

STATE OF THE ART AND LINES OF DEVELOPMENT FOR THE ARTU RISK ANALYSIS SOFTWARE

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ABSTRACT

ARTU, acronym for “Risk Analysis in Tunnels”, determines the societal risk related to fire in road tunnels and calculates the FN-curve accordingly to the European Directive 2004/54/EC. ARTU performs a quantitative assessment of risk, coupling probabilistic Monte-Carlo and deterministic approach.

In the last years, some updates were made in order to make ARTU suitable to address a wider range of tunnel typologies. As an example, a multi-scale approach to fluid-dynamics has been included, based on a zone model developed by Lund University, called MZ.

At the same time, many efforts were put in assuring that ARTU results are reliable. Fire tests have been performed at the Lund University scale tunnel facility to validate the software and study the applicability limits.

Based on these results, a methodology has been drawn up to identify the cases in which ARTU gives satisfactory results and cases in which further analysis are needed. Regarding the smoke dynamic, the use of the 1D model introduces some errors in particular for what concerns the presence of stratification and back-layering. These errors are partially corrected by the multi-scale approach but could have a relevant effect in the risk estimation for tunnels with specific characteristics as the absence of mechanical ventilation or bidirectional traffic. In these case, further analysis, as CFD simulations, could be needed to obtain robust and appropriately conservative results. The methodology aims at a systematically classification of tunnels and procedure to be followed to properly assess the risk.

The present paper discusses the above mentioned methodology in the framework of existing risk analysis methods. The paper also includes an overview of main road tunnel risk analysis developed by ARTU. This allows to clarify the ARTU applicability limits, strong points and possible future developments.

Keywords: ARTU, risk assessment, fluid-dynamics model, methodology.

1. INTRODUCTION

According to PIARC, tunnel risk assessment methodology can be divided in scenario-based and system-based approach. In the scenario-based approach, a set of relevant scenarios is defined and risk assessment is done separately for each single scenario along with the estimation of the probability of occurrence. When applying a system-based approach, instead, risk value for an overall system is estimated, taking into account all events/scenarios which can affect persons in the system [1]. A limitation of scenario-based approach is its sensitivity

to the choice of the set of analysed scenarios. Not accounting for all possible different combinations of fire and evacuation scenarios, it does not consider uncertainties in an efficient way.

ARTU software implements a system-based approach. ARTU performs the risk assessment of a tunnel simulating a large number of scenarios, varying fire position and HRR (Heat Release Rate) curve and traffic conditions. Each scenario returns a certain number of fatalities, the results are cumulated and plotted on a FN diagram. Based on the case, the FN curve can be compared with a reference tunnel, which is a tunnel having the same characteristics of the one under examination, but fully compliant with the European Directive requirements. In this way, it is possible to assess if the lack of some measures, as an example the emergency exits, is likely to increase the risk or it is mitigated by the presence of additional measures.

ARTU includes different sub-models: queue formation, egress, interaction between smoke and people (based on FED – Fractional Effective Dose – parameter), one-dimensional (1D) and zone models fluid dynamics.

One-dimensional (1D) models resolve fluid mechanics equation by assuming that the physical parameters (temperature, velocity, pressure) are all uniform in the cross section [3]. The main advantage of 1D models is that they have low computational requirements, and are particularly attractive for parametric studies where a large number of simulations have to be conducted [4]. This is the case of the methodology implemented in the ARTU software, which aims at the simulation of a large number of scenarios varying the heat release rate (HRR) and position of fire. 1D models permit to model in a complete and compact way complex network systems, constituted by a tunnel and its ventilation ducts [3]. In the case of long tunnels using a transverse ventilation system, the 1D model is the only one capable of modelling the system in its entirety [4]. 1D models are well suited to the study of longitudinal ventilation, since they provide reliable and realistic results when the air velocity is above the critical value [4]. With other ventilation systems, as transverse or semi-transverse systems, using 1D models requires more expertise. Caution is required in interpreting results, due to the possible presence of stratification and back layering phenomena.

