APPLICATION OF IN-HOUSE RISK ASSESSMENT TOOL ON THE ANALYSIS OF A TUNNEL IN THE NEW GRONDA DI GENOVA HIGHWAY

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ABSTRACT

The tool developed by Cantene called ARTU, acronym for "Risk Analysis in Tunnels", determines the societal risk related to fire in tunnels and calculates the FN-curve accordingly to the European Directive 2004/54/EC.

ARTU performs a quantitative assessment of risk, coupling probabilistic and deterministic approach, and including different sub-models: 1D fluid-dynamics, queue formation, egress, interaction between fluid-dynamic conditions and agents. Monte-Carlo approach is used to define different fire scenarios. In each scenario, values coming from statistical distribution are adopted for a set of random variables including pre-movement time and egress velocity, fire position, type of vehicle involved by the fire. The diffusion of smoke along the tunnel and the interaction with escaping agents is calculated in a deterministic way, taking into account the characteristic of tunnel (slope, cross-sectional area, ventilation system) and the position and magnitude of fire.

ARTU focuses on life safeguard. The damage users suffer from the fire is estimated coupling 1D fluid-dynamics and egress models. The movement of agents is calculated considering environmental conditions, FED (Fractional Effective Dose) is calculated for each agent at each time-step.

ARTU has been validated by the Lund University. A set of full-scale experimental data from tunnel fires was used as benchmark. A sub-set of those cases were also compared with a Computational Fluid Dynamics software (Fire Dynamics Simulator FDS). To perform the verification of the key sub-models of the evacuation modelling module and the probabilistic risk analysis calculations, hand calculations of different ideal cases were compared to the results from the tool.

A case study is presented, about a tunnel in the new Gronda di Genova highway. The city of Genova in Italy stretches on a narrow coast between sea and mountains. A new highway, Gronda di Genova, is under construction with a length of 65km, 81% of which are underground tunnels.

Keywords: Risk analysis, 2004/54/EC, life safeguard, 1D fluid-dynamics, probabilistic approach, validation, Gronda di Genova.

1. INTRODUCTION

The number of tunnels used for transportation purposes around the world is steadily increasing (Kazaras & Kirytopoulos, 2014). Factors increasing the potential hazards of road tunnels are rising traffic densities and consequently higher fire loads, increasing length of modern tunnels, transportation of hazardous materials (Bergmeister & Francesconi, 2004).

Since the publication of the Directive 2004/54/EC of the European Parliament, risk assessment has become an integral part of tunnel design (Kohl, Botschek, & Hörhan, 2007) within the Trans-European Road Network which are longer than 500 meters (The European Parliament, 2004).

According to (Høj N.P., 2002), risk analysis can have a number of purposes: (i) to demonstrate and document a sufficient safety level to authorities or to internal corporate policies; (ii) to serve as basis for risk communication to the public, to investors or to other stakeholders; (iii) to represent the ground for decision-making during the planning and design of an infrastructure, helping to balance risks against costs associated with risk-reducing measures; (iv) finally, risk analysis has contributed to increased traffic safety (Høj N.P., 2002).

The concept of risk analysis in the scope of road tunnel environments is still under development (Nyvlt O., 2011). Main issues are related to uncertainties: the expected number of fires in tunnels, the propagation of smoke and heat, the evacuation modelling process, the performance of safety systems and the performance of emergency services are based on several assumptions. It is of most importance for road tunnel safety assessments to be complemented with innovative and suitable methods that have the ability to capture all the key factors affecting road tunnel fire safety (Kazaras & Kirytopoulos, 2014).

2. AIM AND OBJECTIVES OF THE TOOL

The aim of authors was to develop a tool suitable for the evaluation of risk in new and existing tunnels. The focus of the desired tool is on life safety, the expected output of analysis is the societal risk, namely expected number of fatalities per year. The aim of the analysis is to determine the risk related to the occurrence of a fire, based on the assumption that is the most serious threat to tunnel safety (Nyvlt O., 2011). It is assumed that the risk related to other types of accidents (e.g., vehicle collisions) is dealt within the whole road network infrastructure and it is not specifically related to tunnels. Finally, the tool should be suitable for taking into account modifications of the tunnel and its safety systems. This is due to the fact that risk analysis can be used as a tool to evaluate different design solutions, or to check the effect of minor modifications of an existing tunnel. Minor modifications include for example the addition of noise barriers on portals, the addition of new emergency exits, the refurbishment of the ventilation system, etc.

