = T_{\text{environment}}$; $I_{\text{radiation}} = I_{\text{black body}}$; $v_{\text{wall}} = 1/2\ v_0$	
Fire source	20 MW – 6 × 3 m – 1333 kW/m^2, 50 MW – 10 × 3 m – 1666 kW/m^2 100 MW – 15 × 4 m – 1666 kW/m^2	
Longitudinal ventilators	6 × 2 ventilators, $v_{\text{vent.}}$ = 30 m/s	–
Transverse ventilators	–	Intake: 101 × 0.64 m^3/s Exhaust: 3 × 53 m^3/s
Air intake	Through portals	Through import ventilators Through portals
Source dynamics	T = 0.0, F = 0.5, T = 120.0, F = 1.0, T = 500.0, F = 1.0, T = 900.0, F = 1.0	
Longitudinal ventilation dynamics	T = 0.0, F = 0.0, T = 500.0, F = 0.0, T = 560.0, F = 0.5, T = 720.0, F = 1.0, T = 1800.0, F = 1.0	–
Transverse ventilators dynamics	–	T = 0.0, F = 0.0, T = 60.0, F = 0.0 T = 120.0, F = 1.0

Model validation

The CFD model of the tunnel has been the first validated with experimental data from the memorial tunnel test program [21]. The core part of the validation analysis is presented in [8] and is here additionally interpreted through means of risk relevant zones during the fire spread. The validation is focused on two different scenarios, a 50 MW fire with natural ventilation and a 100 MW fire with longitudinal ventilation. The geometry of the tunnel is presented in fig. 1.

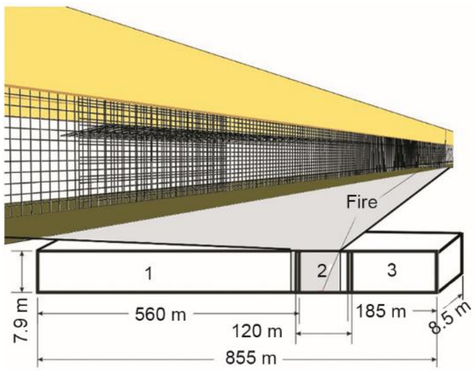

Figure 1. Geometry and mesh set-up

The HRR from the source is 2700 kW/m^2, where the burning is modelled based on the stochiometric equation:

$$11O_2 + C_7H_{16} \rightarrow 7CO_2 + 8H_2O$$

where C_7H_{16} is a heptane, which burns very similar to a diesel oil with less soot release. This is additionally added as product to the combustion model. The space discretization of the mass equations, motive quantity and heat energy is derived with the method of finite difference in the central differential scheme in a square net. The time discretization of the transfer equations is made on an explicit scheme of predictor-corrector. The length of the domain is 855 m divided in three zones, where the central zone – 2 is the fire zone with cell size of 0.3^3 m and the rest of the domain applies a coarser mesh [22]. The geometry of the memorial tunnel model is very similar to the tunnel model analyzed in the research where 12 scenarios have been processed. The difference is mostly the length of the tunnel, but this does not significantly affect the results. The model validation is used also to assess the numerical model of the tunnel and the definition of the appropriate discretization scheme. The FDS uses a finite difference discretization and 800000 cells for the 50 MW fire and 1300000 cells for 100 MW fire are found to be appropriate to fulfill the convergence criteria of the simulation and give comparable results between the experiment and simulation results [8].

The compared data presented here are temperatures measured with thermocouples in the experiment and observed in a simulation. There are 14 observation points selected at 2.5 m and 6.5 m from the floor placed every 100 m from the left portal. The position of the thermocouples is visible in fig. 2.