3D CFD models provides a solution of the Navier–Stokes equations. The need of appropriate boundary conditions along with detailed input data greatly influence the results [4]. Fluid flow processes are complex and, in order to judge the quality and accuracy of a simulation, an understanding of fluid mechanics and experience of the particular class of flows simulated is necessary [3]. CETU [4] suggests to perform and interpretate a preliminary 1D analysis where a 3D CFD model is used for the specific hazard investigation. In tunnel fire studies, the 3D CFD software FDS (Fire Dynamic Simulator) has become one of the primary tools [9]. Its characteristics allow for significantly larger cell volumes of the numerical mesh, making FDS particularly suitable in risk analysis even if the accuracy of course decreases with increasing volume of numerical grid cells [9], [10]. Nevertheless, some issues arise when applying FDS to tunnels [11][12].

In many cases, it is practical to use 3D CFD models to represent a small tunnel portion, and to account for the effects of the remaining portion of the tunnel by means of 1D models. This class of hybrid models, known as ‘multi-scale models’, are usually based on the coupling between multi-dimensional (e.g. CFD) and 1D (e.g. network model) solvers [3].

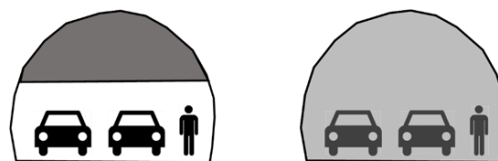
ARTU implements a multi-scale approach coupling 1D model with a multizone (MZ) model [5] developed specifically for the tunnel environment. The MZ model represents the entire enclosure through several smaller computational volumes (zones), for which the conservation of mass and energy are applied. Fire is specified as a heat release rate and empirical models

are used to represent the plume and the ceiling jet [5]. The model was originally developed by Lund University [13] for generic enclosures and has been improved [6] in order to make it suitable to the application in tunnels. The use of the MZ model makes it possible to represent two phenomena that cannot be modelled through 1D fluid-dynamic software, namely the smoke stratification and the presence of back-layering. The MZ model development includes continuous validation by means of scale tunnel fire tests, that lead to the definition of its applicability field. Currently, the MZ tool has been founded reliable in the analysis of fire up to 20MW, and in short domain (<200m from the fire) [6]. As a consequence, the necessity arises to define in which cases the 1D-MZ modelling procedure is suitable to produce reliable and satisfactory results. Further analysis, including more complex CFD solvers as the Fire Dynamic Simulator (FDS), are required case-by-case to validate the ARTU estimation of risk. This approach is in accordance with the recommendations of some regulatory authorities, as the Italian ANSFISA that requires [7] an evaluation of the applicability of the tool used to assess the risk to the specific tunnel under analysis.

Chapter 2 discusses the methodology followed by authors to identify the tunnels that requires specific evaluation in order to determine the best approach to assess the risk. The unreliability index automatically calculated by the ARTU software is presented. Chapter 3 presents a set of 41 case studies analysed following the presented methodology, in order to better clarify the role of the unreliability index and to present a qualitative assessment about the suitability of the ARTU tool in the risk assessment of road tunnels.

2. A METHODOLOGY TO IDENTIFY THE TUNNELS WHICH REQUIRES FURTHER ANALYSIS

In order to identify the tunnels that require in-depth analysis, a methodology has been developed, based on an analysis of the 1D fluid-dynamic and MZ models limitations. The fact that stratification and back-layering are not taken into account when estimating the interaction between tunnel users and smoke could lead to both an over-estimation or under-estimation of risk, depending on the case. The lacking representation of stratification phenomena leads generally to an over-estimation of risk, since the 1D models assumes the smoke as homogeneously distributed, while it can be well stratified at a considerable height, as depicted in **Figure 1**.



