Chapter

Novel Approach in Tunnel Safety Assessment

Peter Vidmar

Abstract

The definition of a deterministic approach to risk analysis stems from the need to understand the conditions that are developed in the event of an accident with a fire in a road tunnel. From the point of view of the tunnel manager and rescuers, these data are important during planning the operation of the tunnel and in coordinating the rescue. The methods of tunnel control in crisis situations are most often based on the experience of operators and crisis plans, which are also made by experience or using simple calculation tools. In recent years, due to many tragic accidents in European tunnels, there has been a lot of talk and work in the field of risk assessment and the possibilities of risk reduction. The methodology of safety analyses and the determination of the level of risk arise predominantly from the nuclear and chemical industry, where it has been in use for more than 50 years. The paper presents the methodology for integrating methods of rapid processing of risk assessment with time-consuming CFD methods for analysing the consequences of fire in the tunnel safety assessment process. The main observed variables are the density and the temperature of the carbon black, which are analysed during the fire step in a minute. Human behaviour is considered in the evacuation model, which is necessary for the assessment of fatalities during the progress of the fire. The use of the methodology is presented by assessing the national tolerable risk for transport in tunnels and compared to the EU reference criteria.

Keywords: tunnel safety, fire safety, risk assessment, F-N curves

1. Introduction

Risk assessment studies and specifically fire consequence analyses are likely applying fast computation models [1]. A risk assessment is a multicriteria process that requires a network approach for process and hazard identification. The events are systematically analysed with a Bayesian network, event tree, fault tree and other well-known approaches [2]. 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. The risk identification for tunnel safety operation is usually presented with a number of scenarios that are further divided into sub-scenarios for different fire sources and locations, types of ventilation, traffic density, etc. The result is a large number of scenarios that are not suitable for CFD calculation, not so much because of computation time, but because results are more suitable for deep hydrodynamic analysis than for the identification of risk for a person or a group of people inside a tunnel.

After the entering in force of EU directive 2004/54/EC [3] on minimum safety requirements for tunnels, the risk assessment methods have been proposed by PIARC [4] with the QRAM model [5]. Other tools and methodologies for risk assessment in road tunnels were developed—the Dutch RWQRA model 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 one-dimensional flow model or at most with zone models, where in every step volume is divided into a hot and cold layer. These models cannot cover a specific flow dynamic, smoke stratification, influence of different ventilation systems, vorticity, and crossflow. Effects like back layering are modelled directly in one-dimensional models, but its reliability is scenario dependent and is not reliable, or in other scenarios overestimated [6]. Following this idea, we believe that a methodology of fire safety valuation, which improves existing methodologies and is based on a deterministic approach, is necessary, as the approach to integrate CFD consequence results in a probabilistic QRA method [7].

The presented analysis includes the fire modelling based on CFD results [8, 9] for different standard fire scenarios and includes basic human behaviour, e.g. resistance on height temperature and gas concentration, evacuation velocity, reaction times and other features. 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.

2. Approach on tunnel safety

A risk assessment of a controlled system is much more reliable than the assessment of a "natural" one. Similarly to an industry 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 keep control of all events that could happen in operational and emergency situations. The paper is focused mainly on fire events and the risk to people arising from it. Fire development and spread are complex phenomena, and CFD programs are reliable and useful for simulations. The authors [10–13] have done a large number of validation tests archiving the reliability of results in a range of 20–30% compared to experimental tests. The author [8] conducted validation tests of the program Fire Dynamic Simulator (FDS) with Memorial Tunnel experiment results. Results from this simulation are further used in this paper as the input for consequence level estimation.

The deterministic approach is used for the analysis of the greater part of physical events like fire source characteristic and its dynamics, the operation of the ventilation system and other conditions as well as their reciprocal interactions. The approach also leads to the definition of the technical system "safety efficiency" in the range of possibilities that exist in the real word and are functionally descriptive. When the approach is used in practice, we should define a number of "safety categories" based on event probability and consequences for individual risk. An example is presented in **Table 1**.

Note that in these schemes a quantitative definition is given in addition to the qualitative definition, mainly to ensure consistency in the course of the analysis and provide benchmarks (semi-quantitative analysis). In schemes of this type, the assessment team, usually comprising members of management, safety engineers and operations personnel, will first identify all hazards, using HAZID, HAZOP or similar approaches, and then assign a severity category to each of these, for both likelihood and consequences [14, 15].

Likelihood categories	Qualitative definition	Quantitative definition (times per year)
A	Once in a year	0.3–3
B	Possible but not likely	0.03–0.3
C	Unlikely	0.003–0.03
D	Very unlikely	0.0003–0.003
E	Remote	0.00003–0.0003
Consequence categories	**Qualitative definition**	**Semi-quantitative definition**
1	Catastrophic	Multiple fatalities
2	Major	Single fatality, multiple injuries
3	Very serious	Permanently disable injuries
4	Serious	Serious injury, full recovery
5	Minor	Lost time injury, short absence from work

Table 1.
Deterministic safety analysis: supposed safety categories.

Following the assumptions in **Table 1**, a "risk matrix" would then be defined as a 5 × 5 matrix with each side corresponding to one severity category.

Different shading in a table indicates different risk levels. Hazards with high risk, such as A1, B1 and A2 in the black squares, are thought of as being very severe and require immediate action to reduce a risk. Hazards with low risk, such as E5, E4 and D5 in white squares, are considered to require no further action. Hazards between these two are considered worthy of some improvement if a cost-effective solution can be found.