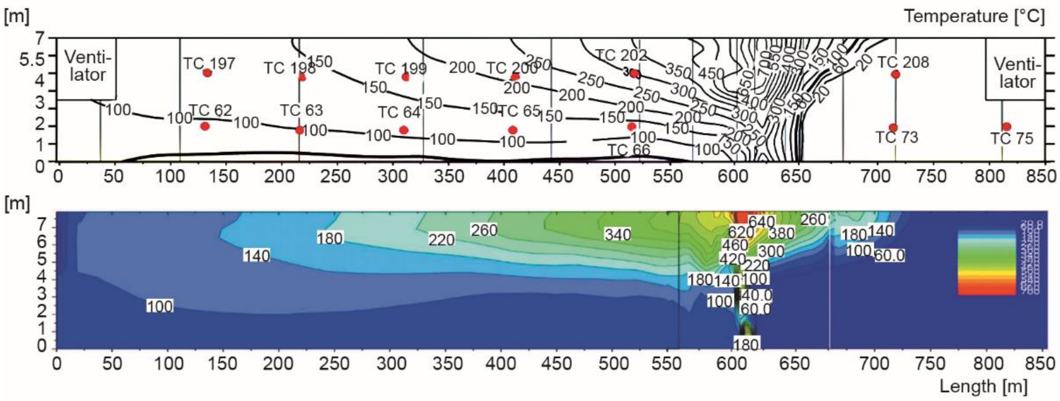

Figure 2. Temperature field along the center of the tunnel for a 50 MW fire 15 minutes after ignition; experiment and simulation

Figure 2 illustrates the comparison of the temperature field after 15 minutes from the start of the fire. At that time, the fire is fully developed, and the temperature field reaches a quasi-steady state profile. The upper part of the figure is the temperature field from the memorial tunnel report [21], and below is the simulated temperature field by the author. The qualitative evaluation of the match between experiment and simulation results is relatively appropriate. From the figure, the length of the back layer is about 710 m in the experiment and about 725 calculated by simulation. The specific comparison of temperatures measured with thermocouples in the experiment and calculated by simulation is presented on figs. 3 and 4.

The maximum deviation occurs within the first 400 seconds of the simulation, after that time the calculated values come closer to the measured ones. Measuring points that measure temperatures on the downwind side (TC 208 and TC 73) of the fire vary considerably, since these errors are greater than 100 °C. This measurement is not representative, since the calculated back layer varies just 10 meters from that measured. Quite representative are the values for TC 202 and TC 66, which are closest to the fire on the upwind side. At the initial stages of the fire (up to 400 seconds), the deviation is large, 50% to 100% or 30 °C to 100 °C. The errors are reduced after 400 seconds and reach the values ±15 °C until the end of the simulation (900 seconds). The deviations at other measuring points are, at the end of the simulation, of an order of magnitude from –10% to +50% or temperature differences from –10 °C to +30 °C.

Figure 4 shows the deviation of the simulated values from the experimental for each measuring point. The greatest deviations are at the measuring points TC 200 and TC 202,

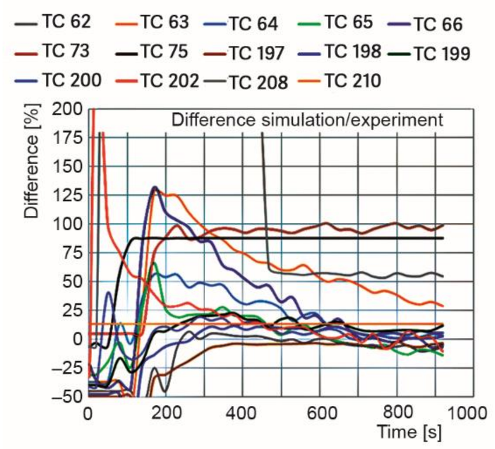

Figure 3. Deviation of simulation results from experimental data [%] for 50 MW fire
(for color image see journal web site)

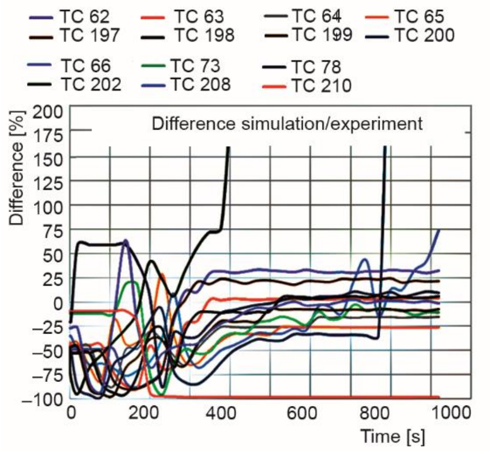

Figure 4. Deviation of simulation results from experimental data [%] for 100 MW fire
(for color image see journal web site)

which are located upwind of the fire, because the calculated reverse current is greater than in the experiment. The fluctuation in the deviation of the results is visible over a period of 200 seconds to 400 seconds, which occurs during the transient of the fan turnover and consequently there is a change in the direction of flow against the buoyant flow. The comparison of the values on the downwind side of the fire at the measuring points TC 208, TC 73, and TC 75 show deviations in the range of ±15%, which is satisfactory for us.

