The verification and validation of a probabilistic risk analysis method for road tunnels

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Lund 2020

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Report 5604
ISRN: LUTVDG/TVBB--5604--SE

Number of pages: 81 (including appendixes)
Illustrations: Kim Genberg and Karin Sandin if nothing else is specified

Keywords
Tunnels, fire, evacuation, probabilistic risk analysis, QRA, verification and validation

Abstract
In this thesis, a new probabilistic risk assessment tool for road tunnels has been verified and validated. The verification and validation were performed along with a literature review to find different key variables that affect the risk in a road tunnel and find out how these variables can be handled. Examples of variables are heat release, ventilation mode and factors within evacuation modelling such as response time, recognition time, walking speed and detection systems. The proposed values can inform the selection of default values and help future users which design values to pick. Uncertainties needs to be handled in a risk assessment and recommendations for this are presented. To perform the validation of the 1D fluid-dynamics representation within the tool, five full-scale experimental data sets from experiments made in the Second Benelux tunnel in year 2000-2001 was used as a benchmark. Simulations with the Fire Dynamics Simulator (FDS) was used to facilitate the validation. To perform the verification of different sub-models within evacuation modelling and of the probabilistic risk analysis, hand calculations of different ideal cases were compared to the results from the tool. The verification of sub-models within the evacuation modelling has shown that the tool gives reasonable, most often conservative results with a margin of error within the order of -13 % and +22 %. The 1D fluid dynamics part gives results that are conservative in four out of five cases. The verification of the probabilistic risk analysis gives results in line with the expected calculated values, with a margin of error within +2 %. Overall, this report has concluded that ARTU provides conservative results for risk analyses in road tunnels. In order to confirm this further, future validation studies could be conducted with different experiments.

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Summary

Underground transportation reduces the number of vehicles at street level and make it easier for countries that want to be able to have transportation under bodies of water and through hills and mountains. Following a set of tragic tunnel fire disasters, e.g. the Mont Blanc tunnel fire in 1999 where 39 people were killed, the European Parliament published a Directive in 2004 that aims at ensuring a minimum level of safety for road users in tunnels with lengths of over 500 m, named *Directive 2004/54/EC*. One way of lowering the risks is to demand risk analysis to be made in tunnels with certain characteristics.

The Italian company Cantene® is in the process of developing a probabilistic risk assessment tool, named “ARTU” (Italian acronym for Risk Analysis in Tunnels), making use of a Monte Carlo approach to evaluate the societal risk (expected number of fatalities per year) in new and in existing tunnels that are due for renovation. The methodology aims to determine the risk associated with the event of a vehicle fire in a tunnel, including 1D fluid dynamics modelling, evacuation modelling and calculation of an FN-curve (cumulative frequency/number of fatalities) for the tunnel under consideration. In order to start using ARTU in their daily work and launching the tool on the market, it must be validated and verified. Verification and validation are two important steps in assuring that simulation and calculation programs are reliable and can be used to model reality. For the fundamental sub-models included in the representation of evacuation behaviour and in the probabilistic analyses, verification was conducted in order to test whether the sub-models are implemented correctly. The 1D fluid dynamics part of the software was validated with full-scale experiments. The 1D fluid dynamics results were also compared with FDS (Fire Dynamics Simulator by the National Institute of Standards and Technology) simulations. In this thesis, only tunnels with natural or longitudinal ventilation have been analysed.

A literature study was initially conducted and knowledge from the study was used to identify the critical factors which may have an impact on the fire development and evacuation conditions. For example, values for heat release rate, fire spread, fire occurrence rate and walking speed in smoke were identified. The proposed values can inform the selection of default values in ARTU and help future users which design values to pick.

In order to analyse the sensitivity of the tool, some key factors that have a large impact on the results were chosen together with Cantene. These factors were changed one at a time to check how much that specific factor affects the overall results. The sensitivity analysis shows that the fire occurrence rate and the percentage of HGVs carrying flammable load have the largest impact on the FN-curve and level of risk when changed and analysed one by one.

The verification of sub-models within the evacuation modelling has shown that the tool gives reasonable, most often conservative results with a margin of error within the order of -13 % and +22 %. The 1D fluid dynamics part gives results that are mostly conservative, which was calculated with functional analysis. The verification of the probabilistic risk analysis gives results with a margin of error in the order of +2 %.

Sammanfattning

Transporter som sker under mark minskar antalet bilar i gatunivå och underlättar för länder som vill ha vägar under vattenmassor och genom berg. Efter ett antal tragiska tunnelbränder, till exempel branden i Mont Blanc-tunneln år 1999 där 39 människor miste livet, publicerade Europaparlamentet år 2004 ett direktiv som heter *Directive 2004/54/EC*. Det syftar till att säkerställa en miniminivå på säkerheten för personer som använder vägtunnlar med en längd över 500 meter. Ett sätt att minska den totala risknivån är att kräva att riskanalyser ska utföras för tunnlar med vissa specifika egenskaper.

Det italienska företaget Cantene®, håller på att utveckla ett probabilistiskt riskanalysverktyg som kallas ”ARTU” (italiensk akronym för riskanalyser i tunnlar), som använder en Monte Carlo metod för att utvärdera samhällsrisken (förväntat antal döda per år) i nya och i befintliga tunnlar som ska renoveras. Metoden syftar till att utvärdera risken kopplad till en brand i ett fordon i en tunnel och inkluderar en endimensionell brandsimuleringsmodell, evakueringsmodeller och beräkning av en FN-kurva (kumulativ frekvens/antal omkomna) för tunneln som analyseras. För att börja använda verktyget och för att kunna lansera det på marknaden måste det bli validerat och verifierat. Validering och verifiering är två viktiga steg för att säkerställa att simule ringar och beräkningsprocedurer är pålitliga och kan användas för att modellera verkligheten. För de fundamentala delmodellerna som inkluderas i utrymningsberäkningarna och för den probabilistiska analysen, genomfördes verifiering för att testa om delmodellerna var korrekt implementerade. Den endimensionella branddelen av verktyget validerades med hjälp av fullskaleexperiment. 1D resultaten jämfördes också med FDS (en: Fire Dynamics Simulator, av the National Institute of Standards and Technology) simuleringar. I denna uppsats har endast tunnlar med naturlig eller longitudinell ventilation analyserats.

En litteraturstudie genomfördes inledningsvis och kunskap från den användes till att identifiera kritiska faktorer som skulle kunna ha en påverkan på en brands utveckling och på förhållanden under utrymningen. Exempel på faktorer som identifierades är effektutveckling, brandspridning, frekvenser för brand i fordon och gånghastighet i rök. De föreslagna värdena kan underlätta vid valet av indata och hjälpa framtida användare med viket värde som kan användas.

För att analysera verktygets känslighet, valdes några nyckelfaktorer som har stor påverkan på resultaten tillsammans med Cantene. Dessa faktorer ändrades sedan en åt gången för att identifiera hur mycket varje enskild faktor påverkar slutresultatet. Känslighetsanalysen visar att frekvensen av brand i fordon och andelen lastbilar som fraktar brännbart gods har den största påverkan på FN-kurvan och risknivån.

Verifieringen av delmodellerna för evakuering har visat att verktyget ger rimliga, oftast konservativa resultat med en felmarginal mellan -13 % och +22 %. Branddelen av verktyget gav resultat som är mestadels konservativa vilket beräknades med funktionell analys. Verifieringen av den probabilistiska riskanalysen gav resultat med en felmarginal som är maximalt 2 %.

Acknowledgements

This Master´s thesis is the final examination for a Bachelor of Science in Fire Protection Engineering and a Master of Science in Engineering, Risk Management and Safety Engineering at Lund University. This thesis was written at the Division of Fire Safety Engineering in collaboration with Cantene® and could not have been written without the support and guidance from some special people to whom we would like to convey our sincerest gratitude:

Enrico Ronchi, for being our supervisor and giving us valuable guidance,

Bjarne Husted, for being our supervisor and giving us great help with FDS,

Rugiada Scozzari and Cantene for giving us this opportunity and for good cooperation during the process,

Håkan Frantzich and Henrik Hassel, for giving us guidance with the risk analysis part,

Erik Smedberg, for giving us help with the functional analysis,

Vicktor Riedel, for helping us with technical issues and

Lego, for being our mascot and for taking us on a walk every day and giving us play breaks when needed.

Abbreviations

ALARP	As Low As Reasonably Practicable
ARTU	Analisi di Rischio in TUnnel
CETU	Centre d'Études des tunnels
CFD	Computational Fluid Dynamics
CO	Carbon monoxide
CO_2	Carbon dioxide
ERD	Euclidean Relative Difference
FDS	Fire Dynamics Simulator
FED	Fractional Effective Dose
FN	Frequency/Number
HGV	Heavy Goods Vehicle
HRR	Heat Release Rate
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
O_2	Oxygen
OECD	Organisation for Economic Co-operation and Development
PIARC	World Road Association
QRA	Quantitative Risk Assessment
SFPE	Society of Fire Protection Engineers
UPTUN	UPgrading methods for fire safety in existing TUNnels

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1. Introduction

The number of tunnels used for transportation purposes around the world is steadily increasing (Kazaras & Kirytopoulos, 2014). It is desirable to have underground transportation in cities which need to reduce the number of cars at street level and for countries that want to be able to have transportation under bodies of water and through hills and mountains. Factors increasing the potential hazards of road tunnels are for example rising traffic densities, increasing length of modern tunnels, transportation of hazardous materials and higher fire loads due to growing traffic volumes (Bergmeister & Francesconi, 2004). Given the possibly dramatic consequences of large fires occurring in tunnels e.g. the Mont Blanc tunnel fire in 1999 where 39 people were killed and where the fire lasted over 50 hours, there is often a need for assessing the level of risk in these infrastructures (National Cooperative Highway Research Programme, 2011).

Historically, quantitative risk assessment has often not been carried out as tunnel design has primarily been done with a prescriptive based design approach in several countries around Europe where risk assessment may not be required by national law (PIARC, 2008). Since the application of Directive 2004/54/EC of the European Parliament, risk assessment has become an integral part of tunnel design (Kohl, Botschek, & Hörhan, 2007). According to the directive described above, risk analysis is required for tunnels within the Trans-European Road Network which are longer than 500 m, see Chapter 2.1 for further discussion (The European Parliament, 2004). The directive has resulted in its acknowledgement by a few national regulatory bodies, e.g. Italy (Ronchi, Colonna, & Berloco, 2012). Italy has more than fifty percent of all tunnels longer than 500 meters in Europe, which makes tunnel safety an important issue in the country (Borghetti, Derudi, Gandini, Frassoldati, & Tavelli, 2017). In many cases, a deterministic approach 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 a specific scenario, is used (PIARC World Road Association, 2019). This deterministic approach has its flaws as it 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.

The Italian fire engineering and thermal science company Cantene® is in the process of developing a probabilistic risk assessment tool with a Monte Carlo approach for tunnels in order to evaluate the societal risk (expected number of fatalities per year) in new and in existing tunnels that are due for renovation. The name of the tool is ARTU, which is short for “Analisi di Rischio in Tunnel” which is Italian for “Risk Analysis in Tunnels”. The methodology aims to determine the risk associated with the event of a vehicle fire in a tunnel. The probabilistic analysis aims to calculate an FN-curve (frequency/number of fatalities) for the tunnel under analysis. The probabilistic analysis is made by a code that involves:

- the probabilistic evaluation
- a one-dimensional (1D) fluid dynamics model
- a simplified egress model
- the interaction between fluid-dynamic conditions and agents during egress

For the representation of the fluid dynamics, ARTU uses an external software based on 1D fluid dynamics which includes geometrical data and characteristics of the ventilation system. The software returns time-varying air temperature, air velocity, and volume airflow along the tunnel which is used as an input for the ARTU tool. Since it is a 1D tool it returns only one value for each variable at a set distance from the fire.

The egress model and probabilistic analysis is made by a code developed by Cantene. The code, together with results from the 1D tool, returns a specific number of points in the ALARP diagram, each point corresponds to one interval of fatalities. The curve connecting these points is the FN-curve for the specific tunnel.

The FN-curve is compared to an ALARP diagram (as low as reasonably practicable) according to the country's legislation which the tunnel belongs to. ARTU places the scenarios in different fatalities intervals, which can be set by the user. The FN-curve can also be compared with a reference tunnel which is built by the regulations in Directive 2004/54/EC.

In order to start using ARTU in their daily work and launching the tool on the market, it must be validated and verified. To perform this, the results produced by ARTU need to be validated and compared to experimental data. The calculations need to be verified by comparing the results to hand calculations.

1.1Purpose and objective

The purpose of this thesis is to analyse whether the risk assessment tool ARTU, developed by Cantene, gives credible results by doing validation and verification of the different parts of the tool and of the whole results provided by the tool.

The following research objectives were formulated; 1) Which are the key factors affecting road tunnel fire safety and how have these been implemented in ARTU? 2) How can a 1D fluid dynamics model be used to model tunnel fire? 3) Can it facilitate the validation to use an already well-established and validated tool as a complement in the validation of fluid dynamics? 4) How can uncertainties be handled when risk assessments are made for road tunnels?

1.2 Scope

The thesis addresses a given set of applications of the tool, namely 1) road tunnels, 2) 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 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 thesis is mostly focused around safe evacuation, factors such as risk of damage to the tunnels and risk for emergency services are out of the scope of this document. Focus lies on technical factors that affect safety rather than organizational factors which can also affect safety.

Due to time limitation and lack of available data only one reference tunnel with five different cases with experimental data was selected for the validation tests. The chosen cases cover the main factors affecting fire safety in tunnels.

1.3 Method

As an initial part of the project, a project plan was made to structure the work and define a time-plan. To gain more knowledge about tunnels and what affects the safety of tunnels, a literature study was conducted, mostly with scientific articles and books. Searches were made mainly via the databases LUBsearch and Scopus and typical keywords were *tunnel fires, design fires, walking speed, walking speed in smoke, combustion products, longitudinal ventilation, risk assessment,* and *risk analysis in tunnels.* The keywords were combined with both each other and other words to find relevant articles. Literature was also found through references in articles that were read and by material shared by the supervisors and Cantene, and books found in the library of the V-house at the Faculty of Engineering at Lund University.

Knowledge from the literature study was used to identify the critical factors which may have an impact on the fire development and evacuation conditions. For example, values for heat release rate, fire spread, fire occurrence rate and walking speed in smoke were identified (Ingason, Li, & Lönnermark, 2015; Fridolf, Nilsson, Frantzich, Ronchi, & Arias, 2018). The sources from which these values were found were later shared with Cantene so they could be implemented as default settings in the code if deemed necessary.

In order to validate and verify the tool, a method was chosen where the different parts (fluid dynamics, and evacuation and toxicity assessment) were analysed separately. Then, the complete results (the FN-curve) was analysed and verified. By first looking at the parts and lastly the complete results of the tool and doing a sensitivity analysis, the credibility of the tool as a whole can be estimated.

A search for case studies for reference tunnel scenarios to validate the fluid dynamics part of the tool was made, well documented full-scale experiments performed in tunnels with natural or longitudinal ventilation were preferred. In consultation with the supervisors and Cantene, experimental data-sets were chosen along with benchmark simulations conducted with the Fire Dynamics Simulator (FDS) (McGrattan, Hostikka, McDermott, Floyd, & Vanella, 2019). Experimental data were included because to do a true validation study, a tool must be compared to experiments or other events in reality, rather than a mere comparison with the results provided by an existing tool with its own uncertainties and limitations. A large set of experimental cases was found, but only cases within the scope of the present work were further studied. Furthermore, the most appropriate cases were selected in dialogue with the supervisors. The selection was based on e.g. which results that were available to compare and the reliability of the source. Based on the selected case studies, suitable input data were listed for each case. Cantene provided the results from the 1D software which were then analysed and compared with already known results from the experiments. All five experimental scenarios were also simulated with FDS, Fire Dynamics Simulator (McGrattan et al., 2019) by the authors of this thesis. FDS has been validated for simulating fires in tunnels (Smardz, 2006). The simulations were made to be able to compare the output from the 1D fluid dynamic software with FDS results as well as to compare FDS results with experimental data. Differences between the experimental results and results from ARTU and FDS were calculated with the Euclidean Relative Difference (ERD) concept, which can be used to calculate the overall agreement between two curves (Ronchi, Reneke, & Peacock, 2014).

As the egress and probabilistic code is still under development, no standalone compiled version of the new software exists during the writing of this thesis, the simulations with ARTU were performed by Cantene. In other words, the input data for the scenarios were provided to Cantene and then used to perform the simulations with ARTU. In order to verify the evacuation part of the tool, different ideal cases were set up by the authors so that Cantene could verify the fundamental sub-models included in the representation of evacuation behaviour. The ideal cases were then run both with the ARTU tool by Cantene as well as with hand calculations by the authors. In order to verify the probabilistic risk analysis, a complete case with both fluid-dynamics and evacuation modelling was simulated with ARTU. The data with the number of fatalities in the respective 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 to see if the FN-curve changes as expected when different factors change. In order to do this, five key factors were chosen and changed one at the time between ±25 % and ±100 %, depending on which variable, to evaluate their impact on the FN-curve. The selected factors were pre-movement time, fire occurrence rate, probability of standstill traffic, number of vehicles and percentage of different vehicle types.

In Figure 1 below, an overview of the method can be seen.

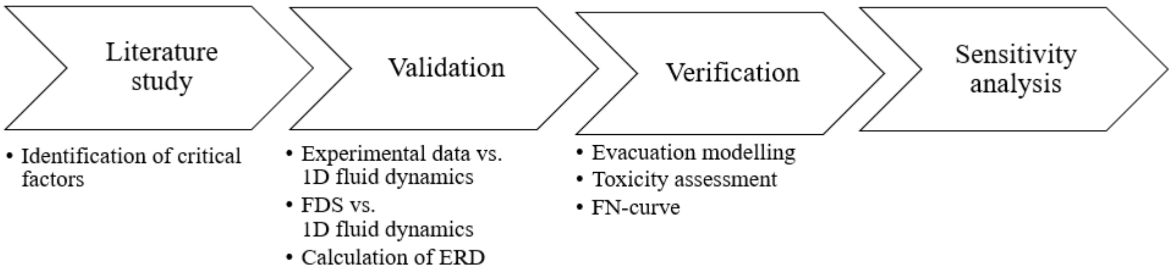

Figure 1. Overview of the method.