Smoke distribution in reality Smoke distribution in 1D model

Figure 1: Lack of smoke stratification representation in 1D models

The lacking representation of back-layering has an effect that depends on the position of tunnel users respect to the fire. In some cases it leads to an under-estimation, while in other case the results is an over-estimation (**Figure 2**).

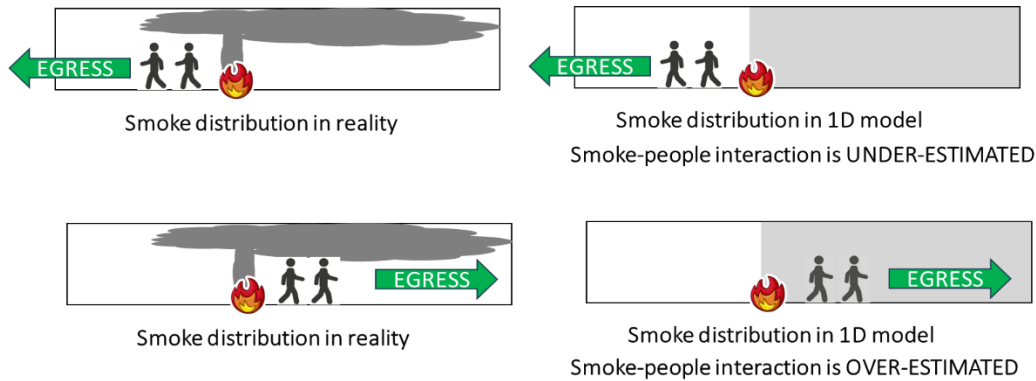


Figure 2: Effect of back-layering missing representation on the estimation of interaction between people and smoke

As previously mentioned, tunnel with longitudinal ventilation are generally well described by 1D models. MZ model is useful to model the first phase of fire, before the activation of emergency ventilation. Usually, this happens by 3-5 minutes from the ignition, and the 1D-MZ representation of smoke behaviour is appropriate. In some case, instead, the emergency ventilation is activated with a larger delay, for example in the case of bidirectional tunnels or monodirectional tunnels in which traffic congestion is frequent. In this case, the ventilation strategy is based on the control of the air velocity that should remain lower than 1 or 1.5m/s, depending on the specific case, in order to promote stratification of smoke and create a fresh air layer in the lower part of tunnel, to allow people egress. Hence, stratification and back-layering lasts for a long time (10-30 minutes) and involves a portion of tunnel for which the MZ application is not fully validated. As a consequence, a case-by-case evaluation is needed for bidirectional or monodirectional congested tunnels.

Regarding transverse and semi-transverse ventilation systems with more than one extraction damper, these always imply the stratification of smoke for the whole duration of emergency. In this case, the 1D representation of smoke could lead to an over-prediction of the interaction between people and smoke. Furthermore, back-layering could appear outside the extraction zone, due as an example to unbalanced pressure related to meteorological conditions at portals. Due to the wide range of possible architecture of the transverse and semi-transverse ventilation system, a case-by-case evaluation is needed.

Naturally ventilated tunnels can be considered as longitudinal ventilated tunnels if their slope is high enough to create a chimney effect able to produce an air flow with velocity similar to the critical value. Nevertheless, chimney effect depends on the position and magnitude of fire, and critical velocity is affected by the tunnel cross-section, so it is difficult to a-priori identify the tunnels that can be treated as longitudinal ventilated.

Finally, each tunnel that shows peculiar characteristics needs to undergo a specific analysis. As an example, a non-exhaustive list of peculiar characteristics includes strong winds at portals, intermediate access/exit ramps, fluid-dynamic connection with other tunnels. All tunnels included in these categories needs a specific evaluation in order to determine whether the risk assessment can be conducted with the ARTU tool or it is necessary to combine it with a scenario-based approach in order to deepen the effect of peculiar characteristics on the overall risk. Based in this discussion, the following flow-chart has been defined.