The conclusion from comparing the results is that the geometry, initial and boundary conditions, and the numerical grid are appropriate for the numerical requirements of the simulation of fluid dynamics, as against the experimental data. The observed model requirements are further used in the preparation of the 650 m tunnel model presented in this paper.

Parameters and approach to the result analysis

The simulation results are presented on levels of fire force and different types of tunnel ventilation are shown. As the simulation of the fire is time dependent the evacuation of people inside the tunnel is simulated according to a 1-D movement model with one-minute time steps.

People in the tunnel are exposed to the risk all the time during evacuation after the fire starts. The evacuation procedure is mainly left to the people's decision but mostly supported by a tunnel safety system like light signs, pictograms and sound signals. A successful evacuation is supported by the efficient ventilation fire protocol. Factors like the time of the beginning of evacuation, evacuation speed, start of ventilation protocol, and the distance to cross passages are the keys to reducing personal risk. Those parameters are also considered in the evacuation model. Especially for large fires, the risk of exposure to smoke is present when the smoke movement is faster than the average evacuation speed. The riskiest examples are when the people do not start with the immediate self-rescue procedure after the start of the fire or when the ventilation protocol is not suitable for that fire source. The other risk criterion is the high temperature, which usually has a lower contribution to the risk than smoke. According to the [23] the chosen limit concentration of smoke particles is 1000 mg/m^3 and the limit temperature is 50 ^{o}C. Further, the risk and consequences are divided into five categories and depend on the time of exposure. This relation of the calculated risk/consequences and expected fatalities is further used for the collective risk calculation. The percentage of fatalities in tab. 4. is selected by the author according to several literatures [23-25].

Table 4. Risk category and consequences applied in the analysis [23]

	Risk category	Consequence severity	Percent of fatalities for every one minute of exposure
1.	Low risk (LR)	Lesser injury	0.1%
2.	Medium risk (MR)	Serious injury with full recovery	2%
3.	Serious risk (SR)	Permanent injury	8%
4.	Very high risk (VHR)	Low casualty number (1-3)	20%
5.	Extremely high risk (EXR)	Numerous casualties	50%

The CFD simulation results are spatially and temporally discrete with extremely small time and space steps. The representation of these data is usually in graphical form with a variable field (temperature, soot density) for a steady-state result or with a time-dependent variable value for an observed location of the geometry. From a safety point of view, such a large amount of information becomes confusing and not very useful. In order to assess the risk to a person in a tunnel, the output files of temperature field and soot density are first properly averaged to a set of zones that a moving person occupies while moving. Thus, the space is averaged in length and, more importantly, in height. In height, the variable fields are averaged into four layers, where the height of each layer is about 1.5 m. This height is defined as the allowed layer height in a partial model. The movement of people is simulated with a linear evacuation mode, which means that the evacuation of a person starts after ignition. The starting point of evacuation is defined as well as the walking speed. In the present calculation, the evacuation speed is 2 m/s.

Next is the interpretation and quantification of the human resistance limits to the actual risk levels. The sub-model developed for the analysis of the results of CFD is based on the logical conditions and is designed for the present data in one-minute time steps for each position along the tunnel. With this approach, all influences of tunnel geometry, fire source and ventilation are considered in the risk assessment. The processing of CFD results follows the logical conditions;

$$\text{LR} : \text{ASD} < 500, \qquad \text{MR} : \text{ASDL} > 500 \wedge \text{SLH} > \text{ASLH},$$
$$\text{SR} : \text{ASD} > 500, \qquad \text{VHR} : \text{ASDL} > 500 \wedge \text{SLH} < \text{ASLH},$$
$$\text{EXR} : ((\text{SR} \vee \text{VHR}) \wedge \text{AT} > 50) \vee \text{ATL} > 50$$

where ASD [mgm^{-3}] is the average smoke density value in profile, ASDL [mgm^{-3}], is the average smoke density value in layer, SLH [m] is the smoke layer height, ASLH [m] is the Allowed smoke layer height, AT [$^{\circ}$C] is the average temperature in profile and ATL [$^{\circ}$C] is the average temperature in layer.