3. EXISTING METHODS AND TOOLS FOR RISK ANALYSIS

In the road tunnel field, risk assessment methods can be divided into two major groups: qualitative and quantitative. Many risk analysis methods are based on quantitative risk assessment (QRA) models, which include: the Austrian tunnel risk model TuRisMo, the Dutch TUNPRIM RWS-QRA model, the OECD/PIARC DG-QRAM model and the QRAFT model (Beard A. C. D., 2007). Quantitative models can be deterministic or non-deterministic. In many cases, a deterministic approach is used (PIARC , 2019), comparing evacuation and fire simulation data for a few scenarios (or a worst-case scenario), where the results are the expected number of fatalities in each specific scenario. This approach does not account for all possible different combinations of fire and evacuation scenarios, which means that it does not consider uncertainties in an efficient way (Modarres, Joglar, Mowrer, & Azarm Ali, 1999). In order to consider uncertainties, a probabilistic approach can be used.

A comparative overview of methods and tools is presented in **Table 1**. The focus here is on the initiating events and the evaluation of damage, expressed as the number of fatalities.

Table 1: overview of existing risk analysis methods and tools

Method /tool	**Initiating events**	**Evaluation of damage (number of fatalities)**
TuRisMo (PIARC , 2008)	fire, collision	based on numerical simulation of a set of cases, done during the method setup
TunPrim (Brussard, 2001)	fire, collision, explosion, toxic gas release	based on a combination of statistics and conditional probabilities

QRAM (PIARC , 2008)	13 incidents related to the presence of DG	based on the determination of the area affected by the event
QRAFT (Meng, 2011)	fire, collision, collapse, flood, toxic gas release, explosion, DG release	based on statistics
(Derudi M., 2018)	fire, DG release	based on CFAST (zone model) fluid-dynamic simulation and (not specified) egress simulation
(Jönsson J., 2007)	fire	based on FDS (field model) fluid-dynamic simulation and hand calculation-based egress simulation

As explained before, initiating events different from fire (e.g. explosion, gas release) are considered out of the scope of ARTU. In the tools and methods presented in Table 1, damage estimation is performed using a wide range of methods. The methods based on the determination of the area affected by the fire and those based on statistics may not sufficiently capture the effects of minor modifications on the tunnel and, for this reason, are deemed not in line with the scope of ARTU. The use of fluid-dynamics modelling of scenarios was assessed to be the most appropriate approach for ARTU. Among the tools that use this method, TuRisMo is deemed to use this in a systematic way, which may be in turn limited in scope due to the set of pre-analysed cases on which it is based upon, since the results are applicable to tunnels considering a pre-defined range of factors. The applicability of the method based on field model representation of fluid-dynamic is limited by the high computational needs. For this reason, the applicability of this method is limited if the analysis of a large number of scenarios is required. The use of zone modelling reduce the computational requirements respect the use of field modelling. Nevertheless, the representation of ventilation devices used in tunnels, such as jet-fans, may require dedicated model input calibration efforts in the zone model environment.

4. DESCRIPTION OF ARTU

A risk assessment tool called ARTU (Italian acronym for “Tunnel Risk Analysis”) was developed. ARTU calculates the societal risk, represented by an FN-curve. The FN-curve can be compared to an ALARP diagram accordingly to the country regulation.

ARTU uses an approach based on pseudo-random sampling from distributions to define hundreds of different fire and egress scenarios. In each scenario, values coming from statistical distributions are adopted for a set of random variables including pre-movement time and egress velocity, fire position, and the type of vehicle on fire.

A deterministic approach is used to describe the interaction between fire products and people involved in each scenario. The diffusion of smoke along the tunnel and the interaction with escaping agents is calculated taking into account the geometric layout of tunnel and the position and magnitude of the fire.