2. Risk analysis

The purpose of risk analysis is to understand the risk in a system and its characteristics, including the level of risk. Risk analysis involves a detailed consideration of for instance uncertainties, consequences, likelihood, events and scenarios. Risk analysis can be performed with varying degrees of detail and complexity, depending on the purpose of the analysis, the availability and reliability of information, and the resources available. Analysis methods can roughly be arranged in two different groups, quantitative or qualitative (International Organization for Standardization, 2018).

A qualitative method has lower complexity than a quantitative one (PIARC, 2008). In this thesis, only quantitative methods were used and compared, therefore qualitative methods are not explained any further.

Quantitative risk assessment, QRA, calculates risk numerically. Numerical values are assigned to input data, often with a measure of uncertainty (Rovins, Wilson, Hayes, Jensen, & Dohaney, 2015). A QRA structures possible scenarios in a logical way and their possible subsequent events are analysed. Frequency and/or consequences are estimated. These quantitative outputs allow the identification of the appropriate risk (PIARC, 2008). Deterministic (scenario-based) and probabilistic (statistical) are the two types of approaches to QRA. Deterministic risk analysis assesses risk based on a single scenario and can give accurate results if the exact input data are known (Rovins et al., 2015). The selected case may be for instance the worst-case scenario, maximum-credible scenario or most likely scenario.

A probabilistic analysis differs from a deterministic analysis in the way that it considers all known possible instances of the hazards over an extended period of time instead of one specific scenario (Rovins et al., 2015). A probabilistic method involves the identification of hazards, the estimations of probability and consequences of each hazard, and quantifies the risk as the sum of probabilities multiplied by consequences.

In order to propagate parameter uncertainty, a Monte Carlo based method can be used (Zio, 2013). Monte Carlo simulations create distributions of possible outcome values by recalculating different sets of pseudo-randomly sampled values from the input probability distributions (Zio, 2013). By doing the calculations thousands of times a Monte Carlo simulation can show how likely a scenario is to happen.

Likelihood and consequence in a probabilistic risk analysis are expressed as a probability distribution (Rovins et al., 2015). Individual and societal risk are the outputs considered. Societal risk is frequently represented as an FN-curve, where F is the cumulative probability that the number of fatalities is equal to or greater than a given number N. An FN-curve is made for each system and is needed to be compared with threshold values of tolerable and intolerable risk. To construct FN-curves using each event that is reasonably probable to occur inside the tunnel, it is required to evaluate the expected frequency of occurrence of the event and the total number of people that are exposed to it. With this information, the cumulated frequency F at which an accident can be expected to occur, and which can cause a certain number of fatalities can be calculated.

An area of conditional tolerable risk is defined between the aforementioned threshold values, which is the so-called ALARP area. There are, according to Rovins et al. (2015) and Hurst et al. (2018) three zones when using the ALARP principle:

- When the risk is intolerable, risk reduction must be made irrespective of the cost to reduce the risk.
- When the risk is tolerable, it is necessary to challenge whether the risk can be further reduced, by balancing the level of risk against the cost to reduce the risk.
- When the risk is broadly acceptable, it is low enough that no additional measures are necessary to reduce risk.

An example of an FN-curve is presented in Figure 2 below. The area between the red and green lines is the ALARP area.

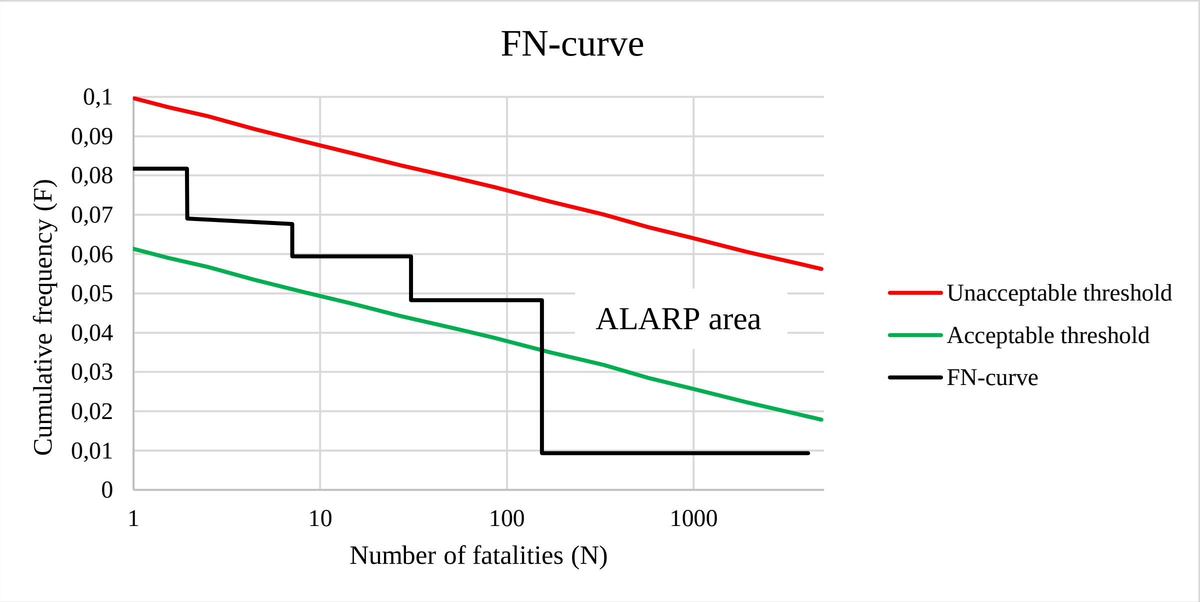

Figure 2. Example of an FN-curve. The red line represents the unacceptable threshold, the green represents the acceptable threshold and the black line is the example FN-curve.

Countries around Europe use different risk analysis methods for road tunnels (PIARC, 2008). France developed, as a consequence of the Mont Blanc tunnel fire in 1999, a methodology and procedure for a specific hazard investigation, which is a scenario-based analysis method (PIARC, 2008). The Netherlands uses, according to PIARC (2008), both a deterministic scenario-based risk analysis method and a QRA-model called "TunPrim" which uses event trees analysis to cover traffic accidents, fire, explosions and leakage of toxic material. PIARC (the World Road Association) and the Organisation for Economic Co-operation and Development (OECD) has developed a QRA model for dangerous goods transportation through road tunnels, which is used in e.g. Austria (PIARC, 2008). The model considers 13 incident scenarios that are representative of some key dangerous goods and can be used to calculate the societal risk for a tunnel (PIARC, 2019).

2.1 European Parliament Directive 2004/54/EC

Following a set of tragic tunnel fire disasters, the European Parliament decided in 2004 to publish a Directive, named Directive 2004/54/EC, that aims at ensuring a minimum level of safety for road users in tunnels with lengths of over 500 m in the Trans-European Road Network by the prevention of critical events that may imperil human life, the environment and tunnel installations, as well as by the provision of protection in case of accidents (The European Parliament, 2004). A risk analysis shall be conducted if a tunnel has special characteristics, which deviates from a set of prescribed characteristics, and shall establish whether additional safety measures and/or supplementary equipment is necessary to ensure a high level of tunnel safety. The Directive does not define what type of methodology should be used for the risk analysis, it is just stated that if risk analysis is needed it should be carried out by a body independent from the Tunnel Manager. It also states that the analysis should consider all design factors and traffic conditions that affect safety, for example, notably traffic characteristics and type, tunnel length and geometry, as well as the forecast number of heavy goods vehicles per day.

In the Directive, it is stated which minimum requirements different tunnel lengths and traffic volumes result in (The European Parliament, 2004). For example, the presence of emergency exits, road signs and water supply. Regarding ventilation, the Directive states that a mechanical ventilation system shall be installed in all tunnels longer than 1 000 m with a traffic volume higher than 2 000 vehicles per lane and day. Longitudinal ventilation systems shall only be allowed in bi-directional tunnels (which means tunnels with traffic that flow in opposite directions in the same tube) if a risk analysis shows it is acceptable.

In 2015, a study on the implementation and effects of Directive 2004/54/EC was conducted in order to analyse how Member States have implemented the Directive to assess whether it has served its purposes (Pastori, Brambilla, Apicella, & Jarvis, 2015). The conclusion drawn was that the Directive has had a positive effect on tunnel safety and has triggered research to find new solutions to achieve the requirements. When the evaluation was made the objects of the Directive were not fully achieved because many tunnels have not yet been upgraded to the point where they meet its requirements (Pastori et al., 2015). For countries with a high number of long tunnels, the work to upgrade tunnels requires both a very significant effort and investment (Pastori et al., 2015).

2.2 Acceptance criteria societal risk

Even though a risk level is calculated, it cannot explain if the level of calculated risk is acceptable. Since zero risk is impossible, a level of acceptance needs to be set. However, when setting the acceptance thresholds, it should be considered that the societal risk associated with a road tunnel must be compared with the possible expected advantages that comes with the risk, for example the reduction in travel time, drop in road accidents, reduction of noise pollution, etc. (Borghetti, Cerean, Derudi, & Frassoldati, 2019). Regarding tunnels, countries may have different acceptance criteria on minimum safety requirements. In Italian regulations, the acceptance criteria for societal risk on minimum safety requirements for tunnels are presented in an ALARP-curve where the limit of unacceptable risk starts at 1.0×10^{-1} for two people and the start of acceptable risk is 1.0×10^{-4} for two people, see Figure 3 below (Condirezione Generale Tecnica. Direzione Centrale Progettazione, 2009). Another example of the risk acceptance criteria is from the Netherlands. Their acceptance criteria for tunnels are as follows: an individual risk of 1.0 × 10^{-7} per person-kilometre and a societal risk of 1.0 × $10^{-1}/N^2$ per km per year (PIARC, 2008). For tunnels in Austria and the United Kingdom, the unacceptable threshold is set to 1.0 × 10^{-1} for one person and the acceptable threshold is set to 1.0 × 10^{-4}, as shown in Figure 3 below (Kirytopoulos, Rentizelas, Tatsiopoulos, & Papadopoulos, 2010).

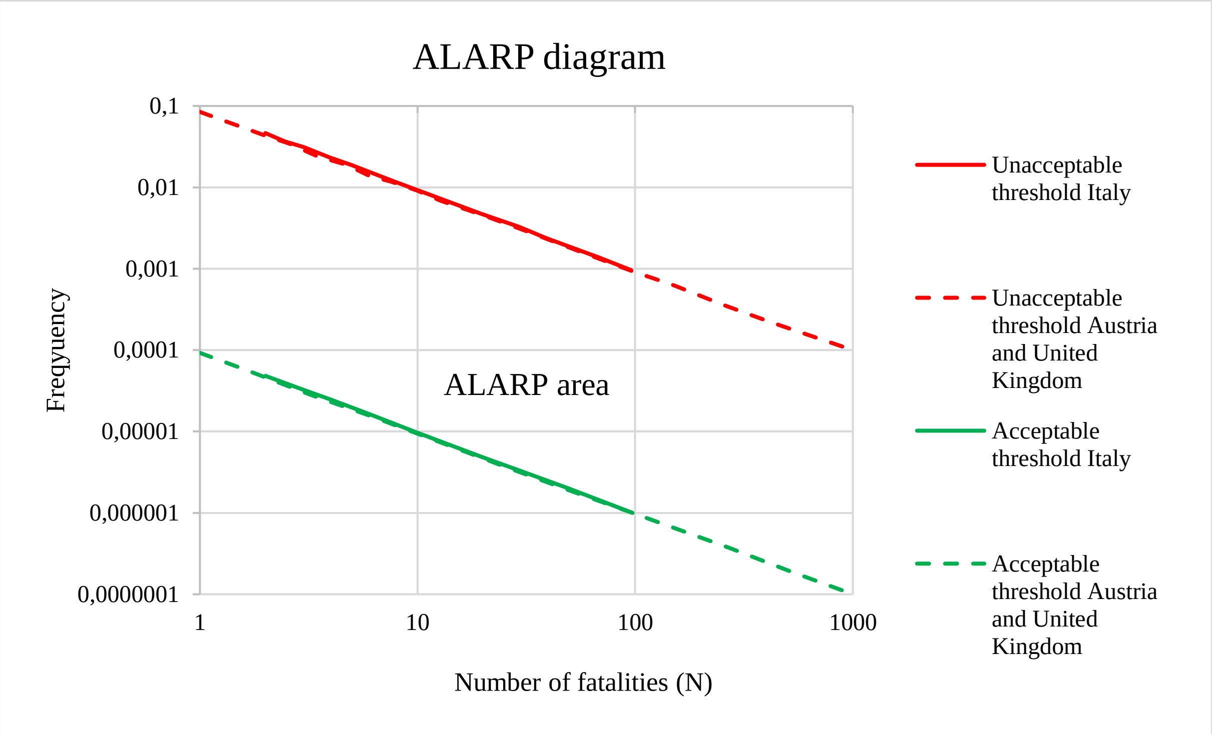

Figure 3. ALARP diagram for road tunnels. Red lines represent unacceptable thresholds and green lines represent acceptable thresholds. (Kirytopoulos, Rentizelas, Tatsiopoulos, & Papadopoulos, 2010; Condirezione Generale Tecnica. Direzione Centrale Progettazione, 2009).

It can be argued that the societal risk output for tunnels should be normalized per tunnel kilometre and per vehicle. If the societal risk is presented per tunnel it entails that a very long tunnel and/or one with high traffic volume can be impossible to make safe enough, just because they naturally have a higher risk compared to a shorter tunnel or a one with less traffic (Hugosson, Ingason, Lönnermark, & Frantzich, 2012)

3. Verification and validation

Verification and validation are two important steps in assuring that simulation and calculation programs are reliable and can be used to model reality. Verification is described by the International Standards Organization (2015) as *"a process to determine that the relevant equations and calculation methods are implemented correctly."* The process of verification can be made by a set of ideal, hypothetical, test cases (Ronchi, Kuligowski, Reneke, Peacock, & Nilsson, 2013). An example of verification is the comparison between a tool that calculates flame heights using a set of equations and hand calculations that use the same equations to see if the results from the tool matches the hand calculated results. Validation is described in the same document as *"[a process to determine] that the calculation method being considered is an accurate representation of the real world."* Validation relies on the availability of experimental data and the subsequent uncertainties associated with them (Ronchi et al., 2013). An example of validation is the comparison between a tool that calculates fire spread speed in bush fires with actual bush fires that have been recorded. Both these processes, verification and validation, must be carried out in order to show that a tool is reliable.

Different models may require different methods for the verification and validation process. As an example for evacuation models, the International Maritime Organization has listed four main forms of tests that have to be performed for the verification and validation process of maritime evacuation simulation tools. These tests are component testing, functional verification, qualitative verification and quantitative verification (Ronchi et al., 2013).

In order to quantify the differences between the results used for the validation, functional analysis, namely calculation of the ERD can be used. ERD represents the distance between two vectors and can be calculated with Equation 1 below (Ronchi, Reneke, & Peacock, 2014). This equation gives the relative difference to one vector y. When ERD is equal to zero, two curves are identical and the further away from zero, the more the two curves differ.

$$ERD = \frac{||\bar{x} - \bar{y}||}{||\bar{y}||} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{\sum_{i=1}^{n}(y_i)^2}}$$

Equation 1

Where

x	is the generic multi-dimensional vector x
y	is the generic multi-dimensional vector y
$\|\|\bar{x}\|\|$	is the norm of vector x
$\|\|\bar{y}\|\|$	is the norm of vector y

In the verification process, a margin of error between the two results can be calculated. This gives a quantitative value on the differences in how many percentages a value is higher than another. Much like with ERD, if the value is equal to zero, the results are equal. The margin of error can be calculated with Equation 2.

$$Margin\ of\ error = \frac{x - y}{x} \qquad \textit{Equation 2}$$

Where

x is a value
y is the value that should be compared with value x

For the evacuation part of ARTU, only verification will be carried out as the evacuation model uses equations and models which are widely adopted in existing evacuation modelling tools and they are based on experimental data. Dedicated validation tests for some of those sub-models have already been conducted for the specific case of tunnel fire evacuations (Ronchi, et al., 2012; Ronchi E. , 2012; Ronchi E. , 2013; Ronchi, Nilsson, & Gwymme, 2012). Nevertheless, it is important to perform a set of verification tests of the evacuation sub-models in order to test whether the equations/sub-models are implemented correctly.

The fire and fluid dynamics part of ARTU needs to be both verified and validated since it is based on a 1D fluid dynamics software, which, to the authors' knowledge, has not been validated for fires in road tunnels. This thesis only includes validation of this part since verification has been conducted by Cantene.

3.1Fire simulation using CFD

Fires and some of their consequences can be modelled using computational fluid dynamics (CFD). A CFD model allows the reconstruction of the geometry of the analysed structure and to simulate a chosen fire and the transportation of heat and smoke from the fire.

Fire Dynamics Simulator (FDS) is a CFD model for fires developed by the National Institute of Standards and Technology (NIST) which solves Navier-Stokes equations numerically for thermally driven flows at low speed (Ma < 0.3) (McGrattan et al., 2019). To visualize the results, NIST has developed Smokeview which shows the flows generated by CFD models in a user-friendly way (Forney, 2016).

FDS has been validated through a number of tests, especially the Memorial Tunnel Fire tests have been used by several authors to validate the tool and the results have been satisfactory (McGrattan, et al., 2017).

3.2Uncertainties

There are two main types of uncertainty that need to be discussed and handled in a risk analysis (Kazaras & Kirytopoulos, 2014). Stochastic/aleatory uncertainty is natural variability in certain variables such as fire load in vehicles or failure rates for detection systems (Kazaras & Kirytopoulos, 2014). Epistemic uncertainty stems from incomplete information and is often difficult to estimate since the factors are complex, such as preparation time for evacuees (Kazaras & Kirytopoulos, 2014). According to Kazaras and Kirytopoulos (2014), if natural variability cannot be reduced any further, it should be modelled in an appropriate way, such as with statistical distributions that fit the variable. Epistemic uncertainty is more difficult to take into consideration as the best way to handle it is to gain more knowledge about the variable in the specific system it is being modelled, according to Kazaras and Kirytopoulos (2014). This can be very difficult and time-consuming in infrastructure projects making it possible to do only to a certain extent.