Results

The risk assessment approach presented here is based on the analysis of CFD model results. The reliability of the methodology has been tested through different tunnel fire scenarios that considered different types of ventilation and fire intensity. The results of temperature and smoke concentration field are processed for each scenario according to the criteria from section *Parameters and approach to the result analysis*. According to the human resistance criteria the individual risk is calculated and presented in a descriptive form from LR to EXR. Different levels of smoke concentration at the individual location influences the first four levels of risk, the presence of a temperature above 50 °C contributes an additional (the highest) risk level.

Table 5 shows a deterministic risk matrix, as a result of processing the previous results. The matrix is representative as it confirms the basic idea on tunnel safety from section. *Methodological approach regarding tunnel safety*; that is, the individual risk increases with fire size and evacuation time. It summarizes all the aforementioned 12 scenarios and represents, in the horizontal direction, the one-minute time steps after ignition. According to the case presented the fire location is 350 m away from the portal and the evacuees' location is 300 m away from the portal. The integrated evacuation model calculates the movement of evacuees who start to move towards the portal 7 minutes after ignition, in this case the walking distance in 300 m. According to the position of the moving person, the values of temperature in smoke density are taken from the database of all 12 simulations, processed according to the previous risk criteria and presented in the form of descriptive risk with additional color from green (LR) to red (EHR). The matrix in is only presented in one part due to space constraints.

Table 5. The deterministic risk matrix for the chosen observer location (part of the matrix)

Safety Category		Consequences																							
		60		120		180		240		300		360		420		480		540		600		660		720	
Power	Ventilation	Distance S→J	Distance from fire	Distance S→J	Distance from fire	Distance S→J	Distance from fire	Distance S→J	Distance from fire	Distance S→J	Distance from fire	Distance S→J	Distance from fire	Distance S→J	Distance from fire	Distance S→J	Distance from fire	Distance S→J	Distance from fire	Distance S→J	Distance from fire	Distance S→J	Distance from fire	Distance S→J	Distance from fire
		330,00	22,00 N	350,00	2,00 N	0,00	352,00 N	500,00	148,00 S	50,00	302,00 N	0,00	352,00 N	0,00	352,00 N	0,00	352,00 N	0,00	352,00 N	0,00	352,00 N	0,00	352,00 N	0,00	352,00 N
C		People initial location		People location		People location		People location		People location		People location		People location		People location		People location		People location		People location		People location	
		300,00	52,00 N	300,00	52,00 N	300,00	52,00 N	300,00	52,00 N	300,00	52,00 N	300,00	52,00 N	300,00	52,00 N	279,00	73,00 N	237,00	115,00 N	195,00	157,00 N	153,00	199,00 N	111,00	241,00 N
		Samoreševanje: začetna lokacija																							
		300,00	52,00 N	300,00	52,00 N	300,00	52,00 N	300,00	52,00 N	300,00	52,00 N	300,00	52,00 N	300,00	52,00 N	279,00	73,00 N	237,00	115,00 N	195,00	157,00 N	153,00	199,00 N	111,00	241,00 N
20 MW	Transverse	LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR	
		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR	
	Semi Transverse	LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR	
		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR	
	Longitudinal	LR		MR		MR		MR		MR		MR		MR		MR		MR		SR		LR		LR	
		LR		MR		MR		MR		MR		MR		MR		MR		MR		SR		LR		LR	
	Natural	LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR	
		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR	
50 MW	Transverse	LR		LR		SR		SR		SR		SR		SR		SR		SR		SR		LR		LR	
		LR		LR		EXR		EXR		EXR		EXR		EXR		EXR		EXR		SR		LR		LR	
	Semi Transverse	LR		SR		SR		SR		SR		SR		SR		SR		SR		SR		LR		LR	
		LR		EXR		EXR		EXR		EXR		EXR		EXR		EXR		EXR		SR		LR		LR	
	Longitudinal	LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR	
		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR		LR	
	Natural	LR		LR		LR		LR		LR		LR		LR		SR		SR		SR		SR		SR	
		LR		LR		LR		LR		LR		LR		LR		EXR		EXR		EXR		EXR		EXR	

[*] Please visit the colour version of the paper on the journal web site; http://thermalscience.vinca.rs

Risk assessment using CFD results

The use of a deterministic approach as the continuation of the event tree is useful for checking the comparability of both methods and in a case when the probability approach does not yield reliable results. As mentioned in section *Methodological approach regarding tunnel safety*, the high risk in tunnels is limited to events with low likelihood and large consequences. The approach proposed by Persson, [9] has complemented the QRA approach promoted by the OECD/PIARC, QRAM model, widely used in EU countries as a consequence of EU directive EU 2004/54/EC.