The two methods of risk analysis (qualitative and quantitative) are often not separable but upgrade each other. **Figure 1** shows the event tree for the example of a fuel leak from a heavy goods vehicle. The quantitative approach is applied because the event probabilities are known from past statistics. The results of the event tree

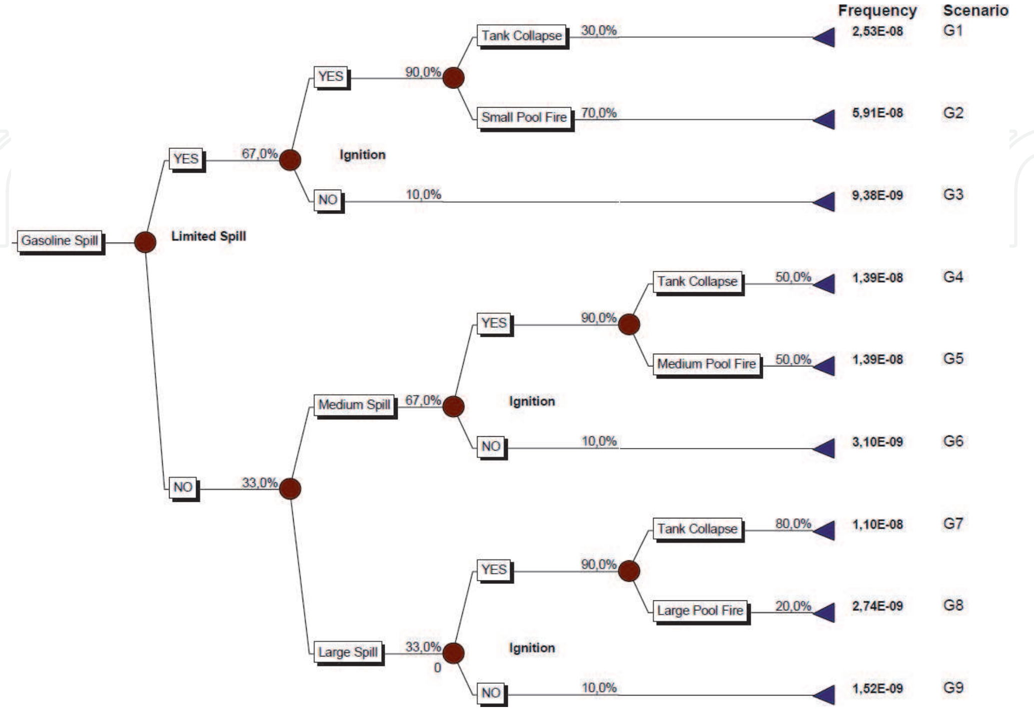

Figure 1.
Event tree for fuel leak out scenario [16].

are several predicted scenarios with calculated final event frequencies. Among nine final scenarios, there are three fire scenarios with a major frequency: G2, G5 and G8. Further work leads to two directions, with a probabilistic or deterministic approach. In the following sections, the methodology and requirements of using a deterministic approach are explained more in detail and developed from this event tree scenario.

2.1 Tunnel fire modelling and simulations

The application of CFD model on tunnel geometry is a demanding task but has been widely validated. Fire dynamics is a three-dimensional, time-dependent process which integrates the interactions among combustion, fluid flow and heat transfer processes. The turbulence process of energy dissipation over which fire dynamics evolve is of the order of 0.1 s and 1 mm, respectively [17, 18], but lengths of realistic tunnels are measured in kilometres. This implies that the turbulence needs to be algebraically modelled.

A good mathematical approximation of the fire is done by a combustion model (instantaneous reaction when fuel and oxygen are properly mixed), radiation model (non-scattering grey gas model) and low Mach variable density formulation of the fluid conservation Eqs. A Fire Dynamics Simulator (FDS) program uses the combination of these models for simulating fire development and smoke spread. The fluid flow is modelled by solving the basic conservation equations: the conservation of mass (1), conservation of mixture fraction Z (2), conservation of momentum (3) and conservation of energy (4) using a form for low Mach number [17]. The approximation involves the filtering out of acoustic waves. The basic conservation equations are written in the form:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \boldsymbol{u} = 0 \tag{1}$$

$$\frac{\partial \rho}{\partial t}(\rho Z) + \nabla \cdot \rho Z \boldsymbol{u} = \nabla \cdot \rho D \nabla Z \tag{2}$$

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + \frac{1}{2}\nabla|\boldsymbol{u}|^2 - \boldsymbol{u} \times \omega\right) + \nabla \tilde{p} = (\rho - \rho_\infty)\boldsymbol{g} + \nabla \cdot \tau \tag{3}$$

$$\rho c_p\left(\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T\right) = \dot{q}_c''' - \nabla \cdot \boldsymbol{q}_R + \nabla \cdot k \nabla T \tag{4}$$

and the equation of state

$$p_0 = \rho R T \tag{5}$$

where ρ is a density, **u** is a velocity vector, Z is the mixture fraction, T the temperature, p_0 the ambient pressure, R the gas constant, c_p is a specific heat and D the molecular diffusivity. $\tilde{p}$ is the perturbation pressure caused by pressure differences, τ the viscosity stress tensor and k the thermal conductivity. $\dot{q}_c'''$ and $\nabla \cdot \boldsymbol{q}_R$ are the source terms of chemical reaction and radiation, respectively. The radiation term has a negative sign because it represents a heat sink [17]. The effect of the flow field turbulence is modelled using large eddy simulation (LES), in which the large-scale eddies are computed directly and the sub-grid scale dissipative processes are modelled [18, 19]. The unknown sub-grid stress tensor τ is modelled by a Smagorinsky model.