3.3 Experimental uncertainties

There are uncertainties when using experimental data to compare with simulations. The documentation of heat release rate (HRR), combustion efficiency, ventilation flow rates and so on needs to be sufficient to be able to compare and validate outputs. For example, when measuring HRR, it is necessary to do it correctly because the HRR will have a large impact on all outputs, but results from experimental tests may vary significantly even if the setup is similar which creates uncertainties. There are four ways to determine the HRR; measuring mass loss rate of the fuel, measuring the convective flow, using carbon dioxide generation calorimetry or by the use of oxygen consumption calorimetry (Ingason, Li, & Lönnermark, 2015). The use of oxygen consumption calorimetry is assumed to be the most correct, and according to Ingason, Li and Lönnermark (2015), the method has increased the quality in HRR results and made it possible to measure HRR from vehicles more correctly. According to Ingason, Li and Lönnermark (2015), the accuracy of the other methods depends on the measuring technique and the used type of probes. Their studies have shown that the measurement error for HRR is in the order of ±15–25 % in full-scale experiments.

Differences in how and where temperature is measured also has an impact on the results. In a one-dimensional model, the temperature may be measured over the cross-section, which will give other results than temperature measured with thermocouple elements in specific points. These uncertainties must be addressed when using experimental data.

4. Fire in road tunnels

Fires in road tunnels can occur in many ways. They are, according to the World Road Association, PIARC, (1999), caused mainly by electrical defects, brake overheating and other defects leading to the autoignition of a vehicle. Other causes are collisions and technical defects of tunnel equipment, but they are far less frequent. However, the largest fires are caused by accidents (National Cooperative Highway Research Programme, 2011).

The probability of a collision and fire in a tunnel is lower than in an open space, partly because the visibility and meteorological conditions are constant. However, it is important to remember that the potential consequences are higher, because of the confined space (Beard & Carvel, 2005; PIARC Technical Committee on Road Tunnel Operation, 2007). Tunnels often provide non-redundant network connections, which means they have a vital role in the transport system in countries with several tunnels, such as the countries within the Alpine region. If a fire occurs there can be major problems in the whole transportation network of the area.

During the last decades, there have been several road tunnel fires in Europe, for example, the fires in St Gotthard tunnel (2001), Mont Blanc tunnel (1999) and the Tauern tunnel (1999), killing 11, 39 and 12 respectively (National Academies of Sciences, Engineering, and Medicine, 2006; Ingason, Li, & Lönnermark, 2015). These fires have in common that they all occurred in bi-directional tunnels. Also, some of the most serious fires started due to collisions, for example, the fire in the St Gotthard tunnel. These fires have shown the importance of adapting tunnels to higher safety standards.

The following sub-chapters describe some general factors affecting tunnel fire risk, the key fire-related factors and sub-models, the factors leading to the inability to evacuate and the key evacuation-related factors and sub-models. These are all different factors that could affect the outcome and consequences of a tunnel fire. Suggestions on how these factors can be handled, and for some factors which equations that can be used, are presented.

4.1 General factors affecting tunnel fire risk

This chapter presents some general key factors affecting tunnel fire risk, including tunnel geometry/characteristics and statistical information about the frequency of fires, the number of people in the tunnel and traffic data. Also, what different scenarios and types of accidents that can occur affect the tunnel fire risk. A wide range of scenarios with different levels of complexity should be analysed when doing risk analysis, but that will not be discussed any further in this thesis.

4.1.1 Tunnel geometry and specific characteristics

The tunnel design affects the outcome of an undesirable event. Design features such as length, width, height and cross-section area characterize each tunnel. Also, the gradient between the entrance and exit portals have an impact on the outcome. A tunnel with a positive inclination angle can cause an increased speed of smoke spread in the ascending direction, i.e., the chimney effect, compared to tunnels having longitudinal grade equal to zero (PIARC Technical Committee on Road Tunnel Operation, 2007). PIARC (2007) describes the chimney effect as a function of smoke temperature and inclination angle which can result in high longitudinal velocities caused by a fire in a steep grade. According to Directive 2004/54/EC, longitudinal gradients above 5 % are not be permitted in new tunnels (The European Parliament, 2004).

It is known that the tunnel geometry (height and width of the tunnel) has an impact on the maximum HRR, but there has not been any consensus on how (Li, Fan, Ingason, Lönnermark, & Ji, 2016). Several authors have studied the effect of tunnel width and height of tunnels on HRR but since no consensus has been established this will not be discussed further and these factors need to be analysed in each specific tunnel.

Whether the tunnel is bi-directional or unidirectional has an impact on the safety level in the tunnel. The consequences have the potential to become much worse in road tunnels with bi-directional traffic when compared to unidirectional tunnels. This is because a fire in a bi-directional tunnel may cause a queue in both directions and with a longitudinal ventilation system the smoke will be pushed towards the queue in the other direction. An illustration of this case can be seen below, in Figure 4. Of course, also accidents in unidirectional tunnels can cause high consequences, especially if there are more than one accident or fire in the same tunnel at the same time. That can cause cars become stuck and thus be exposed to fire smoke that spreads through the ventilation system.

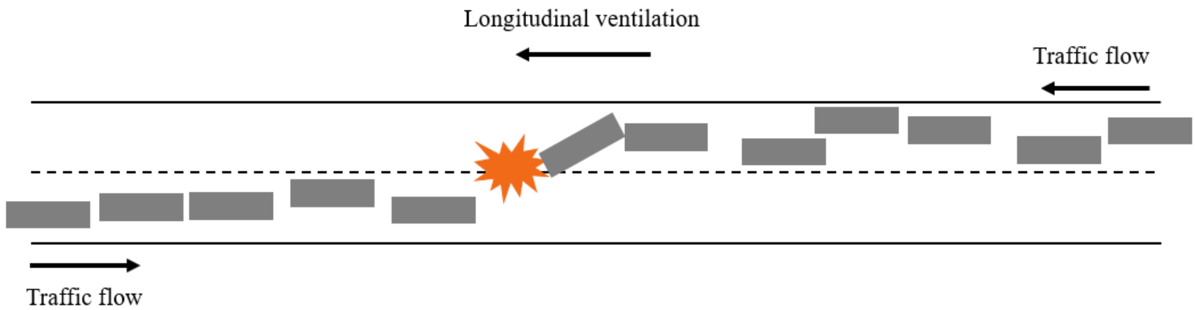

Figure 4. Illustration of a bi-directional tunnel during a fire.

4.1.2 Frequency of fires

General tunnel fire statistics can be used to analyse the frequency of a fire for a specific tunnel under consideration. Fire in road tunnels are rare events, so the statistics of rates of fires are limited (Rattei, Lentz, & Kohl, 2014). To be able to include the gross effects of tunnel length and traffic density, the frequency of fire should be rated not only by number per tunnel but also by number per vehicle multiplied by kilometres. This must be accounted for when comparing different tunnels.

PIARC (1999) has done a study of the number of fires in different tunnels, see Table 1 below. For instance, they have observed the Elb Tunnel in Germany for two years and counted the number of vehicles, the number of Heavy Goods Vehicles (HGV) and the number of fires including the different vehicle types. With this information and together with a lot of other tunnels observed, a frequency of fires in a tunnel per vehicle and kilometre can be calculated, as shown in Table 1 below.

Table 1. Frequency of fire occurrence (PIARC, 1999).

Type of vehicle	Frequency of fire
Passenger car	1-2 fires per 10^8 veh*km
Bus and HGV without flammable load	4-8 fires per 10^8 veh*km
HGV with flammable load	2 fires per 10^8 veh*km

It should be noted that this data is 20 years old and technical development has progressed, which can have an impact on the statistics.

The Austrian state-owned highway operator ASFiNAG (short for "Autobahnen- und Schnellstraßen-Finanzierungs-Aktiengesellschaft" which is German for "Autobahn and highway financing stock corporation") has been collecting vehicle fire data for Austrian tunnels between 2006 and 2012. This data is compiled by Rattei, Lentz and Kohl (2014) and is presented in Table 2 below.

Table 2. Frequency of fire occurrence in Austrian tunnels (Rattei, Lentz, & Kohl, 2014).

Type of vehicle	**Frequency of fire**
Cars (vehicles ≤ 3.5 ton)	4.2 fires per 10^8 veh*km
HGVs and buses (vehicles > 3.5 ton)	25 fires per 10^8 veh*km

This data presents slightly higher values than the data from PIARC presented above, especially for HGVs and buses. In the absence of other available data, the data in Table 1 and Table 2 can be used as a guideline. It can be assumed that this old data makes the calculations conservative, due to technical development. There is also a possibility that tunnel complexity has increased which further affects the frequency and adds uncertainty when using old values. In order to get appropriate data for a specific tunnel, it is recommended to find statistics from a nearby highway or tunnel.

4.1.3 Number of people in vehicles

The number of people involved in an event can affect the outcome in such a way that the number of fatalities can increase, or the evacuation speed can be affected due to for example higher density.

Statistics from 28 European countries shows that the average number of people in a car is 1.7 (Fiorello et al., Dec 2016). The minimum number of people in a car is one and, for most private vehicles, maximum five, therefore a triangular distribution could be applied with minimum 1, average 1.7 and maximum 5.

There are no available statistics for the number of people on a bus, which the authors have found. The most common long-travel bus fits approximately 50 people. Therefore, a uniform distribution could be applied between 10 and 50. It is assumed that at least 10 persons are on a bus ride and its maximum is 50 persons. These values should be in line with statistics for the area within the tunnel under analysis.

4.1.4 Traffic data

The number of private vehicles (e.g. cars) and trucks in a tunnel affect the potential consequences of a fire. An increased number of vehicles increases the social risk level due to a higher frequency of accidents. Furthermore, vehicles act as obstacles and may influence the temperature and smoke spread as well as the ventilation system in case of a fire (Lemaire & Kenyon, 2006).

Within the UPTUN project (UPgrading methods for fire safety in existing TUNnels), Bergmeister and Francesconi (2004) analysed the casualties which occurred due to accidents in the tunnels in the Brenner highway between 1995 and 2003. The authors concluded that 80 percent of the casualties occurred during the day when 70 percent of the traffic is on the highway. This indicates how much the traffic condition may affect the probability of an accident.

Today, most risk analyses are based on annual average daily traffic. This number is a constant which does not fit reality especially well because the number of vehicles in a tunnel can vary seasonally and during the day (PIARC, 2008). Therefore, in some cases, making a risk analysis of a tunnel, based only on the average number of daily traffic might not be justified. If the number of vehicles varies between for example summer and winter seasons, this difference needs to be considered as well.

4.2 Fire-related factors and sub-models

In this chapter, an overview of different key fire-related factors affecting tunnel fire scenarios are discussed.

4.2.1 Design fires

Through experiments, it has been shown that the most important factor for the assessment of the severity of tunnel fires is the HRR (Ingason, Li, & Lönnermark, 2015). The HRR curve of a fire describes the amount of energy released from the fire over time and is dependent on several factors such as fuel composition and oxygen availability. Also, the heat of combustion, which is the amount of heat released during the combustion has an influence on the peak HRR (Ingason, Li, & Lönnermark, 2015).

Values for the heat of combustion for different cars can be obtained from full-scale experiments. In the full-scale experiment in the Second Benelux tunnel, the heat of combustion of a small passenger car was estimated to 30 MJ/kg (Lemaire & Kenyon, 2006). In experiments by National Institute of Industrial Environment and Risks, the heat of combustion was around 36 MJ/kg for a passenger car and around 30-31 MJ/kg for an electrical vehicle (Lecocq, Bertana, Truchot, & Marlair, 2012).

Standardised fires that represent likely fires in tunnels must be determined in order to be used in computations for engineering purposes. These are called design fires and are particularly important as they largely determine the results of a fire simulation. The design fire is most often represented as a single value of a maximum HRR, a time-dependent HRR curve or as a time-temperature curve (Ingason, Li, & Lönnermark, 2015). The design fire should be realistic but conservative, a worst plausible scenario is reasonable as worst scenarios are highly unlikely and can lead to unreasonable cost for the tunnel design (PIARC, 1999). Design fires can be obtained in several manners, two of the methods are to use design fires from standards or to use HRR curves based on experiments. These two methods are further discussed below, and some examples of curves are shown.

Values for peak heat release rates can be found in standards documents such as the NFPA 502 (National Fire Protection Association) (NFPA, 2011), the PIARC report "Fire and smoke control in road tunnels" (PIARC, 1999) or national regulations such as from the French tunnel study centre, *Centre d'Études des Tunnels* (CETU) (Centre d'Études des Tunnels, 2003). Values from these documents are presented in Table 3, Figure 5 and Figure 6 below. NFPA 502 also gives time until peak HRR but since there is a large spread in these values for each vehicle type, they are difficult to use and not further discussed here. It can be concluded that these standard values are quite similar to each other for cars and buses and that there is a larger spread among values for HGVs and tankers.

Table 3. Peak HRRs from standards.

Type of vehicle	NFPA 502[1]	PIARC[2]
Car	5 MW	2.5-5 MW
Bus	30 MW	20 MW
HGV	150 MW	20-30 MW
Tanker	300 MW	100 MW

The French standard CETU does not only give peak HRR and time to peak HRR but also gives complete HRR curves for different types and number of vehicles, see extracted curves in Figure 5 and Figure 6 below.

Figure 5 below shows design fire curves from French standards for a single passenger vehicle, some groups of passenger vehicles and a van with and without a load of liquid combustibles.

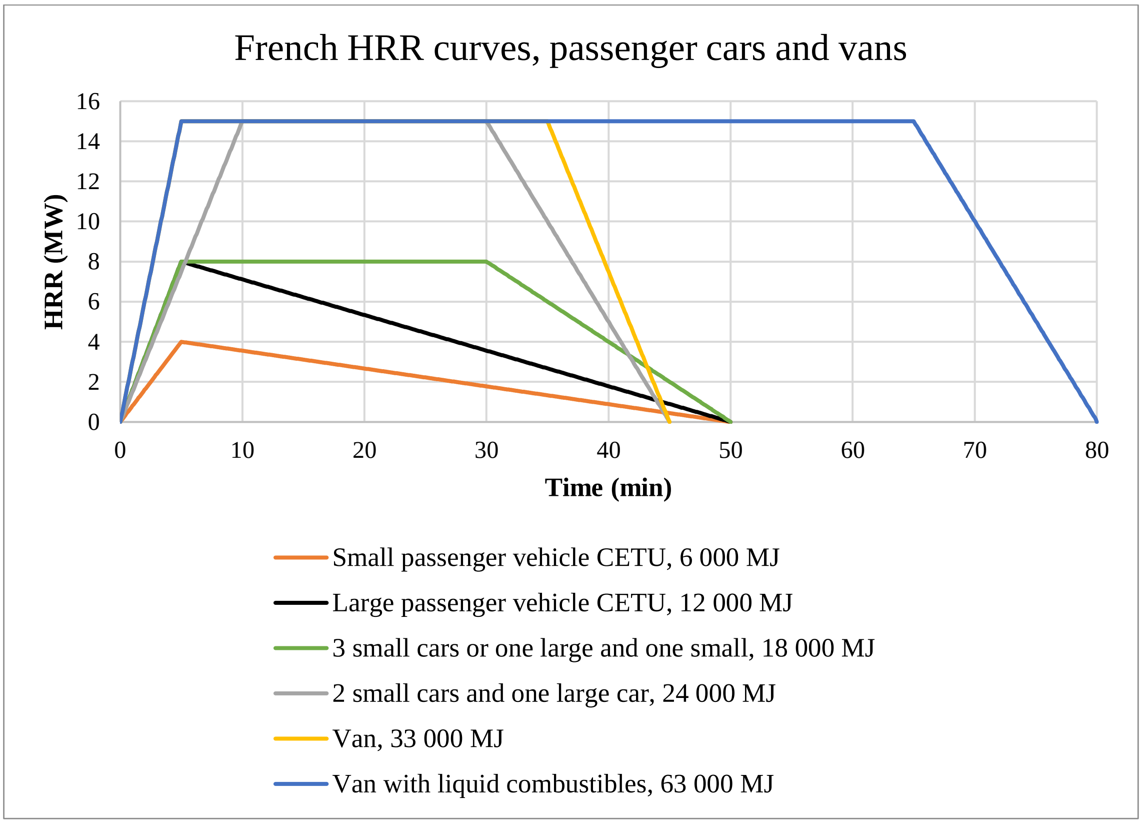

Figure 5. French HRR curves for different cars (Centre d'Études des Tunnels, 2003).

[1] (NFPA, 2011)
[2] (PIARC, 1999)

Figure 6 below shows the design fire curves from French standards for HGVs and tankers with some different loads.