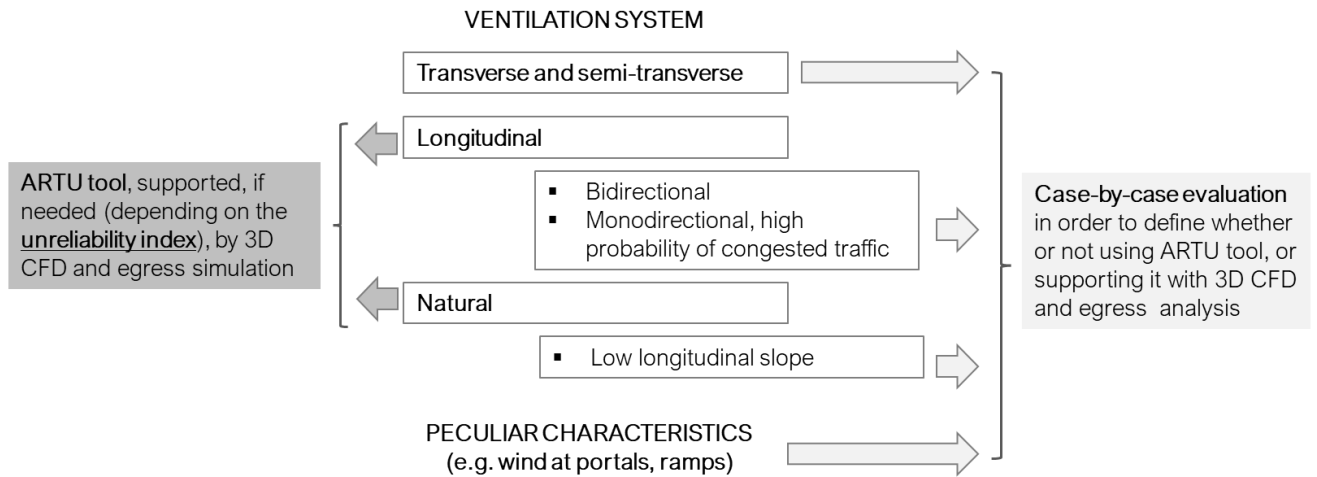


Figure 3: Methodology flow-chart

In any case, regardless a case-by-case evaluation is needed or not, ARTU tool computes an unreliability index in order to quantify the impact, on the FN curve estimation, related to the lacking representation of back-layering.

2.1. The unreliability index

An unreliability index is calculated during the execution of ARTU code, in order to monitor the error in the estimation, due to the use of 1D model, of the smoke-users interaction. The index is defined in order to monitor the cases in which a back-layering has not been taken into account by the 1D model, outside the applicability field of MZ model. The index returns the percentage of cases in which an under-estimation of the interaction between people and smoke could have been happened. The higher the index, the higher the potential under-estimation of risk.

An unreliability index equal to a certain value, as an example 10%, means that in the 10% of the scenarios that composes the FN curve, there is a significant (in terms of duration) lacking back-layering representation. The presence of back-layering does not automatically imply that people will interact with that back-layering. The unreliability index does not state that there is an interaction between people and smoke that was not represented by the software. It states that further analysis, by means of more sophisticated tools as 3D CFD simulations, are required to assess it.

Figure 4 shows the acceptance scale currently associated do the reliability index. Index lower than 25% (green zone) is considered sufficient to guarantee reliable results. Index higher than 75% (red zone) requires further analysis. Values in the range 25% ÷ 75% (yellow zone) suggest to put particular attention in the analysis of ARTU results and, based on the user judgement, could require further analysis.