2.2 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. The consequences of the distance of the smoke and temperature are qualitatively evaluated from the velocity and temperature field. People using the tunnel are exposed to the risk after the fire starts, but not only them. 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. The 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. Especially for large fires, the risk of exposure to smoke is present when the smoke movement is faster than the average evacuation speed. The most risky examples are when the people do not start with the immediate self-rescue procedure after the start of the fire and when the ventilation protocol is not suitable for that fire source [20]. The other risk criterion is high temperature, which usually has a lower contribution to the risk than smoke. In most cases this depends on ventilation. The limit value of the concentration of smoke particles (PM10 heavy particles with the diameter up to 10 μm) is 1000 mg/m^3, and the limit temperature is 50°C [21]. The smoke particles are less problematic from a toxic point of view than other combustible products (CO_2, carbon dioxide; CO, carbon monoxide; HCN, hydrogen cyanide; HCl, hydrogen chloride; etc). Their share of concentration is conditional and often very similar. From different experiments in the Memorial Tunnel, it can be found, for example, that concentrations of smoke particles and CO are in relation around 10:1. A similar relation can be also found in toxic levels of these products. Lethal concentration 50% (LC_{50}) for soot particles is 30 g/m^3 in a 30 min exposure or 1–3 g min/m^3 LC_{50}; for CO it is 2000–3500 ppm, which is 2300–4000 mg/m^3 in a 30–60 min exposure [21]. The limit temperature values of human resistance are, according to Gann and Hall, 100°C for 30 min and 75°C for 60 min of exposure. Because this information is true for an adult man, it is the most optimal. But within the same study, the authors point out difficulties in breathing already at 65°C of air temperature. Taking this into account, there are two values that are used in our result analysis. The chosen limit concentration of smoke particles is 1000 mg/m^3 and the limit temperature is 50°C.

The risk or consequences are divided into five categories shown in **Table 2**.

A further step is the interpretation and the quantification of the human resistance limits to the actual risk levels. The sub model developed during the research analyses of CFD results and according to the following logical conditions marks every 1-minute time step along the entire tunnel length. Using this approach all the influences of the tunnel geometry, fire source and ventilation are considered in the risk evaluation:

	Risk category	Consequence severity	Percent of fatalities every 1 min exposure
1.	LR–low risk	Lesser injury	0.1%
2.	MR–medium risk	Serious injury with full recovery	2%
3.	SR–serious risk	Permanent injury	8%
4.	VHR–very high risk	Low casualty number (1–3), numerous injured	20%
5.	EHR–extremely high risk	Numerous casualties	50%

Table 2.
Risk category and consequences applied in the analysis.

LR: ASD < 500.
MR: ASDL $>500 \land$ SLH $>$ ASLH.
SR: ASD > 500.
VHR: ASDL $>500 \land$ SLH $<$ ASLH.
EXR: ((SR $\lor$ VHR) $\land$ AT >50) $\lor$ ATL > 50.
where the abbreviations mean:
ASD-average smoke density value in profile [mg/m^3].
ASDL-average smoke density value in layer [mg/m^3].
SLH-smoke layer height [m].
ASLH-allowed smoke layer height [m].
AT-average temperature in profile [°C].
ATL-average temperature in layer [°C].

The CFD simulation results are discreet in space and time with extremely small time and space steps. The analysis of so much information is usually done in a graphic form representing a variable (temperature, soot density) field for a steady-state result or with a time-dependent variable value for an observed location of the geometry. From the safety point of view, such a large quantity of information becomes unclear and less useful. To evaluate the risk for a person in a tunnel, the output files of a temperature field and soot density are first properly averaged to a series of zones that a moving person occupies during his movement. The space is thus averaged in length and most importantly in height. In height the variable fields are averaged in four layers, the height of each being about 1.5 metres. This height is redefined in a model as the allowed layer height. One condition for the extreme risk is that the average temperature in this lower layer exceeds 50°C for 1 minute.

2.2.1 Evacuation model

The discussion of results is enforced with the understanding of the human behaviour during the fire in the tunnel after they begin with the self-rescue procedure. This is the evacuation from the tunnel portal or through the first transverse passage in two tube tunnels. The movement of the people in similar conditions is very unpredictable; some become immediately aware of the danger and begin with the self-rescue procedure, while others do not perceive the danger in time and begin late with the self-rescue procedure. A simplified model of human movement is introduced to the risk model. The model takes into consideration the elementary movement parameters as start of the self-rescue, walking speed, tunnel length and the direction of the movement according to the location of the fire. This means the evacuation can only lead away from fire. The model allows the analysis of movement from different starting locations which allows the division of the tunnel into zones depending on the location of cross passages. The calculated locations of persons are then used for checking the temperature and the smoke concentration, and consequently the level of the individual risk is evaluated according to the previous approach.

3. Model validation

This section presents the FDS model validation with experimental data from the Memorial Tunnel test program from 1993 to 1995 in the USA. The experimental tunnel is 853 m long and 7.9 m in height with a 3.2% slope. Many tests have been conducted with different fire source powers and different ventilation programs. The validation presents two different validation scenarios: a 50 MW fire with natural ventilation and a 100 MW fire with forced longitudinal ventilation. The fuel used in the experiment and simulated is oil filled into a flat container [22, 23]. Using the same fuel, different fire heat release rates are obtained by changing the burning surface.

3.1 Geometry of the model

The geometry, initial and boundary conditions are arranged to the tunnel geometry and fire parameters. **Figure 2** shows the geometry of the tunnel from the external view. The upper closure is just few metres long and is a ventilator room. The fire is located 615 m from the west portal and is symmetrical to the cross section. The fire is assumed as a heat release source with a specific power 2700 kW/m^2, where the oxygen and fuel consumption and the release of combustion products depend on the stoichiometric equation $11\ O_2 + C_7H_{16} \rightarrow 7\ CO_2 + 8\ H_2O$. Here C_7H_{16} is a heptane, which burns very similar to a diesel oil just with less soot release. This is additionally added as a product to the combustion model.