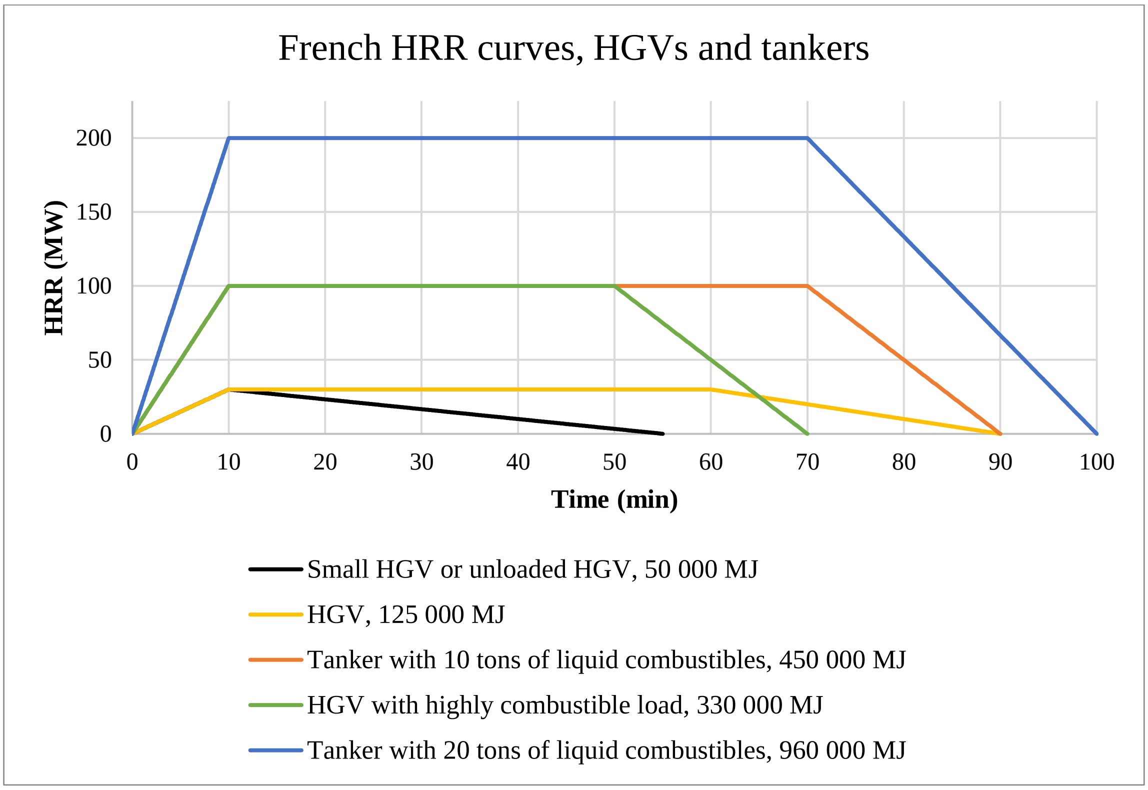

Figure 6. French HRR curves for different HGVs. (Centre d'Études des Tunnels, 2003).

Several experiments have been conducted to, among other things, examine heat release rates from different types of vehicles. Ingason, Li and Lönnermark (2015) have done a study of a large number of experiments to come up with conclusions about heat release rates in tunnels. Many of the plotted experimental curves below come from references mentioned in their work. It is apparent that the issue is complex since there is a large spread among results from different experiments. This can be explained by differences in experimental setups, tunnel geometry, ventilation speed, fuel packages (real vehicles or mock-ups) but also by uncertainties in measurements and estimation. Ingason, Li and Lönnermark (2015) concluded that the uncertainties regarding HRR could be in the vicinity of 15-25 % in large-scale testing in tunnels.

In order to understand the possible HRR curves which can develop in a tunnel, a number of experiments have been analysed. There are numerous ways of creating design fire curves from experiments and one is not necessarily better than the others. For this paper, the approach suggested by Ingason (2005) with a single exponential curve is used, see Equation 3-Equation 6 below. This approach is deemed fitting as it is created by a well-established scientist in the field, it is easy to use because it is just a single correlation and it can be modified to fit the experimental data fairly well. Input values for each vehicle type can be found in its respective section below. For each vehicle type, a proposal for a design fire has been plotted. These are a worst plausible case as they cover most experimental curves, but some extreme values have been left out.

$$Q_t = \dot{Q}_{max} \cdot n \cdot r \cdot (1 - e^{-k \cdot t})^{n-1} \cdot e^{-k \cdot t}$$ *Equation 3*

Where n is approximated as

$$n = 0.74294 \cdot e^{2.9 \cdot \dot{Q}_{max} \cdot t_{max}/E_{tot}}$$ *Equation 4* [3]

and r and k are approximated as

$$r = \left(1 - \frac{1}{n}\right)^{1-n}$$ *Equation 5*

$$k = \frac{\dot{Q}_{max} \cdot t}{E_{tot}}$$ *Equation 6*

Where

Q_{max} is the maximum HRR (kW)

E_{tot} is the total energy released (kJ)

t is the time (s)

For fires in passenger vehicles, 17 individual experimental tests have been used to deduce a typical appearance of a fire in a passenger car, see Figure 7 below. These curves have been extracted by the authors from the following references: (Okamoto, Otake, Miyamoto, Honma, & Watanabe, 2013), (Lemaire & Kenyon, 2006), (Mangs & Keski-Rahkonen, 1994), (Schleich, Cajot, & Pierre, 1999) and (Ingason, Li, & Lönnermark, 2015). Input values for the proposed quadratic curve can be found in Table 4 below. As most of the experiments have been conducted with old cars and newer cars generally contain more combustibles, specifically plastics, a second design fire curve is proposed for newer or larger cars. But since few or no experiments were found with newer cars there is a great deal of uncertainty built into this curve, but it is important to consider the probable higher fire load in newer cars compared to older cars and cars of different sizes.

Table 4. Input values for quadratic curve, one passenger vehicle.

Parameter	Value small/old passenger car	Value new/large passenger car
Q_{max}	4.5 MW	8 MW
E_{tot}	8 000 MJ	14 000 MJ
t_{max}	960 s (16 min)	960 s (16 min)

[3] Simplification by Ingason, Li & Lönnermark (2015).

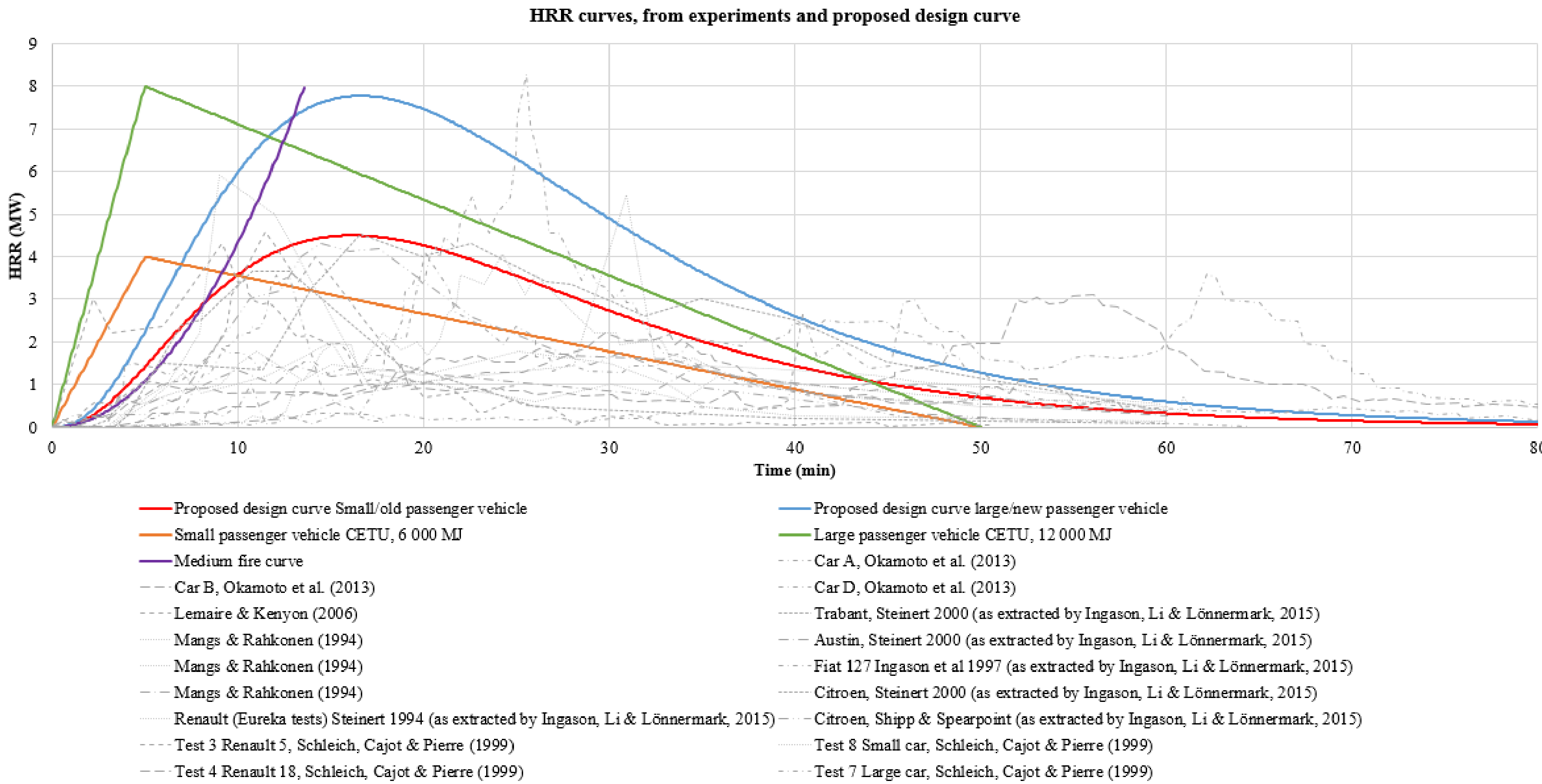

Figure 7. HRR curves for a single passenger car.

For buses only three experiments were found in the literature, for the Eureka bus test 7 two authors have calculated HRR curves, these are both presented in Figure 8 below. Experimental curves have been extracted by the authors from the following references: (Hammarström, Axelsson, Försth, Johansson, & Sundström, 2008), (Ingason, Gustavsson, & Dahlberg, 1994) and (Ingason, Li, & Lönnermark, 2015). Input values for the proposed quadratic curve can be found in Table 5 below. In Figure 8 below the curves for an HGV and a small or unloaded HGV from CETU are also presented for comparison as there were no curves available for buses, as can be seen, the proposed curves resemble the CETU curve for small or unloaded HGVs.

Table 5. Input parameters for a quadratic curve, one bus.

Parameter	**Value**
Q_{max}	30 MW
E_{tot}	41000 MJ
t_{max}	720 s (12 min)

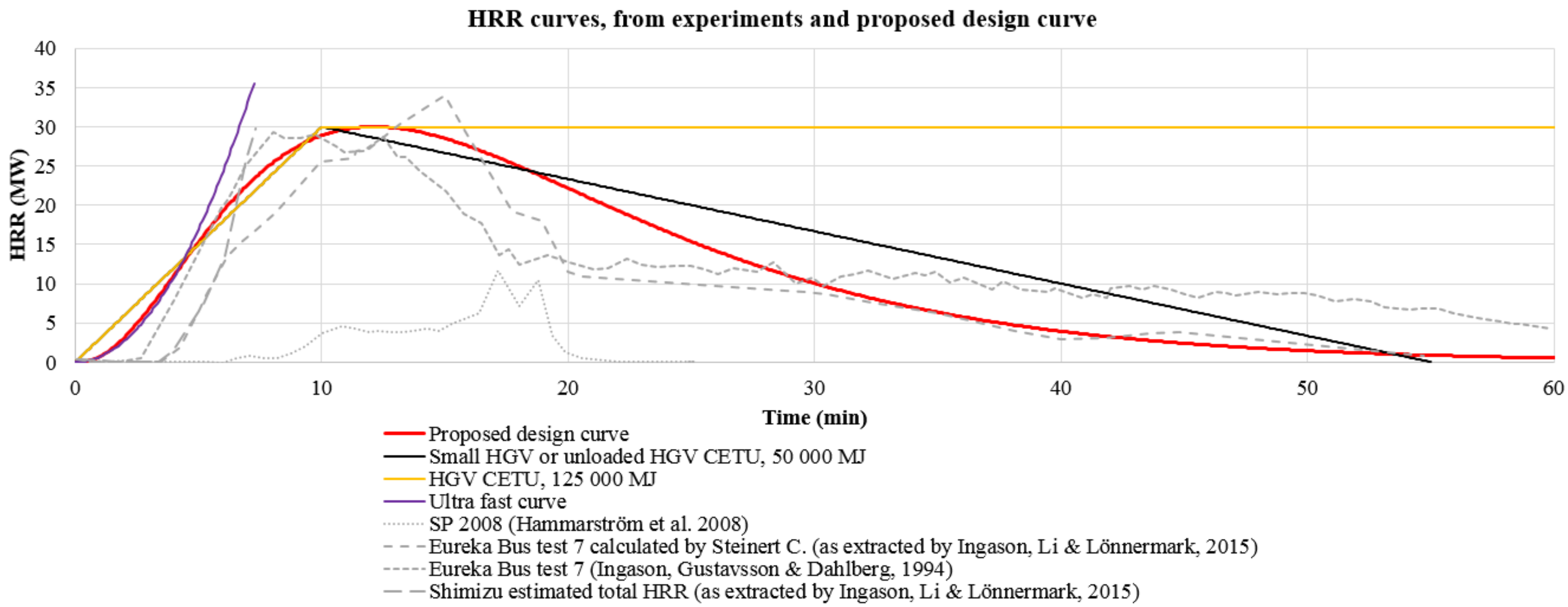

Figure 8. HRR curves for a single bus.

For HGVs, 12 experiments were found in the literature and experimental curves have been extracted by the authors from the following references: (Cheong, et al., 2013), (Ingason, Li, & Lönnermark, 2015), (Ingason & Lönnermark, 2005) and (Lemaire & Kenyon, 2006). These are presented in Figure 9 below. Input values for the proposed quadratic curve can be found in Table 6 below.

Table 6. Input parameters for a quadratic curve, HGVs.

Parameter	**Value**
Q_{max}	150 MW
E_{tot}	200000 MJ
t_{max}	720 s (12 min)

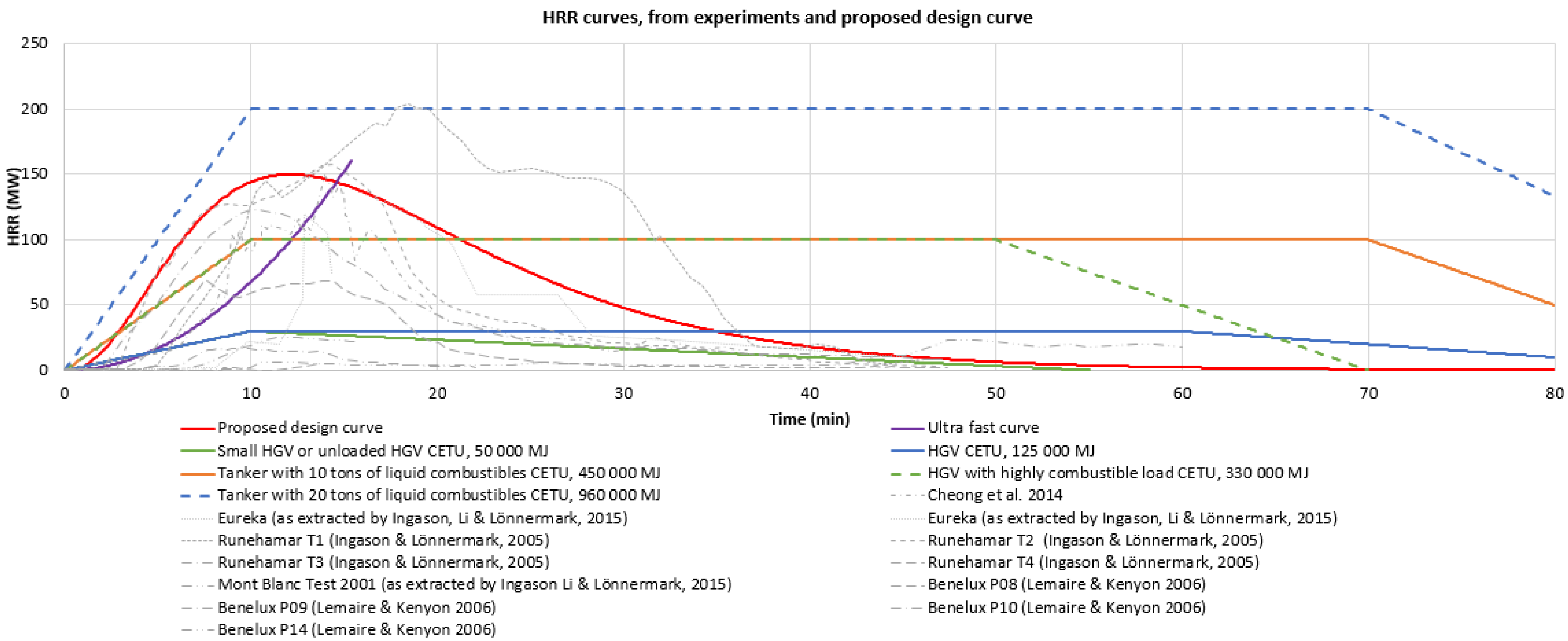

Figure 9. HRR curves for single heavy goods vehicles and tankers.

4.2.2 Fire ventilation mode

In order to maintain tenable conditions during a tunnel fire for as long as possible, fire ventilation is often installed in tunnels. These systems also provide better conditions during emergency situations. The systems are divided into longitudinal and transverse ventilation systems. Transverse systems have separate supply and exhaust ducts in a tunnel to both extract smoke and supply fresh air. There are also semi-transverse systems that only have either supply or exhaust vents (Carvel, Beard, Jowitt, & Drysdale, 2001). Longitudinal ventilation, which the tunnels evaluated in this report are equipped with, is based on the installation of jet fans which produce a longitudinal airflow through the tunnel. This type of ventilation can, in unidirectional tunnels, create a smoke-free zone upstream of the fire in order to provide a safe area for stuck vehicles (Ingason, Li, & Lönnermark, 2015).

As the ventilation can have a major impact on the outcome of a fire, it may be good to consider the risk of the malfunctioning of the system. This can, for example, be made with failure rates specific for each system given by the manufacturer. In the full-scale experiments in the Second Benelux tunnel the impact of ventilation on the fire spread and heat release rate was studied (Lemaire & Kenyon, 2006). It was found that longitudinal ventilation in most cases would delay the fire growth of a car fire. This is because the ventilation will delay the fire spread in the upstream direction from the front of the car (Lemaire & Kenyon, 2006). Nevertheless, if the fire has started in the upstream part of a vehicle, it will spread more rapidly. Experiments by Ingason and Li (2010) show that the fire growth rate increases linearly with ventilation velocity. The experiments by Lemaire & Kenyon (2006) and Ingason & Li (2010) all show that the HRR for car fires is the same with and without ventilation and for truck fires the maximum HRR is up to 1.5 times larger for fires with ventilation. Ingason and Li (2010) claims that the ventilation velocity has a large impact on the fire development. Four HRR curves from the experiments in the Second Benelux tunnel are shown in Figure 10 and Figure 11 below, where the delay is shown in Figure 10 and the difference in peak HRR is shown in Figure 11. In Figure 10 where the curve for test 6 ends, the measurements were stopped, and the fire intensity declined rapidly.