The fluid dynamics representation in ARTU is based on 1D fluid-dynamics, which includes geometrical data and characteristics of the ventilation system. The 1D fluid-dynamics analysis returns time-varying air temperature, air velocity, and volume airflow along the tunnel. The benefit of using 1D representation of fluid-dynamics are (Beard A. C. R., 2005): (i) 1D models have low computational requirements; (ii) 1D models give advantages for the analysis of a complex network system, constituted by a tunnel and its ventilation system, allowing a complete and compact description of the system. Low computational cost makes these models particularly suitable for parametric studies where a large number of simulations have to be conducted.

A queue-formation model is used to determine the initial position of agents along the tunnel, taking into account data about traffic condition and volume. The path of each agent inside the tunnel through the exit is calculated assuming that the people in a straight or curved tunnel can only move in one direction (along the tunnel), which can be approximated with a 1D modelling approach. ARTU takes into account the presence of other agents in the surroundings and the reduction of visibility due to smoke. The estimation of damage is based on the effects of smoke on escaping agents, estimated by means of the FED (Fractional Effective Dose) parameter (Purser & McAllister, 2016). For the majority of toxic products in a fire atmosphere, a given toxic endpoint such as incapacitation or death occurs when the victim has inhaled a particular product dose of toxicant (Purser & McAllister, 2016). As with toxic gases, an exposed occupant can be considered to accumulate a dose of convected heat over a period of time (NFPA, 2011). ARTU calculates the FED for each agent in the domain, based on oxygen, carbon monoxide, carbon dioxide concentration and gas temperature, obtained from the results of the 1D fluid-dynamics routine.

ARTU is also suitable to provide a set of additional results, preventing the needs of further analysis conducted by means of fluid-dynamic and egress models, which typically have high computational cost. Some of these additional results are: (i) air velocity upstream the fire, that can be compared with the critical velocity (Ingason, Li, & Lönnermark, 2015) in order to verify the smoke confinement; (ii) a detailed description of damage in terms of the FED parameter, ranging from 0 to 1 for each agent in the analysed population; (iii) weak points in the tunnel, e.g. a specific position along the tunnel in which a fire can heavily affect the safety.

5. VALIDATION OF ARTU

Verification and validation process is important firstly to know whether the tool can be used in tunnel projects and secondly to determine whether a margin of safety should be recommended and how large it should be. ARTU has been validated by the Division of Fire Safety Engineering of Lund University (Sandin, et al., 2019).

Validation process addressed a given set of applications of ARTU, namely 1) road tunnels, 2) presence of longitudinal or natural ventilation, 3) no fire suppression system or emergency service that extinguish the fire are taken into consideration, 4) no fire spread between vehicles, 5) no consideration is given to the risk of technical systems malfunctioning, 6) tunnels are assumed without slip roads (entry or exit), 7) no boiling liquid expanding vapour explosion or other explosions that can occur due to the transport of dangerous goods. It is therefore assumed that a fire starts in a vehicle, and not due to malfunctioning of tunnel equipment.

The results from ARTU, related to the 1D fluid-dynamic model were compared with already known results from well documented full-scale experiments performed in tunnels. The selection of case studies was based on which results were available to compare and the reliability of the source. A comparison with FDS, the Fire Dynamics Simulator (McGrattan, Hostikka, McDermott, Floyd, & Vanella, 2019) results was performed for cases in which experimental results were not available in the literature or could not be directly compared to ARTU. Based on a comparison of results performed with functional analysis, ARTU provided conservative results in four out of five analysed cases. ARTU gave results with better agreement in cases with ventilation than in cases without ventilation (which provided more conservative results).

The evacuation routine of ARTU was checked by means of a set of different ideal cases, run both with the ARTU tool as well as with hand calculations. The verification of sub-models within evacuation modelling has shown that the tool gives reasonable results with a margin of error that depends mainly on the numerical grid dimension used in ARTU.

In order to verify the probabilistic risk analysis, it was decided to not use another risk analysis method to compare the output with the output from ARTU. Since an existing method can have its own issues that may not be fully understood, a fair comparison is difficult to make. The data with the number of fatalities calculated by ARTU for each scenario were used to calculate frequencies by hand for each fatalities interval. These frequencies were used to draw the FN-curve which then was compared with the curve by ARTU.