3.2 Initial and boundary conditions

Initial and boundary conditions are divided into geometry obstacle conditions and fluid conditions. The walls of the tunnel are defined as thermally thick walls in the model, where heat transfer is computed to and through the walls. The initial temperature of any obstacle is defined the same as ambient (20°C) temperature. The velocity at the wall is calculated as the average value of the velocity in the first cell that touches the wall and zero velocity on the wall cell. The heat release from the fire source is defined as full power at the beginning of the simulation, because data available from the experiment are only for fully developed fires [24]. Thermal radiation initial conditions are defined with radiation intensity based on the initial temperature of objects (ambient temperature) and the energy absorption in the air, mostly formed by nitrogen. The heat of radiation emitted from walls is calculated as black wall radiation intensity [25].

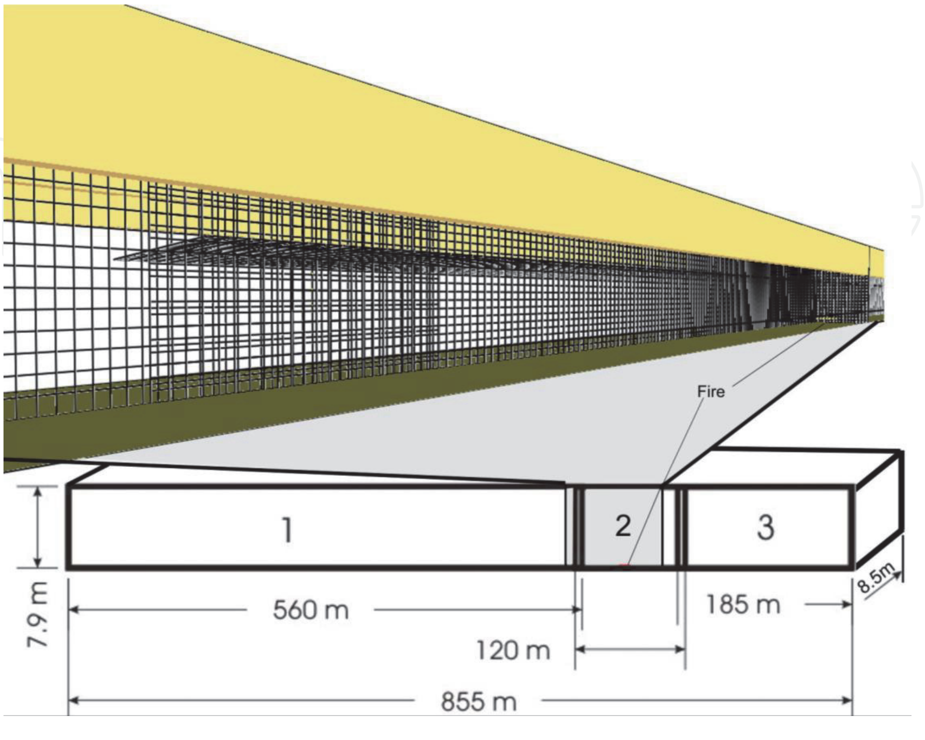

Figure 2.
Geometry and mesh setup.

The model simulates the 3.2% tunnel slope with the additional gravity vector component in the direction of the slope of 0.314 m/s^2. The portals are defined as open boundary conditions that link the tunnel domain with the ambient.

The applied numerical grid is non-uniform. The geometry is divided into three sections over the tunnel length: 560, 120 and 185 m. A 50 MW fire model applies 800,640 cells and a 100 MW model 1,274,220 cells. The reason is the requirement of the combustion model, which computes the reaction and the heat release in the second section where the fire is located. Other parts of the geometry do not require such a dense grid because of lower velocity gradients.

3.2.1 Simulation results

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 and 6.5 metres from the floor placed every 100 metres from the left portal (**Figure 2**).

The maximum deviation is 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 a representative, since the calculated back layer varies just 10 metres from that measured. The values on TC 202 and TC 66 are very representative, which are closest to the fire on the upwind side. At the initial stages of the fire (up to 400 s), the deviation is large, namely 50–100% or 30–100°C. The errors are reduced after 400 s and reach the values $\pm$ 15°C until the end of the simulation (900 s). The deviations at other measuring points are at the end of the simulation of the order of magnitude from −10 to +50% or temperature differences from −10 to +30°C.

Figures 3 and **4** shows the deviation of the simulated values from the experimental ones for each measuring point for 50 MW and 100 MW fire respectively. The largest deviation is at the measuring points TC 200 and TC 202, which are located upwind of the fire, because the calculated reverse current is greater than on the experiment. The fluctuation in the deviation of the results is visible over a period of