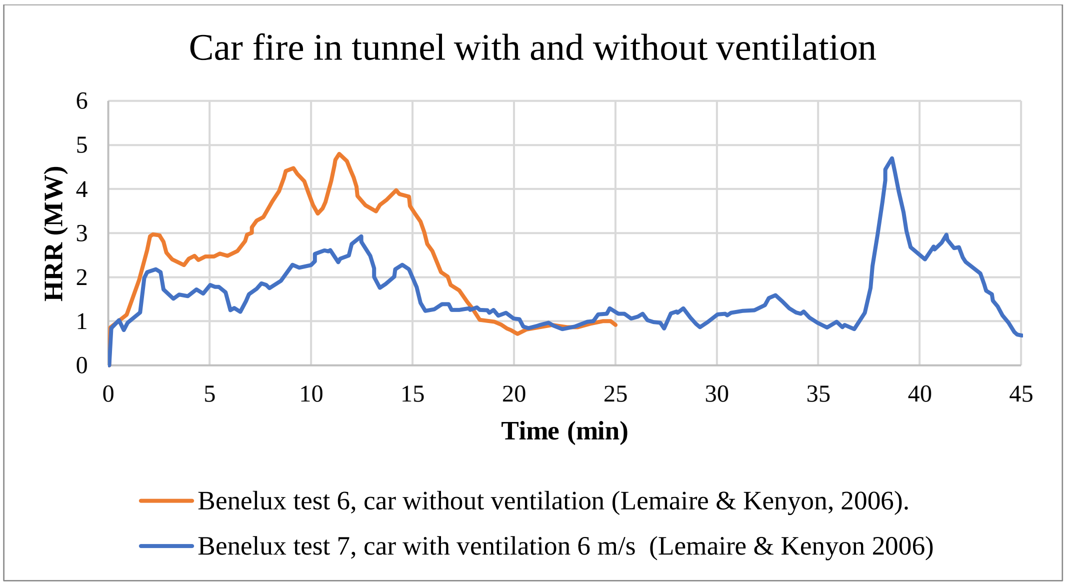

Figure 10. The impact of ventilation on the HRR for car fires (Lemaire & Kenyon, 2006).

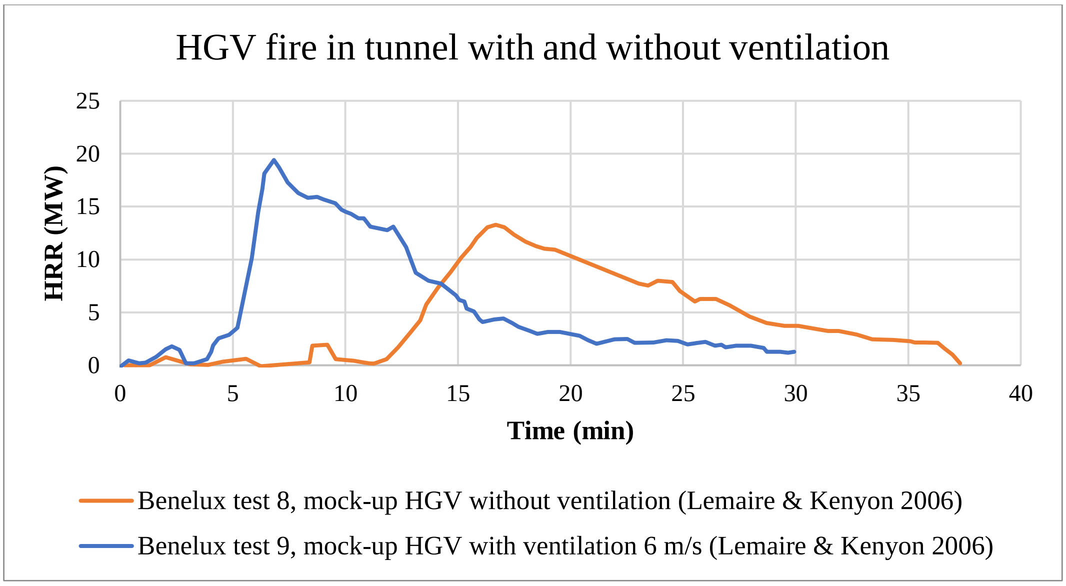

Figure 11. The impact of ventilation on the HRR for HGV fires (Lemaire & Kenyon, 2006).

4.2.3 Back layering and critical velocity

An important consideration to make when it comes to tunnel fire safety is the risk of back layering, which is the phenomenon in which the smoke moves upstream in the tunnel (Carvel, Beard, Jowitt, & Drysdale, 2001). In the case of longitudinal ventilation when the idea is that cars downstream of the fire can drive out of the tunnel before untenable conditions occur, it is only the people upstream of the fire who will need to leave their vehicles to escape the tunnel. The case when there is standstill traffic in the tunnel is clearly different. If the ventilation is strong enough these people upstream of the fire will not be subjected to smoke as there will be no back layering (Carvel, Beard, Jowitt, & Drysdale, 2001). Back layering also makes firefighting more difficult since both sides of the fire will be affected by smoke (National Cooperative Highway Research Programme, 2011).

The critical velocity is the lowest air velocity in a tunnel which eliminates back layering. Oka & Atkinson (1995) found through small scale experiments that critical velocity is independent of HRR in very large fires. Li, Lei & Ingason (2010) carried out small-scale tests on critical velocity and back layering length and came up with equations for non-dimensional critical velocity, presented as Equation 7 to Equation 9 below. As seen in the equations they agree with Oka and Atkinson that large fires are uncorrelated to HRR. The equations were also validated with full-scale tests. These equations can be used to calculate the lowest velocity the ventilation needs to produce and are therefore important when designing a tunnel.

$$u_c^* = \begin{cases} 0.81 * Q^{*1/3}, & Q^* \leq 0.15 \\ 0.43, & Q^* > 0.15 \end{cases}$$ *Equation 7*

Where

$$Q^* = \frac{Q}{\rho_0 \cdot c_p \cdot T_0 \cdot g^{1/2} \cdot H^{5/2}}$$ is the dimensionless HRR *Equation 8*

And

$u_c^* = \frac{u_C}{\sqrt{g \cdot H}}$ is the dimensionless critical velocity *Equation 9*

And

u_C	is the critical velocity (m/s)
ρ_0	is the ambient density (kg/m^3)
c_p	is the thermal capacity of air (kJ/kg*K)
T_0	is the ambient temperature (K)
G	is the gravitational acceleration (m/s^2)
H	is the tunnel height (m)

The effect of blockages in the tunnel in the form of other vehicles was also investigated by Li, Lei and Ingason (2010) and they found that the reduction in critical velocity can be approximated by the blockage ratio in the tunnel.

According to full-scale experiments in the Memorial Tunnel, longitudinal ventilation was capable of managing smoke and heat from fires up to 100 MW (Ingason, Li, & Lönnermark, 2015). To prevent back layering for the 100 MW fire the required longitudinal air velocity was approximately 3 m/s.

4.2.4 Fire spread to other vehicles

Fire spread from the initial vehicles to neighbouring vehicles is one of the key issues for the outcome and the possibility to fight the fire successfully. When a fire occurs, high levels of heat radiation are emitted. This might cause fire spread to adjacent vehicles. Critical factors that determine if a fire will spread or not are the proximity to other vehicles, the heat release rates and the ventilation (Kim, Lönnermark, & Ingason, 2010). Lemaire and Kenyon (2006) has estimated the critical distance at which fire spread will occur as a function of heat release rate, based on the assumption that fire spread will occur if the radiation flux on the adjacent vehicle exceeds 15 kW/m^2. With experiments they estimated the distance where fire can spread to approximately 4.5 m for a burning car and 6-10 m for an HGV, depending on size.

In most cases when a tunnel fire became catastrophic, historically, fire spread to other vehicles has occurred. For example, in the St Gotthard fire in 2001, the Mont Blanc fire in 1999 and the Tauern tunnel fire the same year, the fire spread to adjacent vehicles (Kim, Lönnermark, & Ingason, 2010).

Kim, Lönnermark and Ingason (2010) have studied the cause and the outcome of 69 tunnel fires between the years 1949 and 2005. The authors concluded that all fires that spread to neighbouring vehicles caused fatalities, it is worth noting that some of these fatalities were due to the traffic accidents that caused the initial fire. Also, in almost all the cases in which fatalities occurred, one or more HGVs were involved. This indicates that whether fire spread occurs or not has a large impact on the outcome of an event.

4.2.5 Fuel-controlled and ventilation-controlled fires

One way of dividing fires into groups is considering if they are fuel-controlled or ventilation-controlled fires. This categorization is meaningful as they differ significantly in behaviour and consequences for evacuation. In ventilation-controlled fires, the production of soot, carbon monoxide and hydrocarbons increase which leads to untenable conditions occurring faster (Karlsson & Quintere, 2000). This makes it important to know whether a fire in a tunnel is fuel controlled or ventilation controlled. Ingason, Li and Lönnermark (2015) has proposed Equation 10 below as a way to estimate the maximum HRR which can be achieved in a tunnel with longitudinal ventilation with a known velocity, the equation assumes a flow coefficient of 0.87 and an ambient temperature of 293 K. If the expected peak HRR of a design fire is higher than the calculated using Equation 10, the fire will most likely be ventilation controlled.

$$\dot{Q} = 3130 \cdot u \cdot A \qquad \textit{Equation 10}$$

Where

$\dot{Q}$ is the maximum HRR (kW)
u is the longitudinal centreline flow (m/s)
A is the cross-sectional area of the tunnel (m^2)

4.2.6 Combustion products

Since fires in tunnels differ significantly in fuel composition, it is difficult to assess what combustion products are produced by the fires, this is especially true when HGVs are involved as they can transport a whole variety of goods. Persson & Simonsson (1998; as cited by Lönnermark & Blomqvist, 2006) concluded that passenger vehicles contain approximately 100-115 kg of plastic and 50 kg of fuel and oils. Lönnermark & Blomqvist (2006) also conducted both small scale and full-scale experiments and found that car fires produce a large variety of both asphyxiating and irritating species such as carbon monoxide, carbon dioxide, hydrogen cyanide, hydrogen chloride and sulphur dioxide. They also calculated yields for some of the abovementioned species, see Table 7. It is usually these species below that are the toxic species that are considered for evacuation since they are produced in relatively large quantities and (with exception for hydrogen cyanide) whose effects on humans are relatively well-known. CO, CO_2 and HCN are also the most common species used in Fractional Effective Dose (FED) calculations, which is further discussed in Chapter 4.3.1. Project-specific analysis of which other species should be taken into consideration is necessary as the production of other toxic species could become relevant with certain fuel compositions.

Table 7. Yields for some toxic species in car fires from Lönnermark & Blomqvist (2006).

Species in passenger car fires	Yield (kg/kg)
Soot	0.064
Carbon monoxide	0.063
Carbon dioxide	2.4
Hydrogen cyanide	0.0016

PIARC (1999) also gives suggestions to yields for carbon monoxide and carbon dioxide with reference to the EUREKA tunnel fire experiments amongst others, PIARC gives values for other vehicle types such as buses and HGVs.

Table 8. Yields for CO_2 and CO from PIARC (1999).

Vehicle type	**CO_2 yield (kg/kg)**	**CO yield (kg/kg)**
Passenger vehicle	0.4-0.9	0.02-0.046
Bus/HGV without dangerous goods	1.5-2.5	0.077-0.128
HGV with dangerous goods	6-14	0.306-0.714

As seen in the tables above there is a large spread in values between different vehicles and different authors.

4.3 Factors leading to inability to evacuate

Victims of fires are subjected to both short-term physiological effects and long-term pathological effects. It is most often the physiological effects that cause incapacitation and death as they have the most rapid onset (Purser D. A., 2010). In the following parts, the main factors leading to evacuees being incapacitated or dying in a fire scenario are discussed.

4.3.1 Toxic species

The most common cause of death in fires is inhalation of smoke and toxic species rather than the heat from the fire (Purser D. A., 2010; Ingason, Li, & Lönnermark, 2015). There are two main categories of toxic species, these are asphyxiants and irritants.

Irritants lead to pain in the eyes which together with lowered visibility because of soot, can impair vision. Irritants also lead to pain in the upper respiratory tract leading to breathing difficulties. These combined effects may severely affect walking speed, see Chapter 4.4.4 for a discussion on these topics. Examples of irritants found in car fires are formaldehyde, acetaldehyde, acrolein, hydrochloride and sulphur dioxide (Lönnermark & Blomqvist, 2006).

Asphyxiants lead to hypoxia, either in the body's tissue or by preventing oxygen uptake in the bloodstream. This leads to confusion, loss of consciousness and death if a victim is subjected to the smoke long enough (Purser D. A., 2010). Examples of asphyxiants produced in car fires are carbon monoxide, carbon dioxide and hydrogen cyanide. Carbon monoxide has been shown to be perhaps the most important toxic species produced by fire as a majority of victims die by carbon monoxide poisoning (Nelson, 1998). Carbon dioxide is not only an asphyxiant, but it increases the breathing rate of victims which in turn increases the intake of other toxic species in the body (Purser D. A., 2016). Finally, the impact of hydrogen cyanide is less understood but still important as it is additive to carbon monoxide poisoning (Purser D. A., 2016). Lack of oxygen is also a source of hypoxia which is caused by the lowered oxygen concentration due to oxygen consumption during the fire (Ingason, Li, & Lönnermark, 2015).

The toxic effects of exposure to asphyxiants depends on the dose inhaled (Purser & McAllister, 2016). A threshold concentration and dose, which allows the study of the incapacitation due to asphyxiant substances, can be identified. This concept is called Fractional Effective Dose (FED) or Fractional Effective Concentration (FEC) (Purser & McAllister, 2016). When FED is equal to one, half of the population would be expected to be incapacitated. FED equal to 0.3 translates into expected incapacitation of 11 % of the population (Purser & McAllister, 2016).

Several formulations exist for the FED and FEC calculations. This work refers to Equation 11 to Equation 14 below, as stated in the Technical Reference and User's Guide for FDS+Evac by VTT Technical Research Centre of Finland (2018). These equations can be used to calculate asphyxiation (incapacitation) of an adult in light work, as in walking to an emergency exit, according to Purser & McAllister (2016).

$$FED_{tot} = (FED_{CO} + FED_{CN} + FED_{NO} + FLD_{irr}) \cdot HV_{CO_2} + FED_{O_2} \qquad \textit{Equation 11}$$

Where

FED_{CO} is the fraction of an incapacitating dose of CO
FED_{CN} is the fraction of an incapacitating dose of CN
FED_{NO} is the fraction of an incapacitating dose of NO
FLD_{irr} is the Fractional Lethal Dose (FLD) of irritants
HV_{CO_2} is the hyperventilation factor induced by carbon dioxide
FED_{O_2} is the fraction of an incapacitating dose of O_2

$$FEDco = \int_0^t 2.764 \cdot 10^{-5} (C_{CO}(t))^{1.036}\, dt \qquad \textit{Equation 12}$$

Where

C_{CO} is the concentration of carbon monoxide

$$FED_{O_2} = \int_0^t \frac{dt}{60 \cdot \exp\left[8.13 - 0.54 \cdot \left(20.9 - C_{O_2}(t)\right)\right]} \qquad \textit{Equation 13}$$

Where

C_{O2} is the concentration of oxygen

$$HV_{CO_2} = \frac{\exp(0.1903 \cdot C_{CO_2}(t) + 2.0004}{7.1} \qquad \textit{Equation 14}$$

Where

C_{CO2} is the concentration of carbon dioxide

Tenability limits due to exposure from different asphyxiants for a person in light activity are presented in Table 9 below, originally stated by Purser and McAllister (2016) in the Society of Fire Protection Engineers (SFPE) Handbook of Fire Protection Engineering. These limits are for each species stand-alone and not a combined effect which, as discussed above, can be calculated with the FED concept. However, the tenability limits of the different asphyxiants can be used as a guide to which levels that can lead to undesirable consequences.

Table 9. Tenability limits (Purser & McAllister, 2016).

Asphyxiant	Incapacitation 5 min	Death 5 min
CO	6000-8000 ppm	12 000-16 000 ppm
O_2	10 – 13 %	<5%
CO_2	7-8%	>10 %

4.3.2 Exposure to heat

When a person is exposed to heat from a fire, there are three ways in which it may lead to incapacitation and death (Purser & McAllister, 2016). These are, according to Purser and McAllister (2016) incapacitation through heat stroke, body surface burns and respiratory tract burns.

Skin burns are caused by heating of the skin and are obtained through radiation, convection or conduction. How the heat is supplied is less important than the actual increase in heat in the skin (Purser & McAllister, 2016).

Radiation is emitted in fires from both flames and hot combustion gases, in tunnels these hot gases can travel long distances and affect evacuees. If the radiation is too high people will get burnt and not be able to evacuate. According to Purser and McAllister (2016), pain and the likelihood of skin burns due to radiation and convection from hot gases occur at air temperatures above approximately 120 °C. The tolerable temperature depends on the rate of heat transfer from hot air to the skin which depends on the ventilation, humidity, air temperature and the amount of clothing the evacuees wear.

According to the National Fire Protection Association (NFPA) 130 (2014), the tenability limit for exposure of skin to radiant heat is approximately 2.5 kW/m^2. Exposure can, below this level, be tolerated for 30 minutes or even longer without significantly affecting the time available for a person to evacuate. Above this threshold value, the time to burning of skin due to radiant heat decreases according to Equation 15 below. How the skin temperature increases depends on the balance between the rate of heat applied to the skin and the removal of heat by the blood. This leads to an uncertainty associated with Equation 15, which is estimated at ± 25 %. With the same principle as with toxic gases, a fraction of the equivalent dose of radiant heat over time can be accumulated (National Fire Protection Association, 2014). According to NFPA 130 (2014), the time to incapacitation under conditions of exposure to convected heat from air containing less than 10 % of water vapour can, for a person which is fully-clothed, be calculated with Equation 16 below. This equation is also estimated to have an uncertainty of ± 25 %. The fractional effective dose of heat obtained during exposure can be calculated with Equation 17. The uncertainty with the FED calculation is dependent on the uncertainty that comes from Equation 15 and Equation 16.