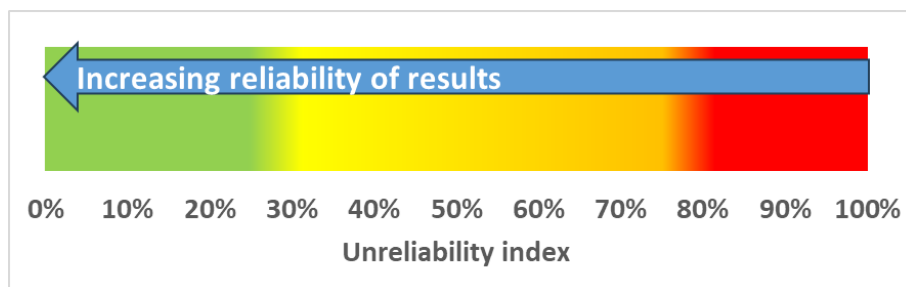


Figure 4: Acceptance scale used to compare the reliability index and dataset results

The acceptance scale (**Figure 4**) is set based on the experience and takes into account the fact that the FN curve obtained by ARTU is computed taking into account some thousands of cases, and only some of them (corresponding to the value of the unreliability index) are potentially affected by underestimation of fatalities. Since ARTU implicitly include conservative assumptions, due to the uncomplete representation of stratification, it is possible that fatalities are generally over-estimated, despite the potential error in back-layering representation.

When required due to the index falling in yellow or red area, further analysis involves additional 3D CFD and egress simulations. The results of 3D CFD and egress simulations, in terms of fatalities calculated by means of FED (Fractional Effective Dose) parameter, are compared with the ARTU results. Worst case scenarios, in terms of back-layering development, are selected.

Depending on the result of the comparison, the FN curve could be adjusted including the results obtained by 3D CFD and egress simulation. In the case the FN curve has to be adjusted, some qualitative considerations are done to extend results related to the specific scenarios analysed with 3D CFD + egress simulations to other scenarios. Such considerations take into account as an example longitudinal profile, cross-section variations, emergency exits position. The process to extend results of some specific scenario to the rest of tunnel involves what recommended in [8], which states that in a scenario-based approach, analysis of the results must be carried out with regard to the scenario considered and the choice of its parameters. For example, significant consequences must be put into perspective if the chosen parameters are unfavourable.

The number of scenarios to be analysed by means of 3D CFD and egress simulations depends on the characteristics of tunnel, namely geometry (slope, cross sectional area, length), ventilation system typology and architecture, and traffic conditions (congestion probability, percentage of heavy goods vehicle and bus). Indicatively, up to 1-4 3D CFD simulations can be needed, depending on the case. For each 3D CFD simulation, one or more egress simulations can be done, varying the number of people in the tunnel or egress-related parameters as the pre-movement time, accordingly to what ARTU does, in order to make results fully comparable.

3. ANALYSIS OF A SET OF CASE STUDIES DEVELOPED BY MEANS OF THE PRESENTED METHODOLOGY

For the present analysis, 41 road tunnels are considered. The larger part are motorway tunnel (37), remaining are rural (2) and urban (2). Tunnel length ranges from 471m to 4250m, with an average value equal to 1270m. 17 tunnels have a length larger than 1km. 37 tunnel have monodirectional traffic, and 4 bidirectional. Amongst the monodirectional tunnel, 22 have longitudinal ventilation system, 15 are naturally ventilated. Number of lanes is 2 for 35 tunnel, and 3 for 6. Cross sectional area varies from 47.6 m² to 123 m², with an average value of 68m².

Longitudinal profile shows a wide range of shapes and slope values. 8 tunnel have a humpbacked profile, 2 have a U-shaped profile. Globally, slope values ranges from 0 to 4.45%. Also the AADT (Annual Average Daily Traffic) ranges on a wide interval, from 4000 to 59100 with average value equal to 19300.

Figure 5 resumes the main characteristics of the tunnels dataset.