In the end, a sensitivity study of the results of ARTU was performed, varying five key factors (pre-movement time, fire occurrence rate, probability of standstill traffic, number of vehicles and percentage of different vehicle types) to evaluate their impact on the FN-curve.

Overall, it was proved that ARTU provides conservative results for risk analyses in road tunnel (Sandin, et al., 2019).

6. CASE STUDY

A case study was selected (see **Table 2**), regarding a tunnel in the new Gronda di Genova, an under construction highway with a length of 65km, 81% of which are underground tunnels.

Table 2: main characteristics of the case study tunnel

Length / Cross sectional area / Slope	6 km / 93m^2 / -0.5%
Number of emergency exit	18
Traffic direction	Unidirectional
Average annual daily traffic / % of heavy goods vehicle	18.800 veh/day / 31%
Ventilation system / Fixed-fire extinguishing system	Longitudinal (jet-fans) / None

Figure 1 shows the FN-curve obtained by ARTU (bold curved line), compared with the Italian ALARP diagram. Diagram is divided in three regions. Region above the upper straight line corresponds to not acceptable risk. Region below lower straight line corresponds to acceptable risk. Region between straight lines is the ALARP (As Low As Reasonably Possible) region.

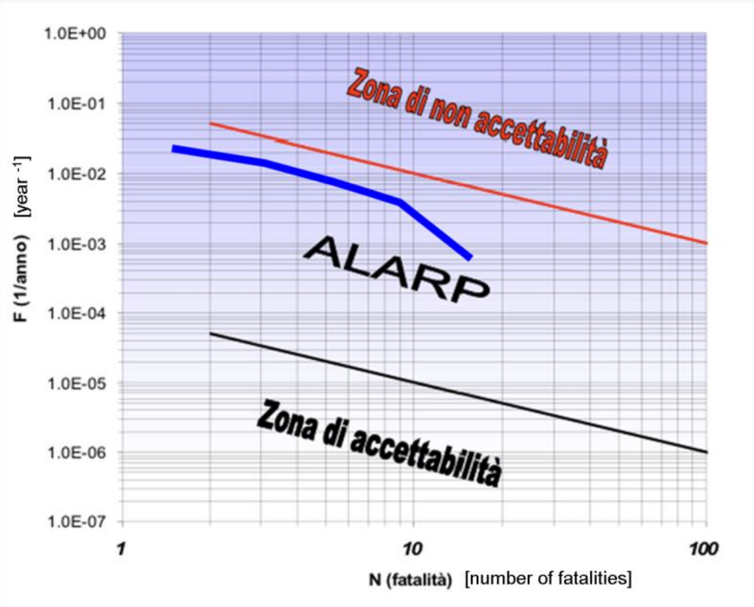

Figure 1: FN curve for the tunnel under analysis

The analysed tunnel falls in the ALARP region, where the risk is considered acceptable, if it cannot be reduced with a reasonable effort.

A sensitivity analysis was done to evaluate the effect, on safety performance of the tunnel, of the emergency exits number and standstill traffic. **Figure 2** show the Expected Value for three sensitivity cases. Expected Value (EV) is the integral of the FN-curve. Higher EV means higher level of risk. In **Figure 2** it can be seen that the number of emergency exits and the probability of standstill traffic have an impact of the safety of the tunnel.