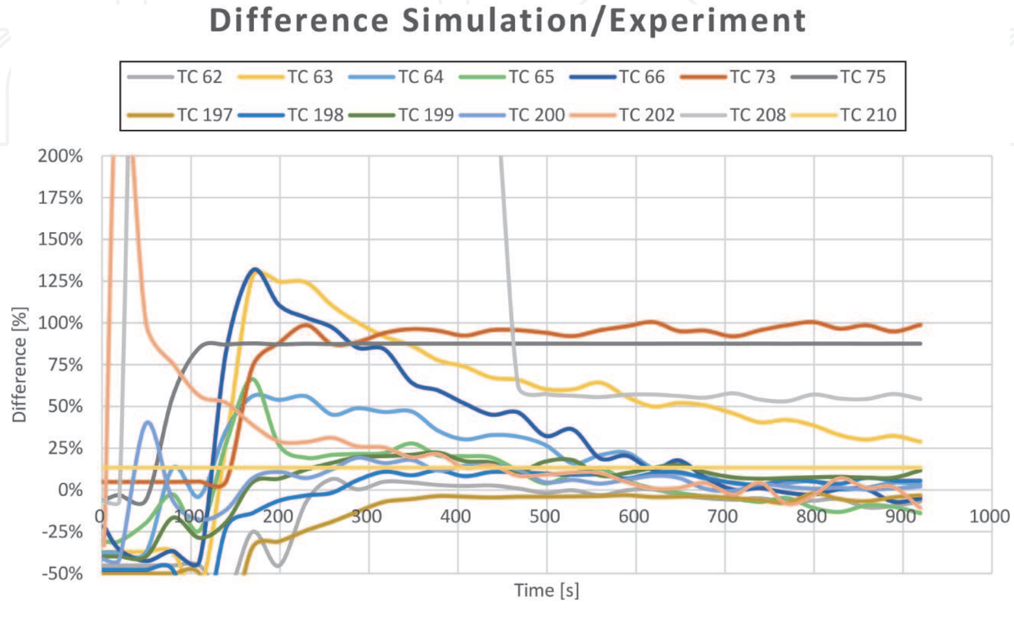

Figure 3.
Deviation of simulation results from experimental data in % for 50 MW fire.

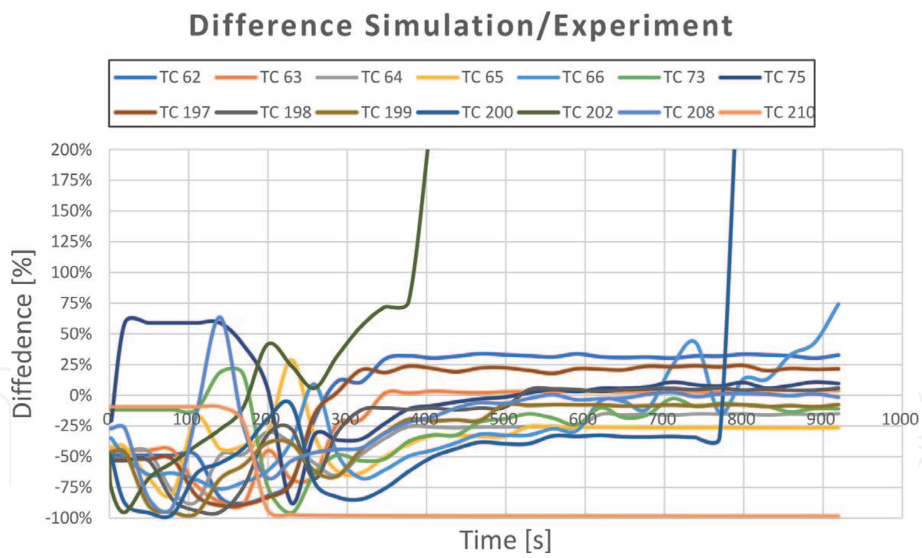

Figure 4.
Deviation of simulation results from experimental data in % for 100 MW fire.

200–400 s, 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 shows deviations in the range of ±15%, which is satisfactory for us.

The conclusion from comparing the results is that the model geometry, initial and boundary conditions and the setting of the numerical grid conform to the numerical requirements for the calculation of fluid dynamics inside the tunnel, against the experimental data. The obtained information is further used in the preparation of other similar models.

4. Tunnel fire and risk analysis

The risk assessment methodology presented here is based on the analysis of CFD model results. The reliability of the methodology is proven with model results and numerous scenarios, where the whole spectre of tunnel fire scenarios is assessed, considering different types of ventilation and different fire intensity. Other parameters, like environmental influence, traffic density and other characteristics of the tunnel, are handled separately [26].

The idea is based on the development of a deterministic risk matrix as presented in **Table 3** based on CFD results. The safety category is represented by the power of the fire and the type of ventilation where the consequences are evaluated in the time during the progress of the fire [27, 28]. The risk criteria are defined as a relation between the hot smoke layer height, the distance from the fire location and the evacuation time of the users. In the case the speed of the smoke is greater than the speed of the evacuation and in case the thickness of the hot layer is higher than the height of the person during the evacuation, the risk is high.

4.1 Tunnel fire scenarios

All together 12 tunnel fire scenarios are processed. Three levels of fire are simulated, each with four different types of ventilation. The span of the fire source is from 20 MW, 50 MW to 100 MW, while the ventilation is sorted from the less to the more effective: (1) natural, (2) longitudinal, (3) semi-transverse and (4) transverse or improved transverse ventilation.

"Likelihood" "Severity category "	Consequences "Severity category"				
	5	4	3	2	1
A					
B					
C					
D					
E					

Table 3.
Deterministic safety analysis: Generic example of risk matrix.

The section of the simulated tunnel is 650 m long, 10 m wide and 8 m in height or 6 m when the roof is lowered for transverse ventilation. The fire is located at a distance of 350 m in all the models, differing only in the size of the burning area. Findings from validation tests are used and implemented also in the following scenario of the definition of initial and boundary conditions of the model and proper numerical discretization.

4.2 Fire simulation

The calculation of the 12 presented scenarios is done on a cluster of four computers—PC 2.8 MHz with a join memory capacity of 32 GB. The discretization of each model is from 800,000 to 1,400,000 mesh points. The numeric and sensitive analysis of the model was conducted but is not presented here. After multiple simulation repetitions, calculation times comparisons and result validations, an optimal relation between numerical grid density, calculation time and result reliability has been obtained.