Most methodologies, the Austrian tunnel risk model TuRisMo, the Dutch QRA-tunnels, the French hazard identification, the Italian risk analysis for road tunnels that considers the transportation of dangerous goods include the use of QRAM software. The consequence models are the key element in the risk estimation. All fire, explosion, and smoke dispersion models used in QRAM are based on simple lumped models and use empirical equations in 1-D space. Therefore, the computation of physical phenomena is fast and appropriate for multiple risk calculations, but the accuracy of the consequence is questionable. The greater the complexity of the fire scenario, the greater is the uncertainty of the results [24].

Results from the risk matrix, tab. 5, are here introduced into the QRAM model. From the previous 12 scenarios three are mostly comparable with scenarios from Persson [9] including the same evacuation concept. The number of fatalities in the study of Persson is defined as *expected*, but this study the number is calculated according to the calculated risk and the percent of fatalities for every 1 minute of exposure in tab. 4. Three scenarios are analyzed on the event tree on fig. 5 – G2, G5, and G8 – that represent three different fire sources. Scenario G2 is a 17 MW fire, G5 is a 50 MW and G8 is a 170 MW fire. Although the G8 scenario is of higher intensity than simulated with CFD (100 MW fire), the heat release rate in the first 15 minutes is almost the same. Assuming this, the fire design for G8 in [9] is very close to the authors CFD model with 100 MW fire. Similarly, is for scenario G2 that assumes 17 MW fire but the CFD in done for 20 MW. The difference is however not highly significant for consequences.

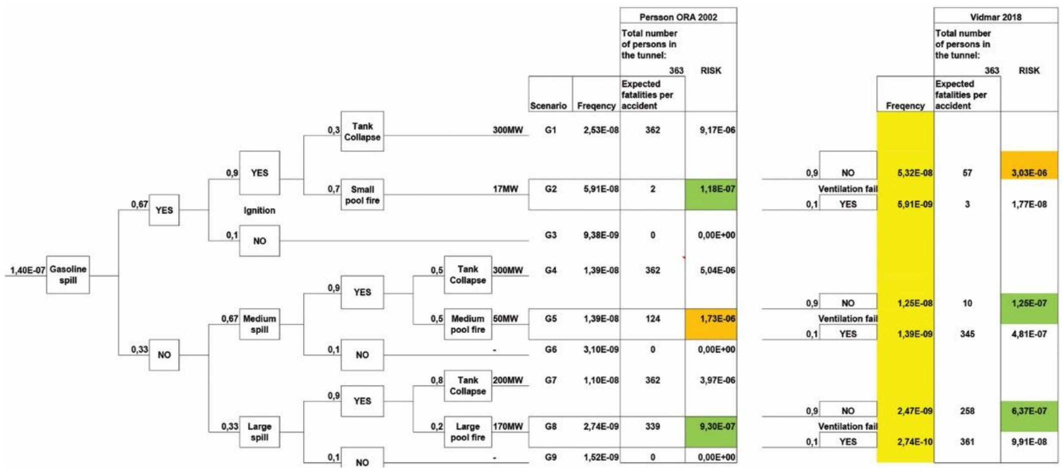

Figure 5. Event tree for gasoline spill

The left side of the event tree is Persson's original, where the author calculated the risk of the three observed scenarios. The right side is the continuation of the left side, including the probability of ventilator failure. The main difference is the calculation of fatalities, which here is based on the results from CFD, including all geometries of the tunnel, fire dynamics, emergency ventilation measures, and movement of evacuees. The CFD Results show some undetectable phenomena that cannot be found by 1-D models. For example, the simulation of a 17 MW fire (scenario G2) shows that the use of longitudinal ventilation, according to the emergency ventilation plan, is worse than no ventilation for the whole evacuation time. The reason is hidden in the smoke movement dynamics. In the case of natural ventilation, the smoke layer is kept stratified under the ceiling and evacuation is possible through the lowest layer. The start of longitudinal ventilation after 10 minutes causes the formation of vortices that break the stratification and fill the tunnel with smoke. It takes several minutes for the jet fans to clear the evacuation side of the tunnel of smoke [26]. Similarly, but in inverse correlation, is the 50 MW scenario where ventilation failure results in a large number of fatalities, but few fatalities when ventilation is working properly. The comparison of the calculated risk of QRA (left side) and the author (right side) shows the main differences and could be further used for decision making.