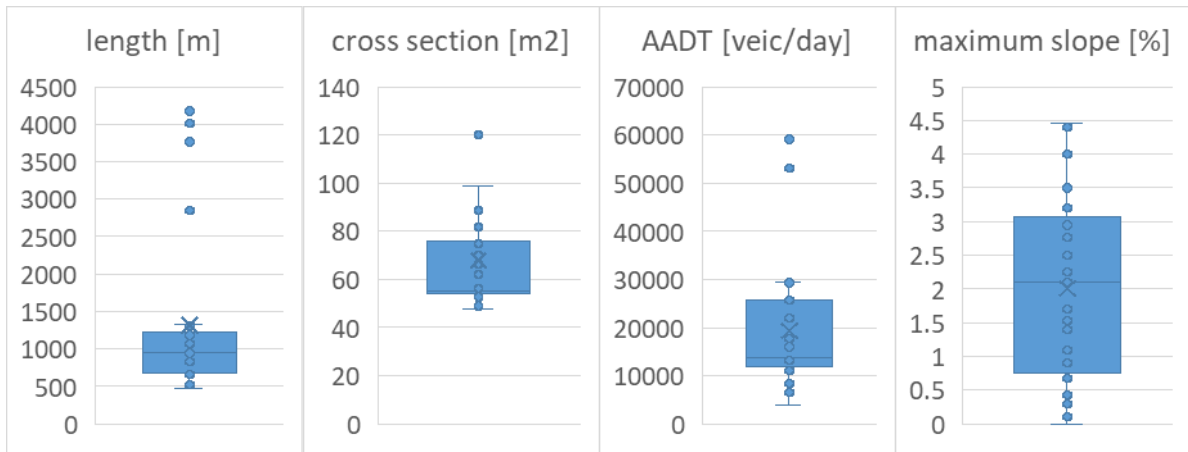


Figure 5: Main characteristics of the case studies dataset

Half of the analysed tunnels are monodirectional, with a length included in the range 500 ÷ 1200m and are provided with longitudinal ventilation system. Between them, nevertheless, 2 tunnels are characterized by a high probability of congested traffic occurrence (more than 3 hours per day).

7 tunnels required a case-by-case evaluation due to their peculiar characteristics, as resumed in **Table 1**. This was done preliminarily, before the analysis of the unreliability index. In particular, case 3 was out of ARTU applicability limit due to the slope = 0%.

Table 1: Outlier case studies

Case study	Tunnel characteristics	Approach to the risk estimation
1	Length = 4013m, bidirectional traffic, mixed (transverse and longitudinal, depending on fire position) ventilation system, few (2) emergency exit	ARTU analysis + semiquantitative analysis about the low number of exits
2	Length = 736m, monodirectional traffic, natural ventilation, frequent windy conditions (~4.5m/s) at portals	ARTU analysis + 4 3D CFD simulations, 3 of which took into account wind at portals, that lead to an adjustment of FN curve
3	Length = 714m, monodirectional traffic, natural ventilation, slope = 0%	ARTU cannot be used due to the 0% slope. 9 3D CFD simulations and 31 egress simulations have been done to draw the FN curve.
4	Length ~ 700m, monodirectional, longitudinal ventilation, high probability of congested traffic (3 hours per day)	ARTU analysis + 1 3D CFD analysis in order to assess the interaction between people and smoke in low longitudinal velocity (1m/s)
5		
6		
7		

Unreliability index varies from 0% to 100% in the analysed dataset. **Figure 6** shows the cumulate frequency of occurrence of different index values. 3 small squares over the graph indicates the percentage of cases in the dataset that fall in each zone (green, yellow and red).

It can be seen that 75% of dataset cases has an index $\leq 25\%$. 49% of analysed tunnels have an unreliability index equal to 0%.