The definition of the initial and boundary conditions is different for each model but based on findings from the validation models. Four different ventilations are defined: natural, longitudinal, semi-transverse and transverse. The tunnel models with natural and longitudinal ventilation take the whole section of the tunnel; the tunnel models with semi-transverse and transverse ventilation consider only the light section of the tunnel (without the ventilation ducts).

4.3 Results

The presentation of the results in a form of temperature of smoke concentration field can provide useful information only to an experienced user but yields unclear information about a true risk. Results of simulation are therefore processed for each scenario according to the criteria from paragraph 2.2. The temperature and smoke values are the most influential risk parameters in the tunnel. According to the human resistance criteria, the individual risk is calculated and presented in a descriptive form low risk (LR) to extreme high risk (EXR). The presence of smoke on the individual location influences the first four levels of risk, depending on concentration; the presence of high temperature contributes to an additional (the highest) risk level. **Table 4** presents a deterministic risk matrix for a constant location in a tunnel during a fire that is 252 m north of the fire. The picture is very representative because it confirms the theory on safety analyses from

Safety Category		Consequences														
		60	120	180	240	300	360	420	480	540	600	660	720	780	840	900
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	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	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	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	69,00 / 283,00 N	27,00 / 325,00 N	0,00 / 352,00 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	69,00 / 283,00 N	27,00 / 325,00 N	ZUNAJ / ZUNAJ 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	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	LR	LR	LR	LR	LR	LR
	Longitudinal	LR	MR	MR	MR	MR	MR	MR	MR	MR	SR	LR	LR	LR	LR	LR
		LR	MR	MR	MR	MR	MR	MR	MR	MR	SR	LR	LR	LR	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	LR	LR	LR	LR	LR	LR
50 MW	Transverse	LR	LR	SR	SR	SR	SR	SR	SR	SR	SR	LR	LR	LR	LR	LR
		LR	LR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	SR	LR	LR	LR	LR	LR
	Semi Transverse	LR	SR	SR	SR	SR	SR	SR	SR	SR	SR	LR	LR	LR	LR	LR
		LR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	SR	LR	LR	LR	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	LR	LR	LR	LR	LR	LR
	Natural	LR	LR	LR	LR	LR	LR	LR	SR	SR	SR	SR	SR	SR	SR	LR
		LR	LR	LR	LR	LR	LR	LR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	LR
100 MW	Transverse	SR	SR	SR	VHR	VHR	VHR	VHR	VHR	VHR	VHR	VHR	VHR	SR	SR	LR
		EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	SR	SR	LR
	Semi Transverse	SR	SR	SR	SR	SR	VHR	VHR	VHR	VHR	VHR	VHR	VHR	SR	SR	SR
		EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	SR	SR	SR
	Longitudinal	LR	LR	LR	LR	LR	LR	LR	LR	SR	VHR	LR	LR	LR	LR	LR
		LR	LR	LR	LR	LR	LR	LR	LR	EXR	EXR	LR	LR	LR	LR	LR
	Natural	LR	LR	LR	SR	SR	SR	SR	VHR	SR	SR	SR	SR	SR	SR	SR
		LR	LR	LR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR	EXR

Table 4.
The deterministic risk matrix for the chosen observer location.

Section 2, that is, the individual risk increases with fire size and evacuation time. Further, for the largest fire, the contribution to the risk of the ventilation may be observed.

Table 4 is made as a functionally dependent dynamic matrix that selects the calculated values from the database of CFD processed results. The matrix model allows the selection of the observed location and then calculates the risk. According to the evacuation model, the start position—the beginning of the self-rescue procedure and the walking speed—is defined, and the users' movement may be observed as the smoke concentration and the temperature height to which tunnel users are exposed. The individual risk is therefore calculated.

5. Risk assessment using CFD results

CFD simulation results could provide relatively accurate information on fire dynamics. As presented in Section 2 there is a possibility to connect the deterministic approach to a probabilistic approach. I especially refer to the consequences as they are shown in **Table 1**. The processed results from tunnel modelling as presented in a risk matrix are quantified first according to **Table 1**. The information presents the quantification of risk that is taken as a final result of the risk during a tunnel fire or as an input for the continuation of events in the event tree assessment of the risk.

The continuation of the event tree from **Figure 1** for the G2 scenario is presented in **Figure 5**.

The use of a deterministic approach as the continuation of the event tree is useful for checking the comparability of both methods or in a case when the probability approach does not yield reliable results. As mentioned in Section 2, the high risk in tunnels is limited to events with low likelihood and large consequences. The approach proposed by Persson [16] 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 of the methodologies—Austrian tunnel risk model TuRisMo, the Dutch QRA tunnels, the French specific hazard identification and the Italian risk analysis for road tunnels that consider the transportation of dangerous goods—include the use of QRAM software. Consequence models are the key elements in the risk estimation. All fire, explosion and smoke dispersion models used in QRAM are based on simple lumped models and empirical equations in one-dimensional space. Therefore, the computation of physical phenomena is fast and appropriate for multiple risk calculations, but the accuracy of the consequence is questionable. The higher the complexity of the fire scenario, the greater is the uncertainty of the results [29].