In order to take this uncertainty into account, the time to reach the threshold value of FED should be reduced with 25 % (National Fire Protection Association, 2014).

$$t_{Irad} = 106 \cdot q^{-1.35}$$ *Equation 15*

Where

t	is time (min)
q	is the radiant heat flux (kW/m^2)

Equation 16

$$t_{Iconv} = (4.1 \cdot 10^8) \cdot T^{-3.61}$$

Where

t	is time (min)
T	temperature (°C)

$$FED = \sum_{t_1}^{t_2} \left(\frac{1}{t_{Irad}} + \frac{1}{t_{I\text{conv}}} \right) \cdot \Delta t$$ *Equation 17*

If the radiant flux to the skin is under the threshold value of 2.5 kW/m^2, the first term in Equation 17 is set to zero.

4.3.3 Soot particles

Soot particles can be dangerous when inhaled because small particles cause damage in the respiratory system and can also be absorbed into the blood where they can cause blood clots and allergic reactions.

Soot particles also lead to lowering of the visibility in the vicinity of the fire (Ingason, Li, & Lönnermark, 2015). Lack of visibility does not cause incapacitation or death by itself, but it affects the walking speed of evacuees in a negative way, see Chapter 4.4.5. This, in turn, leads to evacuees staying longer in environments with worsening conditions which may lead to them not being able to escape. Lack of visibility is also an issue as people may not see where they are going and where emergency exits are located, this sometimes leads to people missing the nearest emergency exit.

4.4 Evacuation-related factors and sub-models

In this chapter, some general key evacuation-related factors for road tunnel fire scenarios along with exemplary sub-models adopted are provided.

4.4.1 Detection systems

A detection system is necessary to be able to alert tunnel users about an accident or a fire. This can be made by detectors inside the tunnel in combination with the use of surveillance cameras, which are commonly used as a part of the alerting system in order to know exactly where the fire is located (Ingason, Li, & Lönnermark, 2015).

Different types of detection systems used in tunnels are flame detection, smoke detection, line or spot heat detection and systems based on gas compositions. The most common type of system in road tunnels is line heat detectors, which detect fire by temperature changes (Ingason, Li, & Lönnermark, 2015). In most tunnels, CO_2 and CO sensors are installed for controlling the air quality inside the tunnel, according to Ingason, Li and Lönnermark (2015). According to the authors, these sensors can be used as a complementary detection system in tunnels, but the distance between the installations may be shortened for better performance. Ingason, Li and Lönnermark (2015) propose linear heat detection systems in combination with smoke/dust detectors and/or surveillance cameras. Due to exhaust from vehicles, smoke detection is difficult to have as the only detection system, and a combination of detection systems should result in fewer false alarms. Maciocia and Rogner (2005) gives a suggestion on which requirements that a fail-safe and false-alarm-safe fire detection system must meet. These requirements are, e.g. strong-air fluctuations (due to ventilation), temperature changes (due to external condition in entrance and exit portals), hot exhaust fumes from HGVs and large amounts of corrosive air, dirt and dust. Maciocia and Rogner (2005) propose, just like Ingason, Li and Lönnermark, linear heat detection systems with specially constructed smoke and flame detectors which have been developed to use in the aggressive tunnel environment.

4.4.2 Recognition time

The recognition time for occupants during an evacuation depends on which detection and alarm systems there are in the tunnel. The recognition time is described by Nilsson (2015) as *"the time taken for people to interpret the cue as indicating fire/emergency*".

If there is a detection system, the recognition time normally is equal to the time for activation of the alarm system. Otherwise, the recognition time for one individual is depending on, for example, whether the person sees the fire (or senses other fire cues) or not and is influenced by how other evacuees behave.

In the evacuation experiments conducted in the Second Benelux tunnel presented by Norén and Winér (2003), the conclusion was that the recognition time and the motorists' behaviour may change from case to case. The authors did seven tests with a total of 193 people (one person in one car), where an HGV stopped in the middle of the tunnel and smoke started to develop. In all tests, an announcement was made five minutes after the truck stopped and again two minutes after the first announcement. The participants were divided into two groups, depending on if they left their cars before or after the first announcement was made. In the seven tests, 20 % of motorists left their car before the announcement, the rest reacted after the announcement. The time until the motorists left their cars is also different in each case, which indicates that the recognition time varies.

4.4.3 Response time

The response time is described by Nilsson (2015) as "*the time taken to do preparatory actions before starting to move".* The response time is measured from when the recognition time ends until people start moving towards an exit. The initial phase of the evacuation process is characterized by uncertainty, according to the people's behavior sequence model (Canter, Breaux, & Sime, 1980). The response time can vary depending on people's behaviour and the type of alarm system, which has been investigated in full-scale experiments by e.g. Bayer and Rejnö (1999). The authors did unannounced evacuation experiments in a movie theatre with different types of alarm systems to investigate which type that initiates evacuation the fastest. The conclusion drawn was that the most effective system was the one that could combine fast recognition time and could supply the evacuees with enough information, which leads to a faster response time.

A voice message was played in an evacuation experiment by Frantzich et al. (2007) in the Göta Tunnel. After the experiment, the participants were asked if they could hear the message and it was concluded that the message was hard to hear for the people who were in their cars. It was slightly easier to hear the message outside the car, but half of the participants that were outside their car when the message was played still thought the message was unclear. This indicates that the acoustic environment in tunnels is challenging due to echo and noise from e.g. jet fans. In any case, it is necessary to have some type of alarm system so the motorists can be aware that something has happened. Frantzich et al. (2007) suggest the use of signals to make motorists aware and then convey clear and concise information about how to act by information signs. According to Frantzich, Nilsson and Rød (2016) motorists will, in an ideal case, not be exposed to smoke and therefore technical systems such as signs and alarms are important to shorten the time the motorists spend in the tunnel during the fire. As a complement to alarm systems, information could be sent out via the car radio or phones within the tunnel area (Frantzich, Nilsson, & Rød, 2016).

For the combination of recognition time and response time, the so-called pre-movement (or pre-evacuation) time, the Italian guidelines for tunnel safety design provide average values for the time to abandon vehicles, which is 300 seconds for vehicle users and 90 seconds for truck drivers (Condirezione Generale Tecnica. Direzione Centrale Progettazione, 2009). These values can be used as a guideline for which time it takes for motorists to leave their vehicles and start the evacuation, preferable as a statistical distribution.

4.4.4 Unimpeded walking speed

Movement speed of evacuees is a central issue within the field of evacuation and has been studied for many years. People have different walking speeds, which depend on many factors, e.g. age and physical characteristics, which can make it hard to set a value that is realistic for a large group of people. Fridolf et al. (2018) suggest using an unimpeded walking speed for visibility levels above three meters. They propose to set peoples' walking speed for an adult able-bodied population using a randomised value from a normal distribution with a mean of 1.35 m/s and a standard deviation of 0.25 m/s with minimum and maximum thresholds of 0.85 and 1.85 m/s (Fridolf, Nilsson, Frantzich, Ronchi, & Arias, 2018).

4.4.5 Walking speed vs visibility

Studies show that once a given visibility threshold has been reached, people tend to walk slower in smoke-filled environments than in smoke-free areas (Fridolf, Ronchi, Nilsson, & Frantzich, 2015). An important aspect during evacuation in tunnels is the impact of smoke and lack of visibility on walking speed. People may reduce their walking speed due to smoke. There are experiments made by e.g. Ronchi et al. (2018) which have analysed peoples walking speed in smoke. Fridolf et al. (2016), presented a correlation between visibility and walking speed based on a range of experimental data collected under different visibility conditions. The correlation is created from six different experimental studies and gives a threshold value of three meters (as mentioned above) where people tend to start reducing their walking speed and a minimum value for walking speed of 0.2 m/s. Between these two values, there is a linear decrease of 0.34 m/s per meter lowered visibility. This means that the visibility (below 3 m) where a certain walking speed is expected depends on the person's unobstructed walking speed, see Figure 12.

The correlation can be used in three main ways, either with one group with a set unimpeded walking speed, several groups with different unimpeded walking speeds or by assigning randomised individual unimpeded walking speeds from a decided distribution. See Figure 12 and Figure 13 for the first two cases. The use of this correlation is currently under discussion within the Sub-committee 4 on fire safety engineering, part of the technical committee 92 on Fire Safety of the International Standards Organization (ISO). Noteworthy is that the correlation is based on studies with non-irritant smoke which might influence its usability for fires producing very irritant gases.

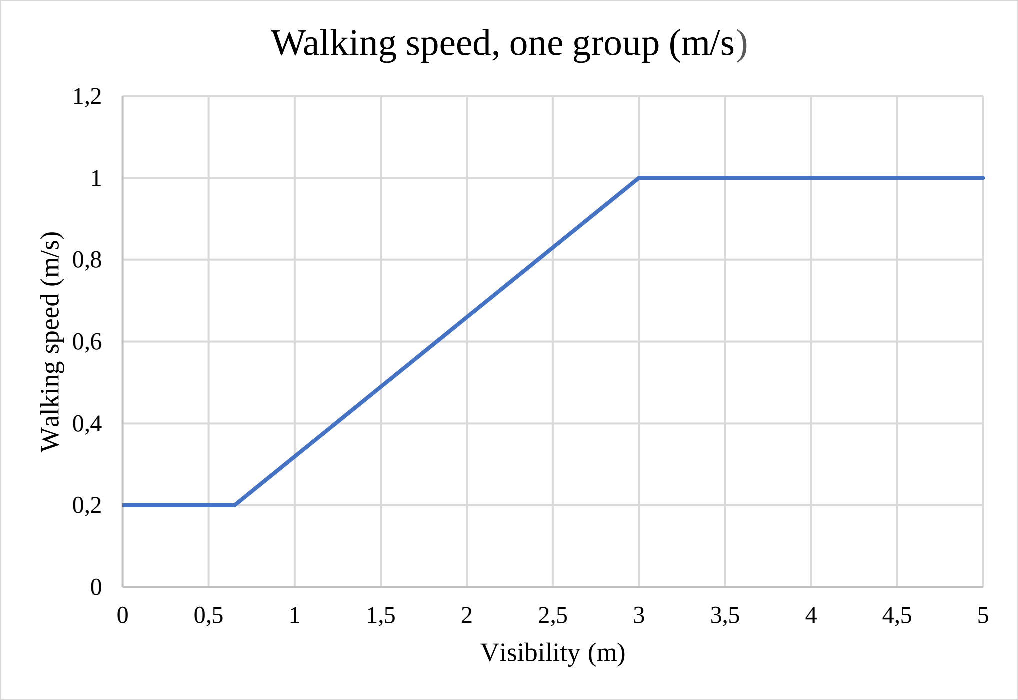

Figure 12. Walking speed of one group as a function of visibility (Fridolf, Nilsson, Frantzich, Ronchi, & Arias, 2018).

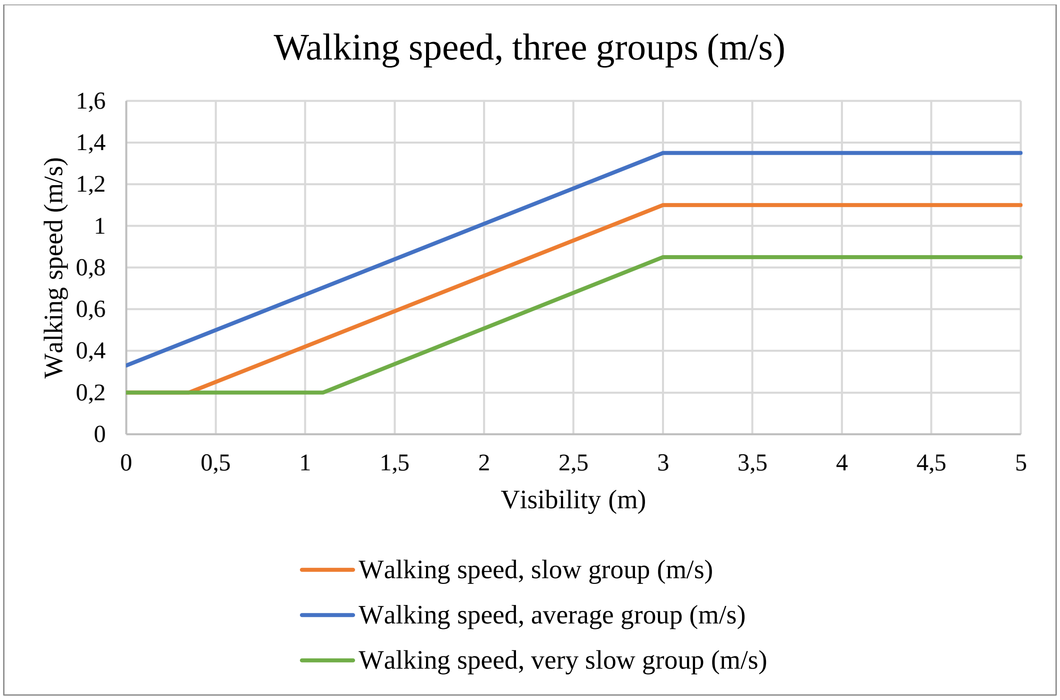

Figure 13. Walking speeds of three groups as a function of visibility (Fridolf, Nilsson, Frantzich, Ronchi, & Arias, 2018).

4.4.6 Walking speed vs people density

Walking speed is dependent on the presence of other people during the movement. The space occupied by people can be described as a density number. For example, the SFPE Handbook of Fire Protection Engineering (Gwynne & Rosenbaum, 2016) describes a hydraulic model to calculate walking speed as a function of density. The creators of Pathfinder, Thunderhead Engineering, have modified the equations for simulation purposes, these can be seen in Equation 18 and Equation 19 below (Thunderhead Engineering, 2018).

$$v_b = v_{max} \cdot v_f(D) \cdot v_{ft} \qquad \textit{Equation 18}$$

Where

v_{max} is the person's unobstructed walking speed (m/s)

$v_f(D)$ is a speed fraction as a function of density, see Equation 19

v_{ft} is a speed fraction depending on terrain (equal 1 on level terrain)

$$v_f(D) = \begin{cases} 1 & D < 0.55\ pers/m^2 \\ \max\left[v_{fmin}, \frac{1}{0.85} \cdot (1 - 0.266 \cdot D)\right] & D > 0.55\ pers/m^2 \end{cases} \qquad \textit{Equation 19}$$

Where

v_{fmin} is a minimum speed fraction (default 0.15 in Pathfinder)

4.4.7 Route/exit choice

Experiments made by Norén and Winér (2003) indicate that six percent of evacuees missed the first emergency exit. The probability of missing the first emergency exit may also be correlated to the visibility and the signage and way-finding aids available in the tunnel. The way-finding systems (i.e. exit signs) available in the tunnel may therefore have a significant impact on exit usage (Ronchi, Nilsson, & Gwymme, 2012). Different experiments have been done with different lights, different colours and with flashing lights e.g. virtual reality experiments by Ronchi and Nilsson (2015). Which type of way-finding system that is most suitable for a specific tunnel is up to each tunnel manager do decide, suggestively in line with the results of the most recent experiments.

4.4.8 Flow through doors

The flow through a door is dependent on how many people are trying to get through the door at that specific time. The amount of people can be described as a density. One way of calculating the flow through doors depending on density is with the hydraulic model described above (Gwynne & Rosenbaum, 2016). The developers of Pathfinder, Thunderhead Engineering, have modified this correlation to fit evacuation simulations (Thunderhead Engineering, 2018). See Equation 20 and Equation 21 below for flow through doors and time to evacuate a room. Equation 20 is clamped at values between 1.9 and 3.5 because it is quadratic. This is so that the flow does not become zero at high densities and so that it does not decrease at low densities.

$$F_s = (1 - 0.266 \cdot D) \cdot k \cdot D \qquad \textit{Equation 20}$$

Where

F_s	is the flow through a door (pers/s*m)
D	is the density of people (pers/m^2)
k	is a terrain constant, 1.4 for level terrain

F_s should then be multiplied by the effective width of the door to gain a value in persons per second, this can be used to calculate the time to evacuate a room with a certain door width, flow and number of people (Pauls, 1980).

$$T = \frac{n-1}{F_s} \qquad \textit{Equation 21}$$

Where

T	is the time required to evacuate a room (s)
F_s	is the specific flow through a door (pers/s)
n	is the number of people in the room

5. Validation and verification of ARTU

In this chapter validation and verification of ARTU are presented. The validation and verification process consisted of different stages as explained in Chapter 1.3. During the validation of the fluid-dynamics part, it turned out that uncertainties in experimental results required a further comparison with FDS. For example, the wind conditions in cases without mechanical ventilation caused issues in the comparison. Examples of experimental uncertainties are presented in Chapter 3.2. Also, the fact that the 1D software gives a single value for each variable at set distances from the fire caused issues as to whether it was possible to compare results. The validation of the fluid-dynamics part is found in Chapter 5.1 below. The verification of evacuation modelling was done with hand calculations and is found in Chapter 5.2. For the verification of the FN-curve, no cases were found in the literature that could be used as a suitable comparison, which is a validation. This led to the decision to only make a verification of the FN-curve which ARTU produced. This verification is found in Chapter 5.3. A sensitivity analysis of some input variables can be found in Chapter 5.4.

5.1 Validation of fluid dynamics

To be able to validate the 1D fluid dynamic part of ARTU, different cases with full-scale experiments must be used to compare the results from the 1D fluid dynamic software with results from the experiments. In order to do this comparison, five experimental cases performed in the Second Benelux tunnel have been chosen. All those five cases have also been simulated in FDS. Results from ARTU and FDS will be presented, together with experimental data, below.

The Second Benelux tunnel is an 840 m long tunnel located just outside of Rotterdam in the Netherlands and helps vehicles, trains and pedestrians cross the New Meuse River. It consists of six bores, where three are for road traffic, one for bicycles and pedestrians and two for the metro (van Aart & van Vliet, 1999). The bores for road traffic are 9.85 m wide each and provide two traffic lanes each, with uni-directional traffic (van Aart & van Vliet, 1999). The tunnel has a maximum slope of 4.4 %, with the lowest point of the tunnel located in the middle of the tunnel (van Aart & van Vliet, 1999). The tunnel is provided with longitudinal ventilation consisting of jet fans and has emergency exits every 100 m (Lemaire, Leur, & Kenyon, 2002).