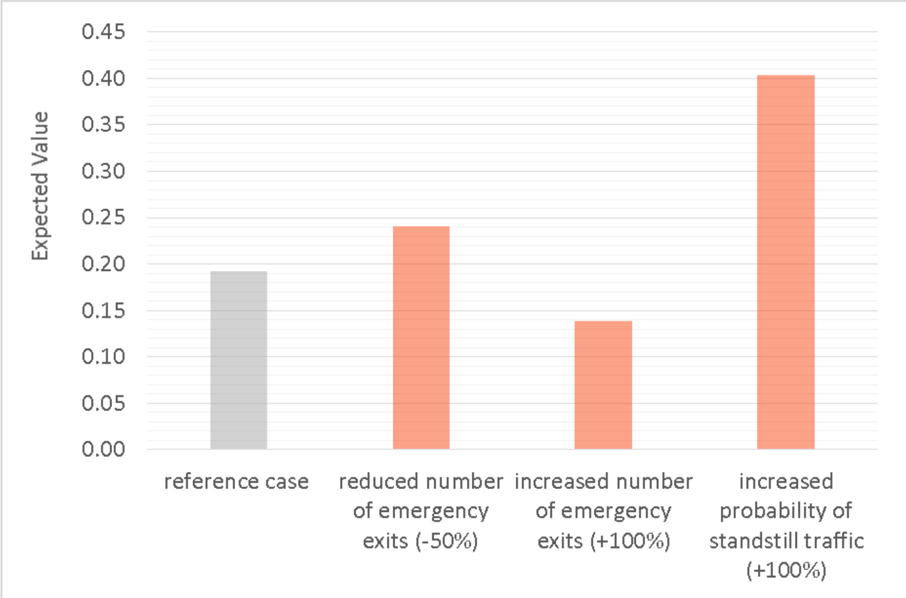

Figure 2: Sensitivity analysis varying the number of emergency exits

In order to make a comparison with ARTU, a scenario involving a fire in the middle of the tunnel was analysed with FDS+EVAC (McGrattan, Hostikka, McDermott, Floyd, & Vanella, 2019), (Korhonen, 2018). FDS+ EVAC includes a field-model for fluid-dynamic description and an agent-based model for evacuation description. In this scenario, the fire has a linear growth from 0 to 600s, when it reaches a maximum power equal to 100MW. A plot (**Figure 3**) is obtained post-processing the FDS+EVAC outputs. Plot refers to the first half of the tunnel (upstream the fire). The background colour indicates the visibility level in correspondence of the sidewalk, at 2m from floor. Plot shows also the path of agents (narrow white lines) through an exit (which position is indicated by a green, vertical straight line).

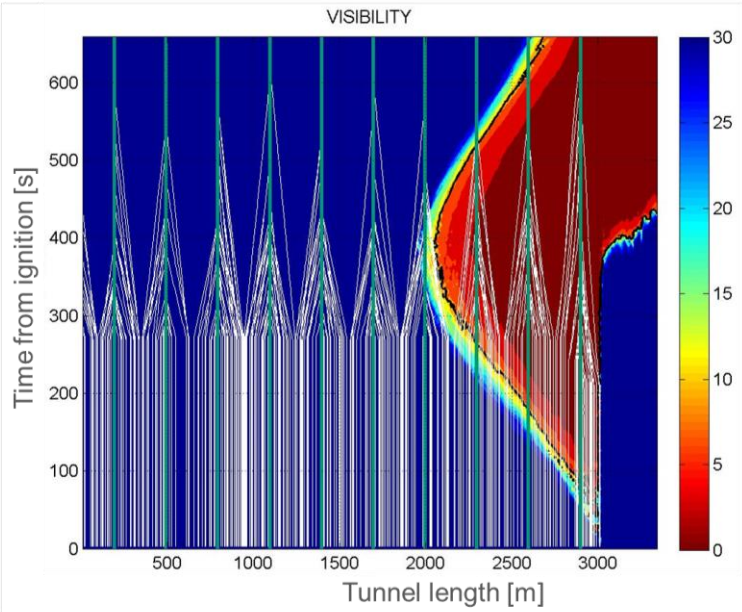

Figure 3: Results obtained by FDS+EVAC simulation

FDS+EVAC analysis returns a maximum FED value equal to 0.05. An analysis carried by ARTU, considering 750 scenarios with the same HRR curve in the same position, returns an averaged maximum FED equal to 0.14. ARTU is hence proved to give conservative results. This is also due to the fact that ARTU takes into account gas temperature in the FED estimation, differently from FDS+EVAC, which considers only chemicals.

7. SUMMARY AND CONCLUSIONS

The methodology and tool presented, ARTU, aims to the risk assessment of tunnels. ARTU couples probabilistic and deterministic approach, and gives societal risk (FN-curve) as result. ARTU has been validated by Division of Fire Safety Engineering of Lund University. It was proved that, overall, it provides conservative results for risk analyses in road tunnel (Sandin, et al., 2019). A case study is here presented, related to a longitudinal ventilated tunnel. The case study showed that ARTU gives results, in terms of Fractional Effective Dose, that are comparable (and more conservative) to those obtained using FDS+EVAC.

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