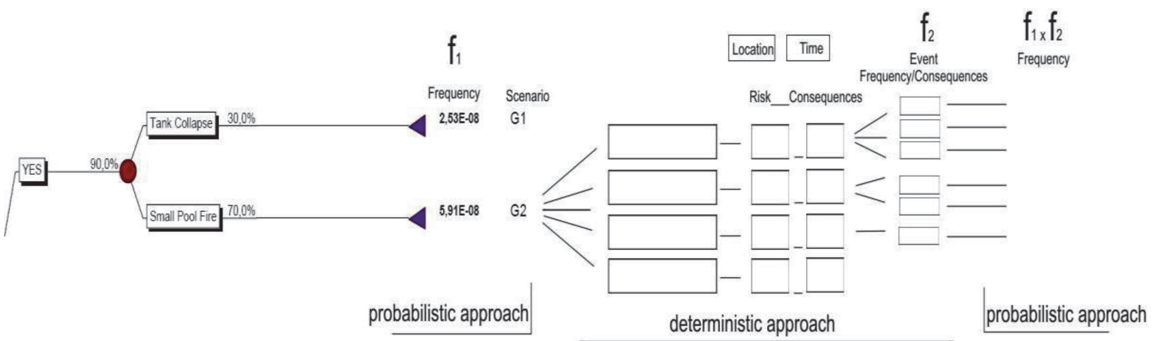

Figure 5.
Passage from a deterministic to a probability risk analysis method.

The calculation of consequences with a CFD program is performed for the same scenarios as Persson [16], including the same evacuation concept, and the number of fatalities is calculated. Three main scenarios are analysed, G2, G5 and G8, which represent three different fire sources (**Figure 6**).

Findings observing CFD results are important because they show some undetectable phenomena. 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 without ventilation for the whole evacuation time. The reason is hidden in the smoke movement dynamics. During natural ventilation the smoke layer is kept stratified under the celling, and evacuation is possible through the bottom layer. The start of the longitudinal ventilation after 10 minutes causes the formation of vortices that break down the stratification and fill up the tunnel with smoke. It takes several minutes for jet fans to clean the evacuation side of the tunnel from smoke.

This transition process is usually not correctly covered by simple 1D models as presented in Persson [16].

5.1 Risk levels

Based on the calculated individual risk frequencies, 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 by a given event. **Figure 7** illustrates the modelled risk level for a gasoline spill in the F-N diagram.

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 analysed accidents. This is the potential loss of life risk (PLL) per year for scenarios that endanger a calculated number of persons in **Table 5**. Further, the cumulative fatality frequency is calculated, and the F-N curve is plotted in **Figure 7**.

Two F-N curves in **Figure 7** are compared in order to understand the applicability and advantage of simulating fire scenarios with CFD. The boundary of risk is

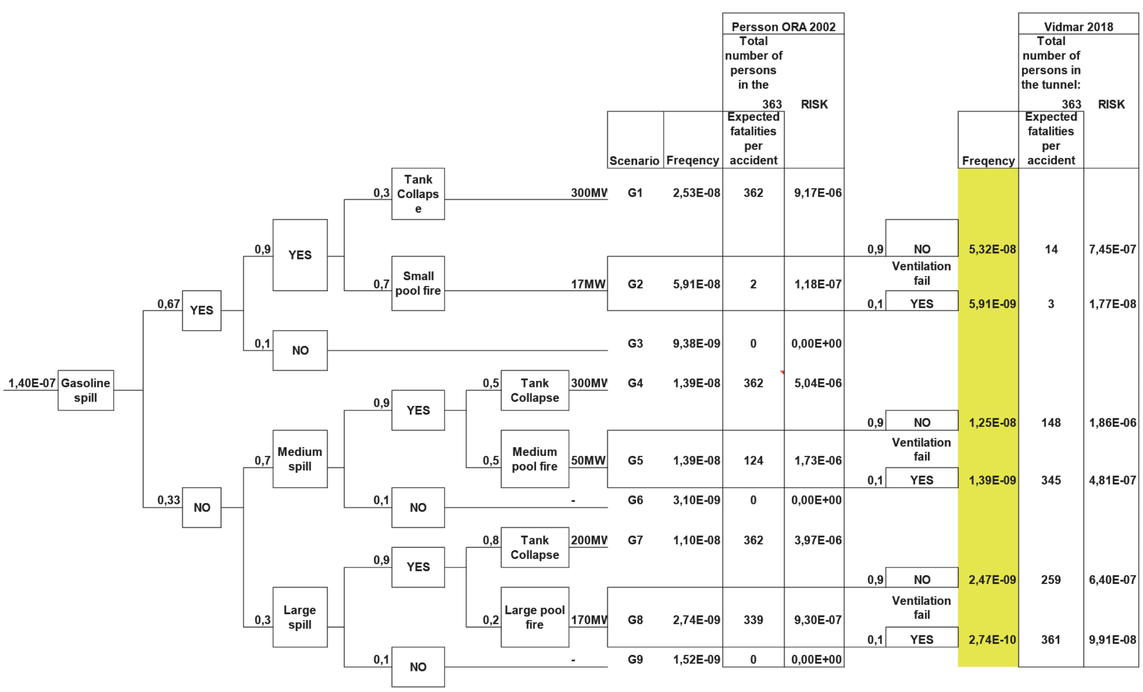

Figure 6.
Event tree for gasoline spill.