In the years 2000 and 2001, fourteen full-scale experiments were performed in the tunnel by the Dutch Ministry of Transport and the TNO Centre for Fire Research (Lemaire & Kenyon, 2006). The test site was located 265 m from the northern portal and the ventilation system was in the south part, consisting of six fans whereof three were in the entrance and three were 250 m from the entrance. The measurements were performed from 50 m upstream to 200 m downstream of the fire. Several types of fire sources were used, such as fuel pans, cars, a van and covered wooden pallets. The tests were performed with and without longitudinal ventilation in order to investigate the impact of ventilation. In Table 10 below experiments that have been used are presented. In reports from the experiments, data on temperature, visibility, velocity and concentration of carbon monoxide are available. The exact input variables that were used in the 1D fluid dynamic software cannot be presented here due to confidentiality issues. However, the tool is in some way considering factors as tunnel geometry, ventilation mode and HRR et cetera. Calculations according to Equation 10 show that all cases with 1.5 and 6 m/s ventilation are well-ventilated. In test 14, only the first 20 minutes are relevant due to sprinkler activation after 20 minutes. For the other tests, the whole fire is relevant.

Table 10. Experiments from the Benelux tunnel.

Test	Type of fire	Heat release rate	Ventilation
6	Car	5 MW	Natural ventilation
7	Car	5 MW	Longitudinal ventilation max 6 m/s
8	Canvas covered wooden pallets	20 MW	Natural ventilation
9	Canvas covered wooden pallets	20 MW	Longitudinal ventilation max 6 m/s
14	Wooden pallets	25 MW	Longitudinal ventilation 1 m/s

In order to make an HRR curve, the fire sources were placed on a weighing plateau that was placed on four load cell sensors in order to determine the rate of heat release from the mass loss rate of the burning material (Lemaire, Leur, & Kenyon, 2002). The smoke and air temperatures were measured at five different heights in the middle of the tunnel cross-section with thermocouple trees located at upstream distances of 10, 20 and 50 m and downstream distances of 10, 20, 50, 100 and 200 m with respect to the fire center. Type K-thermocouples were used with a diameter of 0.5 mm (Lemaire, Leur, & Kenyon, 2002).

Ventilation velocities were measured at three positions upstream of the fire (with hot wire anemometers) and at three positions near the tunnel downstream portal (with bi-probes), but only results from the measurement point at 50 m upstream was given (Lemaire, Leur, & Kenyon, 2002). The velocities results from the 1D fluid dynamic software are therefore also taken at this distance. All the tests were recorded on video using six cameras located at positions upstream and downstream of the fire. The visibility was measured for reflecting objects, with visual observations during the tests (video recordings). Optical density is also measured, but it is not clear how it is used. The visibility was just measured in a qualitative way, with the following limits (Lemaire, Leur, & Kenyon, 2002):

- *Slightly reduced visibility*: 50 m visibility for illuminated objects. At least one of the (illuminated) escape doors can be seen.
- *Moderate visibility*: 25 m visibility for illuminated objects. At least one of the escape route signs can be seen.
- *Poor visibility*: 5 m visibility for reflecting objects. At least one of the walls can be seen.
- *Disorientation*: 2 m visibility for reflecting objects. None of the tunnel walls can be seen.

5.1.1 Results of experiments compared with 1D fluid dynamics software

Results from the 1D fluid dynamic software are compared with experimental results and are shown in Table 11 below. Input data for the calculations and complete results together with further explanations can be found in Appendix B. With Equation 1, a functional analysis has been conducted and ERD has been calculated for temperature and velocity curves and are found in Appendix B. For temperature, ERD is calculated for all distances where an experimental result is available but the value that is presented is the average between those values. When ERD is equal to zero, two curves are identical, and the further away (higher value) from zero, the less alike the curves are. In these specific cases, a higher value corresponds to ARTU being more conservative. In the comparison between experiments and 1D fluid dynamics, the experiment curves are seen as the correct. In the temperature comparison, the following thresholds are set:

- Good agreement is equal to ERD between 0-0.3
- Conservative is equal to ERD between 0.3-1
- Very conservative is equal to ERD above 1

In the velocity comparison, the following thresholds are set:

- Good agreement is equal to ERD between 0-0.3
- ERD between 0.3-1 corresponds to ARTU being lower than experiments

For variables that do not have curves where ERD can be calculated, i.e. carbon monoxide concentration and visibility, a qualitative comparison is made, which is presented in Table 11 below.

Distances from the fire (downstream) in the ARTU simulations are rounded off to match the distances in experiments and since the simulations measure variables with a distance step of 16.8 m. The temperature measurements in the experiments are made at one and two meters height and the data are an average from those values, except for the 25 MW fire where temperature was measured at 1, 2, 3, 4 and 5 m height and the presented results is an average from those results.

In the test report by Lemaire, Leur and Kenyon (2002) a maximum concentration of carbon monoxide in the experiments is presented. The measurements of CO failed to produce reliable results for technical reasons/defect equipment, so the CO concentrations were instead determined with known CO production together with the mixing factor (Lemaire, Leur, & Kenyon, 2002). It is somewhat futile to measure a maximum value from a certain point in a tunnel to a maximum out of the results given by a 1D fluid dynamics tool since they are not comparable. In the FDS comparison in Chapter 5.1.2, a further comparison is made where the 1D results are compared to mean values over cross sections at the same distances which is a more valid comparison.

As described above, it is not clear how the optical density was measured during the experiments and the visibility was only measured in a qualitative way with visual observations. Therefore, it is difficult to draw any conclusions about how the 1D results match the experimental results. Only a general comparison is therefore made, which is seen in Table 11 below.

Table 11. Results of comparison between ARTU and experiments.

Test no.	Temperature[4]	Carbon monoxide concentration[5]	Visibility	Velocity[6]
6	Very conservative	Conservative	Conservative	ARTU results lower than experiment
7	Good agreement	Slightly conservative	Good agreement	Good agreement
8	Very conservative	Not conservative	Conservative	ARTU results lower than experiment [7]
9	Conservative	Not conservative	Good agreement	Good agreement
14	Conservative	Not conservative	Conservative	ARTU results lower than experiment [8]

5.1.2 Comparison between 1D fluid dynamics software and FDS simulations

Since the results obtained from ARTU did not fully agree with the ones from the experiment for some variables and are difficult to compare in some cases, FDS simulations with FDS 6.7.1, for all tests were run to provide a benchmark for comparison and to investigate the causes of these differences.

For a simulation to maintain the information in the plume, the grid resolution must be small enough to simulate the eddies created in the plume. A mesh sensitivity analysis where the grid size is gradually reduced until there is no longer a change in results should be made to ensure that the grid size is small enough. Because of time constraints and the fact that the comparison between ARTU and FDS is not actual validation but merely a comparison between tools with their own uncertainties, an analysis of some variables has been made instead.

D*/dx is a dimensionless relationship that shows the number of grid cells of the size dx which covers a fire with the characteristic fire diameter D* (McGrattan et al., 2019). This relationship can be used to determine how well the flow is calculated by FDS. D* is calculated using Equation 22 below.

[4] Intervals according to description above.
[5] Difficult to compare maximum values from experiments to results from the 1D fluid dynamics tool.
[6] Intervals according to description above.
[7] It differs in the beginning where ARTU has no velocity and the experiments has 1.5 m/s velocity.
[8] It differs in the beginning where ARTU has no velocity and the experiments has 1 m/s velocity.

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty \cdot c_P \cdot T_\infty \cdot \sqrt{g}}\right)^{\frac{2}{5}}$$ *Equation 22*

Where

$\dot{Q}$ is the total heat release rate of the fire (kW)

ρ_∞ is the ambient air's density (assumed to be 1.2 kg/m^3)

c_P is the specific heat capacity of air (assumed to be 1 kJ/kg*K)

T_∞ is the ambient temperature (K)

G is the gravitational acceleration (assumed to be 9.81 m/s^2)

The creators of FDS ran a series of grid sensitivity analyses for NUREG 1824 and came to the conclusion that a value of between 4 and 16 for D*/dx gave reasonable results without requiring an unreasonable amount of simulation time in those specific simulations (McGrattan, Klein, Hostikka, & Floyd, 2007). The authors specifically say that these values are not intended as guidelines for all simulations and that a simulation specific evaluation must be made.

D*/dx was calculated for all test cases and can be seen in Table 12 below, the values are deemed acceptable in all cases.

Table 12. Calculated D/dx for Benelux cases.*

Test no.	**Grid size (m, dx)**	**Area of fire (m^2)**	**HRRPUA (kW/m^2)**	**Q***	**D*/H**	**D*/dx**
6	0.2	8	599.7	0.24	0.35	7.21
7	0.2	9.36	501.9	0.19	0.35	9.06
8	0.2	26	510.8	0.15	0.52	10.83
9	0.2	38	510.6	0.14	0.61	15.97
14	0.2	52	493.6	0.12	0.69	17.86

Only half the tunnel was modelled to reduce calculation time and because there was no substantial back-layering, meaning that it was not necessary to model the parts of the tunnel where there is no change from ambient conditions.

The walls, floor and ceiling were made from concrete with values corresponding to Concrete 1-2-4 Mix from Appendix 2 of the Handbook of Fire Protection Engineering, see Table 13 below (Society of Fire Protection Engineers (SFPE), 2016).

Table 13. Material properties of concrete (Society of Fire Protection Engineers (SFPE), 2016).

Material	Conductivity (W/m*°C)	Specific heat capacity (kJ/kg*K)	Density (kg/m^3)
Concrete	1.37	0.88	2100

Two different reactions were used depending on the composition of the combustibles used: wood and polyester from Chapter 36, Appendix A of the SFPE Handbook of Fire Protection Engineers and data from experimental information, see Table 14 below (Khan, Tewarson, & Chaos, 2016; Society of Fire Protection Engineers (SFPE), 2016; Lemaire & Kenyon, 2006).

Table 14. Material properties of combustibles (Khan, Tewarson, & Chaos, 2016; Society of Fire Protection Engineers (SFPE), 2016; Lemaire & Kenyon, 2006).

Material	Chemical formula	CO yield (g/g)	Soot yield (g/g)	Heat of combustion (MJ/kg)
Wood	$CH_{1.7}O_{0.83}$	0.004	0.015	18.7
Polyester	$CH_{1.4}O_{0.22}$	0.063	0.064	30.0

The slope of the tunnel was modelled by changing the direction of gravitation in the simulation using the GVEC function in FDS. A slope of 4.4 % in positive x-direction corresponds to the vectors x = -0.431. y=0.0 and z = -9.81.

In an initial simulation, the number of pressure iterations was kept at the default 10 but the results showed that this maximum number was hit at some time-steps in the simulations which can cause issues with accuracy. An attempt to re-run all simulations with a maximum of 50 pressure iterations was made, but due to issues with numerical stability only the 5 MW case could be run with a maximum of 50 pressure iterations. This issue with numerical instability due to pressure and velocity spikes is known by the developers of FDS and a proposed solution is to create small holes in the tunnel to relieve the pressure (McGrattan, 2016). Due to time constraints and that it takes longer to simulate with more pressure iterations and the fact that the FDS comparison is not the main validation (which is the comparison with experiments) the simulations with numerical instability at 50 iterations were kept at 10 iterations. A comparison of the results in the 5 MW case using a maximum of 10 and 50 pressure iterations shows very slight differences in results. There might have been a bigger difference in the 20 MW or 25 MW cases because the number of pressure iterations reached the maximum at more time-steps, but this could not be analysed due to above mentioned numerical instability and FDS crashing.

The geometry can be seen in Figure 14 and Figure 15 below, a part of the ambient outside of the portal has also been simulated with an open vent at the top and front to create realistic results.

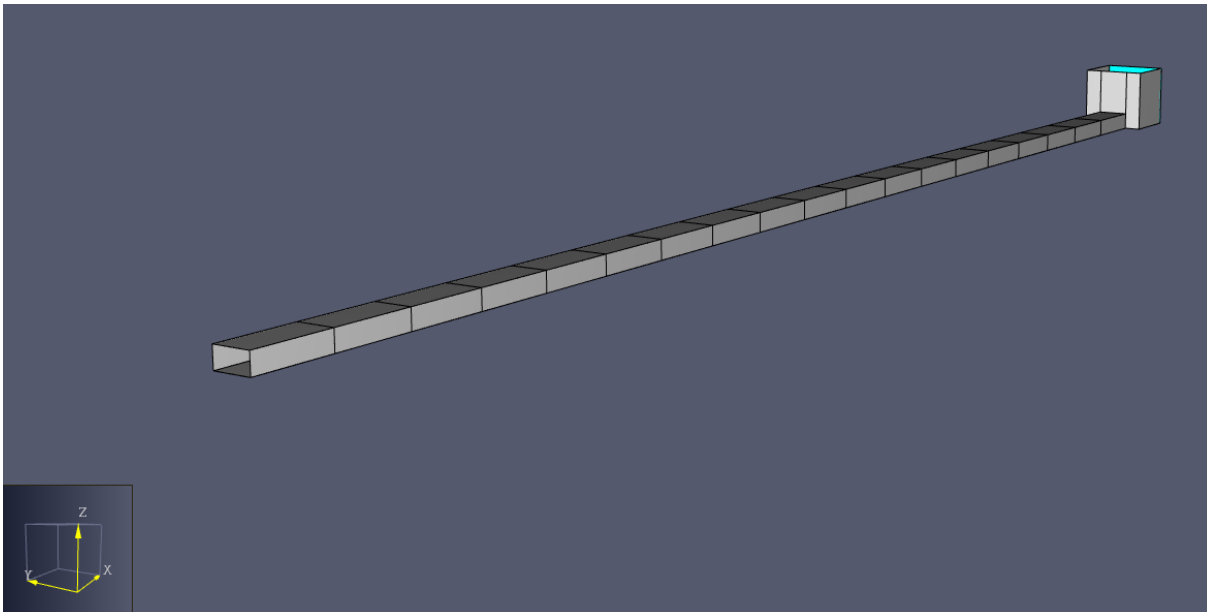

Figure 14. Full geometry of simulations, picture taken from Pyrosim.

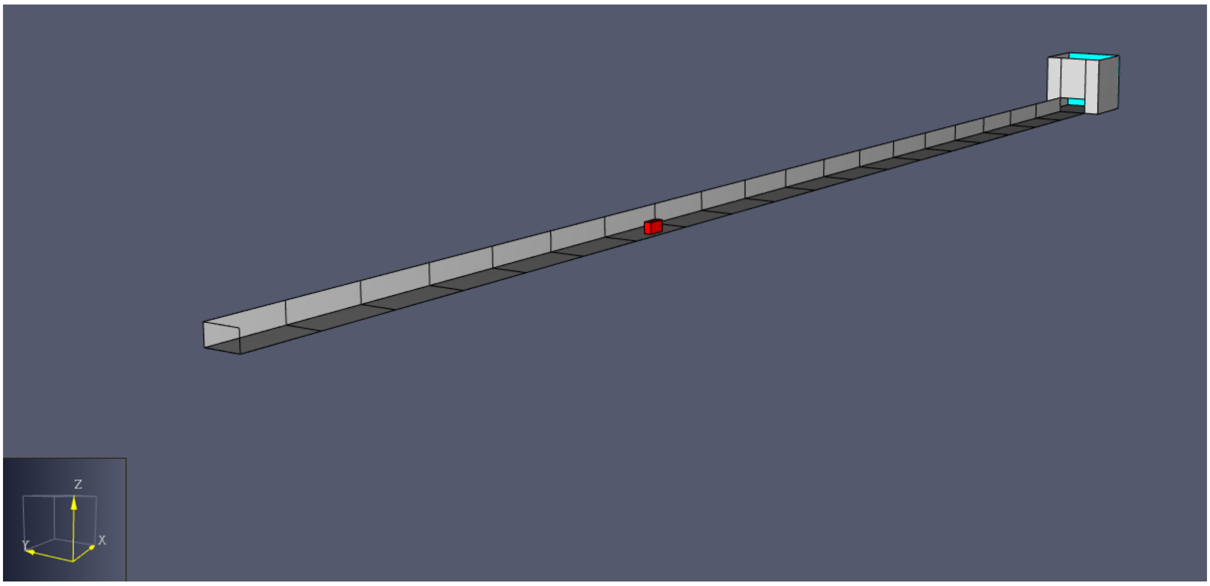

Figure 15. Partial geometry of simulation with fire visible, picture taken from Pyrosim.

Measurements were made in the simulations for comparison with experiments and the 1D fluid dynamic software. To compare with experiments, point measurements for temperature were made in the same places as in the experiments and in the case of carbon monoxide concentration a maximum was measured in each mesh since this was the only available result from the experiments. To compare with the results from the 1D software, averages over the cross-section were made at the same distances from the fire as in ARTU. See Table 15 below for further descriptions.

Table 15. Measurements in FDS simulations.

Variables	Type of measurement	Downstream distance from fire
Temperature	Point (TEMPERATURE and THERMOCOUPLE, bead diameter 0.5 mm)	10, 20, 50, 100 and 200 m
Temperature, carbon monoxide concentration, carbon dioxide concentration, oxygen concentration and visibility	Average over cross-section	13, 29.8, 46.6, 63.4, 97 and 197.8 m
Carbon monoxide concentration	Maximum volume fraction	Calculated in each mesh
Velocity	Average, min and max over cross-section	-50 m (upstream from fire)

A temperature comparison was made between FDS and the experiments as this is the most interesting value to see whether FDS can simulate correctly. ERD was calculated both for the comparison between 1D fluid dynamics and FDS, and FDS versus experiments. As in the comparison between experiments and 1D fluid dynamics, ERD was calculated for the distances where an experimental result is available but the value that is presented is the average between those values. In some cases, the smoke layer is lower in the experiments than in FDS which leads to FDS giving lower temperatures than the experiments. Since tests 6, 8 and 14 were affected by natural ventilation (wind) which cannot be modelled in detail by a 1D-model, there were two FDS simulations made for each case that included wind. One with the same velocity curve as in the experiments (caused by wind and buoyancy from the fire), used to make a comparison with the experiments, and one with no initial ventilation to compare with results from the 1D-software. For the full results from the simulations, see Appendix C-Appendix J.