Risk levels

Based on the calculated individual risk from the event tree the collective risk is computed. Integrating the probability of death for each event over the number of people in the tunnel, represents the number of fatalities for a given event.

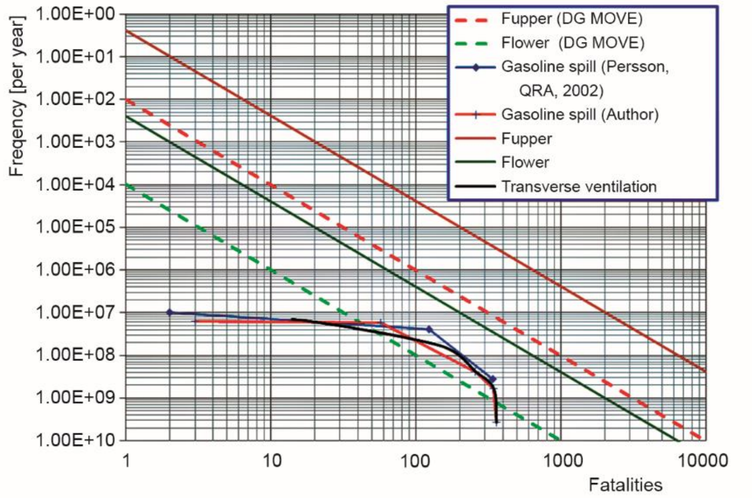

Figure 6. Collective risk level for gasoline spill in a tunnel

Figure 6 illustrates the modelled risk level for a gasoline spill in the F-N diagram according to the event tree previously discussed. Each scenario frequency obtained from the event tree is multiplied by the calculated number of fatalities from the CFD simulation results. The risk level is calculated as the sum of the fatality frequency per year for the analyzed accidents. This is the potential loss of life risk (PLL) per year for scenarios that endanger a calculated number of persons. Results are presented in tab. 6. The table includes the calculated frequencies from the event tree and calculated PLL-risk according to the calculated fatalities per accident. The right part of the table is taken from the Persson report [9], and the left part of the table is calculated by the authors. Further, the cumulative fatality frequency is calculated, and the F-N curve is plotted.

Since the risk criteria vary from country to country it is difficult to generalize and say whether the risks are acceptable or not. The harmonization of risk acceptance criteria for the transport of dangerous goods proposed in the final report of the DG-MOVE project [18] are compared with those calculated for the national accident statistics. The straight lines on

Table 6. Cumulative risk for gasoline spill accident

Gasoline spill (authors)				Gasoline spill (Persson QRA, 2002)			
Fatalities (per accident)	PLL-Risk (fat. per year)	Event frequency (1/year)	Cumulative fatality (fat. per year)	Fatalities (per accident)	PLL-Risk (fat. per year)	Event frequency (1/year)	Cumulative fatality (fat. per year)
0	0.00E+00	1.25E-08	7.58E-08	0	0.00E+00	1.40E-08	1.15E-07
3	1.77E-08	5.91E-09	6.32E-08	2	1.18E-07	5.91E-08	1.01E-07
57	3.03E-06	5.32E-08	5.73E-08	124	1.73E-06	1.39E-08	4.16E-08
258	6.37E-07	2.47E-09	4.14E-09	339	9.30E-07	2.74E-09	2.74E-09
345	4.81E-07	1.39E-09	1.67E-09	362	9.02E-06	2.49E-08	0.00E+00
361	9.91E-08	2.74E-10	2.74E-10				

fig. 6 presents the risk criteria calculated for the analyzed country. The calculated ALARP region is much above that of the criteria of the EU. We should understand that the calculated risk criteria are based on the actual tunnel transport's economic value and accidents statistics. A higher economic value of the transport business would result in the reduction of tolerable risk. In other words, high value business requires a safe environment in which to operate as the risk control option could be expensive and reduce the profit of the sector. On the other hand, if the number of predicted fatalities is reduced to one in ten years, the tolerable risk reaches the same values as proposed by EU criteria. This would result in appearing as if both ALARP regions were almost overlaid.