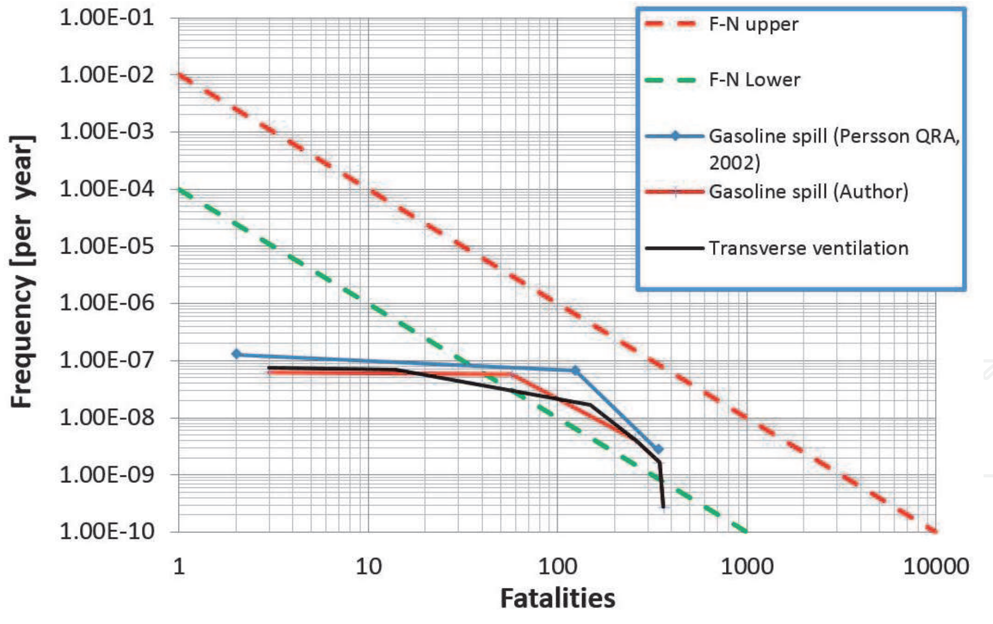

Figure 7.
Collective risk level for gasoline spill in a tunnel.

Gasoline spill (author)			
Fatalities [per accident]	**PLL risk (fatalities) [per year]**	**Event frequency [per year]**	**Cumulative fatality frequency [per year]**
0	$0.00E + 00$	$1.25E - 08$	$7.58E - 08$
3	$1.77E - 08$	$5.91E - 09$	$6.32E - 08$
57	$3.03E - 06$	$5.32E - 08$	$5.73E - 08$
258	$6.37E - 07$	$2.47E - 09$	$4.14E - 09$
345	$4.81E - 07$	$1.39E - 09$	$1.67E - 09$
361	$9.91E - 08$	$2.74E - 10$	$2.74E - 10$

Table 5.
Cumulative risk for gasoline spill accident.

defined with a risk acceptance criteria. Since the risk criteria vary from country to country, it is difficult to generalise and say whether the risks are acceptable or not. Author Trbojevic [30] and others have emphasised the individual risk criteria based on the existing national standards and guidelines. The harmonisation of risk acceptance criteria for the transport of dangerous goods is proposed in the final report of the DG-MOVE project [31]. The upper and lower risk used is (**Table 6**):

Parameters for societal risk criteria	Value	Denomination
F_{upper} (dotted line between ALARP and intolerable)	$1 \bullet 10^{-2}$	Fatalities/year
F_{lower} (dotted line between ALARP and negligible)	$1 \bullet 10^{-4}$	Fatalities/year

Table 6.
Limits for societal risk.

The F-N curve modelled by Persson [16] is very close to the curve modelled in this paper by the authors. 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 (ROCs) are needed. In case one, if the risk curve would exceed the upper risk criteria and therefore impose the ROCs, a precise calculation of consequences could reduce the actual risk. **Figure 7** also shows the F-N curve for the same scenarios (G2, G5, G8) using transverse ventilation during a fire. 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 for a transfer ventilation indicates the advantage of this ventilation for long tunnels.

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 one-dimensional flow movement models is appropriate, under the authors' consideration, for the verification of ventilation plans, but is not reliable enough for the estimation of individual risks.

Risk assessment is normally a continuous process observed on 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 (TEN) 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 us that assessments have been conducted once for the majority of tunnels, there is a strong justification to perform 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 or other methods.

6. Conclusion

A complexity of fire scenarios with different tunnel ventilations and fire forces is presented in the paper. Despite the long computational time required to process CFD simulation of fire in a tunnel, the process is worth the time and necessary for evaluating the most likely consequences to users during an accident. The reliability of CFD results is significant, and the validation of the fire model is presented compared with experimental results. This is a mandatory process of a model preparation before the actual scenario simulations. A deep focus on CFD models is omitted from the paper although a large number of referenced authors have applied FDS to tunnel simulation. The processing of results is further presented in the paper. Several authors, referenced during the discussion, never used CFD results to assess the risk to individuals, including during evacuation. The risk is here presented ranging from simulation results to risk levels from low to extreme risk, depending on temperature and smoke concentration at different tunnel heights. According to human resistance to high temperature and smoke concentration, the exposure risk is evaluated and presented in the number of fatalities per exposure time. The overall risk of a scenario is presented for natural, longitudinal and transverse ventilation.

The use of CFD programs in fire analysis is not new and has been widely used for more than a decade and has become a powerful tool for deep consequence analysis. The risk assessments of fire scenarios, on the other hand, still use a faster computational method. This is understandable where the risk is continuously assessed, but for tunnels with an unchanged geometry and ventilation systems, it is done but once. The most recognised representation of a societal risk is with a risk matrix, or, better, risk curves, as used in this paper. The methodology regarding how to link the calculated fire dynamics variables to consequences for human lives is explained, as well as, further, the use of these consequences to quantitatively determine the risk for users. Although the process for CFD calculation is time demanding, the author believes that taking such time is important, as it provides more reliable results and better support for the decision-making in the selection of effective risk control options.

The new improvement for the future risk assessments in tunnel would be the implementation of new fuels in the automotive technology either pressurised gas like LPG or hydrogen and LNG. Similarly, a larger introduction of hybrid and electric vehicles would influence the change in the concept of tunnel safety.

Author details

Peter Vidmar
Faculty of Maritime Studies and Transportation, University of Ljubljana, Portorož, Slovenija

*Address all correspondence to: peter.vidmar@fpp.uni-lj.si

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