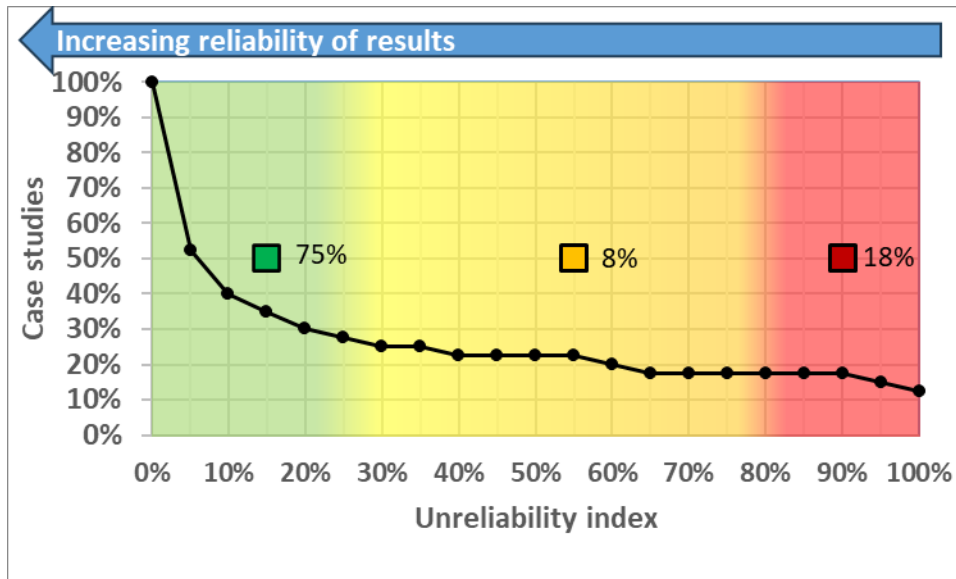


Figure 6: Cumulate frequency of occurrence of different index values

11 tunnels, having index higher than 25%, required a further 3D CFD and egress analysis. Amongst them, in 7 cases, this further analysis confirmed the ARTU estimation of risk. In the remaining cases it was necessary to adjust the FN curve. Hence, the correction was needed in 4 tunnels over 40 analysed with ARTU, in a dataset in which just 1 case (case 3 in **Table 1**) was out of applicability limits, due to the 0% longitudinal slope. Depending on the tunnel, the number of required 3D-CFD and egress simulations varied from 1 to 4. This number is far lower than the number of simulations that would have been required in a scenario-based approach. As an example, the outlier case 3 (see **Table 1**), which was not suitable to be analysed with ARTU required 9 3D CFD simulations and 31 egress simulation to produce the FN curve.

4. SUMMARY AND CONCLUSION

The need to check the suitability of the ARTU tool used in the tunnel risk assessment, combined with the necessity to keep the computational time reasonably low, lead to the development of a methodology that permits to evaluate, in a systematic and repeatable way, the suitability of the tool in the risk assessment of each specific tunnel. Beside the development of this methodology, an unreliability index was included in the code in order to estimate the accuracy of the ARTU risk estimation in a systematic way, taking into account the main limitations of its fluid-dynamic sub-routines, based on 1D model and the MZ (multi-zone) model.

An analysis carried out on 41 real tunnels showed that 7 of them were outlier, namely had peculiar characteristics that required specific analysis before launching ARTU analysis. Apart from that, based on the unreliability index, for 11 tunnels it was necessary to carry out further analysis based on 3D CFD analysis. Nevertheless, the number of 3D CFD simulations was far lower than the number of simulations that would have been required for the same tunnel if studied with a scenario-based approach. For 7 cases in 11, the additional 3D CFD analysis confirmed the results obtained by ARTU, while in 4 case it was necessary to adjust the FN curve.

Overall, the analysis showed that the software ARTU can manage a wide range of real cases, with a good accuracy, allowing a strong reduction in the number of necessary 3D CFD simulations. This is particularly significant considering that 3D CFD simulations require a

certain level of expertise, are generally time consuming and cannot cover the whole range of possible tunnel fire scenarios.

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