Two F-N curves are compared in order to understand the applicability and advantage of simulating fire scenarios with CFD. The F-N curve modelled by Persson [9] is very close to the curve modelled in this paper. Although both risk curves are within the ALARP area the author's is closer to the low-risk criteria. In both cases no additional risk control options (ROC) are needed. In case one, if the risk curve would exceed the upper risk criteria and therefore require the ROC, a precise calculation of consequences could reduce the actual risk. The F-N curve for the same scenarios (G2, G5, G8) using transverse ventilation during a fire are also presented in the graph. However the comparison of risk applying transverse ventilation in the same tunnel was not possible, because Persson report [9] does not have these scenarios. All simulations are done on a relatively short tunnel and the F-N curve shows no significant difference between the two ventilation systems. The risk curve drop, above 350 fatalities for transfer ventilation, indicates the advantage of this ventilation for long tunnels and when the cross passage is far from the fire or there are no cross passages, as in some old tunnel.

Risk strategy improvements

Risk assessment of a road tunnel is normally divided into risks arisen from traffic density, influenced by environmental and infrastructural elements, fire scenarios in a tunnel considering tunnel equipment and evacuation/rescue plans. The overall risk is influenced by all these elements. However, the most unknown remains the smoke dynamics under the influence of a tunnel ventilation system, pressure difference between cross passages and pressure difference between portals. The use of empirical fire models and 1-D flow movement models are appropriate, in the author's opinion, for the verification of ventilation plans, but are not reliable enough for the estimation of individual risks.

Risk assessment is normally a continuous process observed in daily, weekly or seasonal intervals, to assure the acceptance of a tunnel's operational risk. In practice risk assessments have been conducted once after 2004 for all EU operating tunnels on Trans European Network and for every new building to fulfil legal requirements. After that these same tunnels have updated their risk assessments mainly after some reconstruction or traffic regime changes. The increased traffic density and the increased share of dangerous goods on HGV are not assessed after a decade since QRA implementation. Although the CFD fire simulation takes more time to be processed than simple fire models they could provide the assessor consolidated and reliable results on fire and smoke dynamics, which is mandatory for evaluating the magnitude of consequences for human lives. Because the recent history of QRA for tunnels shows the assessments have been conducted once for the majority of tunnels, there is strong justification for performing fire dynamics analysis with the most reliable possible approach. In this case the presented paper promotes the approach for this part of the QRA process that is fully compatible with existing approaches like QRAM and the like.

Conclusions

Risk assessments are an essential part of any transportation activity because transportation reliability is strongly related to transportation revenue. The risk acceptance criteria of tunnel transportation are calculated in this paper for the Republic of Slovenia based on available statistics. The presented approach is compared with the QRAM approach and leads to comparable results. However, the risk criteria are different, as the criteria calculated in the paper are evaluated strictly from the statistics for a specific country in 2017.

An important part of the paper is the use of the results from CFD to assess the consequences of a tunnel fire. These results have already been presented by the authors, but the validations have never been done for societal risk assessment. The methodology for linking the calculated fire dynamics variables to the consequences on human lives is explained and furthermore the use of these consequences to quantify the risk to users. The validation of the methodology is presented by comparing the results between the QRA and CFD fire scenarios. The main findings are that the CFD modeling requires more computational time, but the results better account for the specifics of fire dynamics and the influence of ventilation on smoke and temperature distribution. Although the process to compute CFD is time consuming, the authors believe that it is important to take this time as it provides more reliable results and better support for decision making in selecting effective risk control options.

The use of CFD programs in fire analysis is not new and has been widely used for more than two decades and has become a powerful tool for deep consequence analysis. A more important point is that CFD programs cannot be used as a *black box*, especially open-source codes. The results can often be misleading if the model is not properly set up and validated on experimental results before use. However, the paper proves the possibility and procedure of implementing CFD simulation into the existing QRA, which could improve the reliability of risk assessment in tunnels.

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Paper submitted: November 8, 2020
Paper revised: March 17, 2021
Paper accepted: April 1, 2021