The comparison shows a good agreement between the experimental results and the FDS simulations, except test 9 where FDS gives lower temperatures than in the experiments, as can be seen in Table 16 below. For Table 16, the following thresholds are set:

- Good agreement is equal to ERD between 0-0.3
- ERD 0.3-1 corresponds to FDS lower than experiments

Table 16. Results from comparison between FDS and experiments.

Test no	Temperature
6	Good agreement
7	Good agreement
8	Good agreement
9	FDS results lower than experimental results
14	Good agreement

A comparison was made between ARTU and FDS to be able to compare more comparable results, which is difficult using only the available experimental results. A summary of the comparison (ERD results) between ARTU and FDS can be seen in Table 17 below. For the full results, see Appendix C- Appendix J. The results show that ARTU gives conservative results in almost all cases, especially for cases without ventilation where the results from ARTU are highly conservative in general. This can be partly explained by ARTU giving lower velocities due to buoyancy than FDS does, hence giving higher temperatures and build-up of smoke. For temperature and carbon monoxide concentration, the following thresholds are set:

- Good agreement is equal to ERD between 0-0.3
- Conservative is equal to ERD between 0.3-1
- Very conservative is equal to ERD above 1

In the velocity comparison, the following thresholds are set:

- Good agreement is equal to ERD between 0-0.3
- ERD between 0.3-1 corresponds to ARTU lower than FDS

For visibility where the curves obtained cannot be easily compared and where ERD cannot be calculated, a qualitative comparison is made, which also is presented in Table 17 below.

Table 17. Results from comparison between ARTU and FDS.

Test no	Temperature	Carbon monoxide concentration	Visibility	Velocity
6	Very conservative	Very conservative	Conservative	ARTU lower than FDS
7	Good agreement	Conservative	Conservative	Good agreement
8	Very conservative	Conservative	Conservative	Good agreement
9	Good agreement	Good agreement	Slightly conservative	Good agreement
14	Very conservative	Conservative	Slightly conservative	Good agreement

5.2 Verification of evacuation modelling and toxicity assessment

In order to verify the evacuation module of ARTU, different tests have been conducted, both for walking speed, density versus flow and time to reach critical levels of chemical substances and heat. These tests have been chosen for verification as they cover the core sub-models in ARTU and because they affect the resulting evacuation results to a great extent. A short explanation of the tests is given in the following sections together with the results from both the tool and from hand calculations. Also, an estimation of uncertainty is presented.

ARTU uses a fixed time-step which can be modified by the developer. The developer can modify the precision in both time and space discretization. In the following section, two different settings, five seconds and one decimeter, and one second and one centimeter, are used. Five seconds and one decimetre has been shown in the tests to give reasonable results which is why it has been set as the default value.

5.2.1 Verification of walking speed vs visibility

A number of tests have been conducted for the verification of walking speed with reduced visibility. In each test, there is only one person evacuating and the visibility is constant throughout the evacuation. The visibility is tested with values of 10, 5, 2 and 0.5 m. The evacuees' unimpeded walking speeds are tested for 1.0, 0.75, 0.5 and 0.25 meters per second. The distance to the closest unobstructed exit is 100 m in all cases. The calculations are made with the correlation in Figure 12. The results are the time it takes for the person to reach the exit and there is no recognition or response time included. Results produced by hand calculation are presented in Table 18 below.

Table 18. Table of results (s), hand calculated.

		Unimpeded walking speed			
		1 m/s	**0.75 m/s**	**0.5 m/s**	**0.25 m/s**
Visibility	**10 m**	100	133	200	400
	5 m	100	133	200	400
	2 m	152	244	500	500
	0.5 m	500	500	500	500

Results from ARTU are presented in Table 19 and Table 20 below, with two different time-steps but with the same truncation for distance.

Table 19. Table of results (s), simulated with ARTU, time-step Δt= 5 s.

		Unimpeded walking speed			
		1 m/s	**0.75 m/s**	**0.5 m/s**	**0.25 m/s**
Visibility	**10 m**	95	130	195	415
	5 m	95	130	195	415
	2 m	150	245	495	495
	0.5 m	495	495	495	495

Table 20. Table of results (s), simulated with ARTU, time-step Δt= 1 s.

		Unimpeded walking speed			
		1 m/s	**0.75 m/s**	**0.5 m/s**	**0.25 m/s**
Visibility	**10 m**	99	142	199	399[9]
	5 m	99	142	199	399[10]
	2 m	142	249	499	499
	0.5 m	499	499	499	499

The analysis of the results shows that simulation with a time-step of five seconds is in line with hand calculations with a margin of error, calculated with Equation 2, between -5 % to +3.75 %. With a time-step of one second, the simulation has a margin of error of between -6.58 % to +24.75 %.

For the cases that were run, the results indicate less precise results but faster computation time when truncation is made at five seconds and one decimeter compared to one second and one centimeter which gives more precise results but with higher computation time.

[9] This value is calculated with truncation at centimetres instead of decimetres.
[10] This value is calculated with truncation at centimetres instead of decimetres.

5.2.2 Verification of walking speed vs density

A set of tests with a person walking through a corridor together with other people, resulting in a given density, has been performed for the verification of walking speed with a variable density of people. The density is tested with values of 1.5, 2.5, 3.0 and 3.5 persons/m^2. The corridor is identical in each case and is 20 m long and the effective width is 2 m. The visibility is 10 m and the evacuees' unobstructed walking speed is 1 m/s, these parameters are also identical in all cases. The calculations are made with Equation 18 and Equation 19.

Results produced by hand calculation are presented in Table 21 below.

Table 21. Table of time for a person to walk through a corridor (s), hand calculated.

	Density (pers/m^2)			
	3.5	**3**	**2.5**	**1.5**
Velocity (m/s)	0.15	0.24	0.39	0.71
Evacuation time (s)	133	84	51	28

Results from ARTU are presented in Table 22 and Table 23 below, with two different time-steps but with the same truncation for distance.

Table 22. Table of time for a person to walk through a corridor (s), simulated with ARTU, time-step Δt= 5s.

	Density (pers/m^2)			
	3.5	**3**	**2.5**	**1.5**
Velocity (m/s)	0.15	0.24	0.39	0.71
Evacuation time (s)	140	80	45	25

Table 23. Table of time for a person to walk through a corridor (s), simulated with ARTU, time-step Δt=1 s.

	Density (pers/m^2)			
	3.5	**3**	**2.5**	**1.5**
Velocity (m/s)	0.15	0.24	0.39	0.71
Evacuation time (s)	133[11]	99	49	28

ARTU produces, with a time-step of five seconds, results with a margin of error, calculated with Equation 2, between -13 % and +11 %. With a time-step of one second, the tool produces results with a margin of error between -4 % and +35 %.

Also, in this case, the results are less precise but with a faster computational time when truncation is made at five seconds and one decimeter compared to one second and one centimeter which gives more precise results but with higher computation time.

[11] This value is calculated with truncation at centimetres instead of decimetres.

5.2.3 Verification of flow through doors vs density

To verify the flow through doors depending on density in the room the following test has been conducted. There is a set number of people in a room that corresponds to a certain density. Tested densities are 3.53, 3.0, 2.53 and 1.47 persons/m^2. The room is identical in each case, 15 m^2 and the door's effective width is 1 m. The visibility is 10 m and the evacuees' unobstructed walking speed is 1 m/s, these parameters are also identical in all cases. The time to reach the door is neglected. The hand calculations are made with Equation 20 and Equation 21. In order to verify the case where the density decreases, simulations were made in Pathfinder. The same test as described above was conducted and each test was simulated ten times, and the presented result is an average from these simulations.

Results produced by hand calculation are presented in Table 24 below. In the first row the results from hand calculations, which ignore the decreasing density's effect on flow, are available. It is assumed in the hand calculations that the density in the room is constant. In the second row, the results are made with Pathfinder, with decreasing density using SFPE mode in the tool (Thunderhead Engineering, 2018).

*Table 24. Table of flow through door (pers/s*m) and total time until finished evacuation of room (s), hand calculated and an average from ten Pathfinder simulations.*

	Number of people in the room			
	53 pers (3.53 pers/m^2)	**45 pers (3.0 pers/m^2)**	**38 pers (2.53 pers/m^2)**	**22 pers (1.47 pers/m^2)**
Flow (pers/s*m)	0.34	0.85	1.16	1.32
Pathfinder (SFPE-mode) evacuation time (s)	49	37	30	17
Hand calc. evacuation time (s)	154	52	32	16

Results from ARTU are presented in Table 25 and Table 26 below. In the first row, the time calculated by the tool with default mode is presented. Here, the tool calculates the density at each time-step which means it is considering that people are exited from the domain. The second row shows the time calculated by the tool when it is forced to set the density constant and equal to the initial value, this is this row that can be directly compared with the hand calculations.

*Table 25. Table of flow through door (pers/s*m) and total time until finished evacuation of room (s), simulated with ARTU, time-step Δt= 5 s.*

	Number of people in the room			
	53 pers (3.53 pers/m²)	**45 pers (3.0 pers/m²)**	**38 pers (2.53 pers/m²)**	**22 pers (1.47 pers/m²)**
Flow (pers/s*m)	0.30	0.85	1.17	1.30
Evacuation time with decreasing density	60	40	30	20
Evacuation time with constant density	180	55	35	20

*Table 26. Table of flow through door (pers/s*m) and total time until finished evacuation of room (s), simulated with ARTU, time-step Δt= 1 s.*

	Number of people in the room			
	53 pers (3.53 pers/m²)	**45 pers (3.0 pers/m²)**	**38 pers (2.53 pers/m²)**	**22 pers (1.47 pers/m²)**
Flow (pers/s*m)	0.30	0.85	1.17	1.30
Evacuation time with decreasing density	51	37	30	17
Evacuation time with constant density	179	54	33	17

ARTU produces, with a constant density and a time-step of five seconds, results with a margin of error, calculated with Equation 2, between +6 % and +25 %. With a decreasing density and a five-second time-step, ARTU produces results with a margin of error between 0 % and +22 % compared to Pathfinder calculations with corresponding inputs and using SFPE mode. With a time-step of one second and constant density, the tool produces results with a margin of error between +6 % and +16 %. With a time-step of one second and decreasing density, the tool produces results with a margin of error between 0 % and +4 %.

5.2.4 Verification of chemical FED

In order to verify the calculations for time to incapacitation due to inhalation of chemical species, a test has been made to check when the time to FED=1 and FED=0.3 is reached. This has been calculated and simulated for two different combinations of concentrations of CO, CO_2 and O_2 (as this is the formulation implemented in ARTU). It is assumed that the person is exposed to a constant concentration of the specified species and does some light movement (walks to the exit). The calculations were made with Equation 11-Equation 14. Since ARTU only calculates FED for CO, CO_2 and O_2, Equation 11 is modified and the following parameters are set equal to zero: FED_{CN}, FED_{NO}, FLD_{irr}.

Results produced by hand calculation are presented in Table 27 below.

Table 27. Time to reach FED (s), hand calculated.

	3 % CO_2, 4000 ppm CO, 17 % O_2	**8 % CO_2, 10 000 ppm CO, 9 % O_2**
FED = 0.3	64	9
FED = 1	215	29

Results from ARTU are presented in Table 28 below.

Table 28. Time to reach FED (s), simulated with ARTU.

	3 % CO_2, 4000 ppm CO, 17 % O_2	**8 % CO_2, 10 000 ppm CO, 9 % O_2**
FED = 0.3	70	10
FED = 1	220	35

With a time-step of five seconds, ARTU produces results with a margin of error between +2 % and +21 %.

5.2.5 Verification of thermal FED

A verification test has been made in order to verify the calculations for time to incapacitation due to heat. This is performed by checking at what time Thermal FED=1. This has been calculated and simulated for four different temperatures. It is assumed that the temperature is constant the entire time and that the person is fully-clothed. Radiation has been excluded since this is not included in ARTU. It should be noticed that these results have not been reduced with 25 % according to NFPA recommendations (National Fire Protection Association, 2014). Results produced by hand calculation are presented in Table 29 below.

Table 29. Time to FED=1 (min), hand calculated.

Temperature (°C)			
100	**150**	**200**	**250**
24.70 (1482 s)	5.72 (343 s)	2.02 (121 s)	0.90 (54 s)

Results from ARTU are presented in Table 30 below.

Table 30. Time to FED=1 (min), simulated with ARTU.

Temperature (°C)			
100	**150**	**200**	**250**
24.75 (1485 s)	5.75 (345 s)	2.08 (125 s)	0.92 (55 s)

Analysis shows that simulation is correct with a margin of error, calculated with Equation 2, between +0.2 % and +3.0 %.

5.3 Verification of calculation of FN-curve

The probabilistic analysis aims to calculate an FN-curve for the tunnel which is under consideration. ARTU calculates the frequency for a specific number of fatalities per year, which is plotted in the ALARP diagram. The equation which is used in ARTU cannot be presented here due to confidentiality issues. However, the tool is in some way considering all factors presented in Chapter 4, except fire spread between vehicles, in the probabilistic analysis.

In order to verify the FN-curve which ARTU produces, a complete simulation was performed, with both fluid dynamics and evacuation modelling. The analysed simulation included 60250 scenarios with different numbers of fatalities. These numbers could then be used to calculate the frequency of fatalities per year in each interval, which made it possible to draw an FN-curve by hand. The complete simulation was based on a real tunnel, but changes have been done, e.g. is the longitudinal ventilation removed which worsens the consequences and therefore the FN-curve. The presented curve is therefore not representative of any real tunnel. The two curves, from ARTU and the hand calculated, are shown in Figure 16 below. The hand calculated frequencies are approximately 1.5-2 % lower than the frequencies produced by ARTU, which makes ARTU slightly conservative.

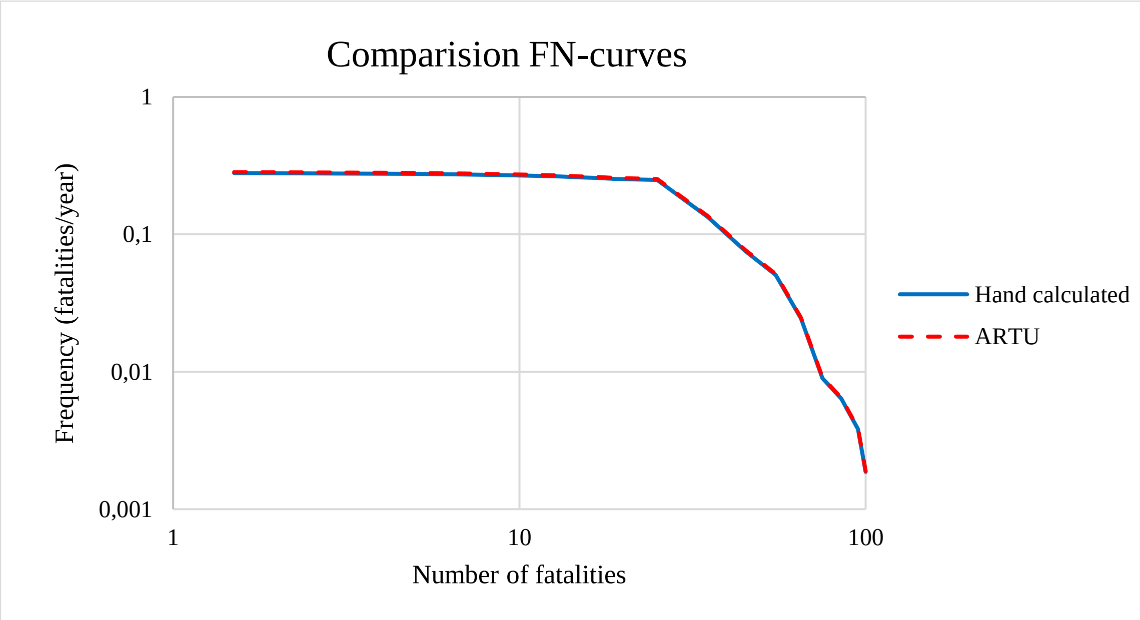

Figure 16. Comparison between hand calculations and ARTU output.

5.4 Sensitivity analysis

In order to analyse the sensitivity of the tool, some key factors that may have an impact on the results have been chosen together with Cantene. These factors were changed one by one to see how much that specific factor affects the overall results. The results of the sensitivity analysis can be used by the users of ARTU to evaluate which variables should be studied more in detail. The chosen factors are pre-movement time, fire occurrence rate, probability of standstill traffic, number of vehicles and percentage of different vehicle types. Their values were changed between ±20 % and ±100 %, depending on the variable and its uncertainty. The difference in percentage in the input was chosen by the authors. The different variables and their change in values are given in Table 31 below.

Table 31. Variables and the change in values in the sensitivity analysis.

Variable	Difference in percentage	Original value	Low value	High value
1. Pre-movement time (s)	±20 %	μ: 279 σ: 134.5 5th percentile: 58 95th percentile: 500	μ: 223.2 σ: 134.5 5th percentile: 2 95th percentile: 444	μ: 334.8 σ: 134.5 5th percentile: 114 95th percentile: 556
2. Fire occurrence rate (per 10^8 vehicle km)	±50 %	Light vehicle: 4 HGV or bus: 15 HGV carrying flammable load: 10	Light vehicle: 2 HGV or bus: 7.5 HGV carrying flammable load: 5	Light vehicle: 6 HGV or bus: 22.5 HGV carrying flammable load: 15
3. Probability of standstill traffic (%)	±50 %	5.0	2.5	7.5
4. Number of vehicles (per lane and hour)	±50 %	Minimum entrance rate (off-peak): 400 Maximum entrance rate (peak): 2250	Minimum entrance rate (off-peak): 200 Maximum entrance rate (peak): 1125	Minimum entrance rate (off-peak): 600 Maximum entrance rate (peak): 3375
5. Percentage of HGVs carrying flammable load and light vehicles (%)	±100 %	Light vehicle: 89 HGVs: 6 Bus: 1 HGVs carrying flammable load: 4	Light vehicle: 93 HGVs: 6 Bus: 1 HGVs carrying flammable load: 0	Light vehicle: 85 HGVs: 6 Bus: 1 HGVs carrying flammable load: 8

The result from this sensitivity analysis are ten new FN-curves that can be compared with the curve with the original inputs. In all the studied variables, the original value curve is in the middle between the low and the high-value curves. The two variables with the largest impact, where the low-value curve and the high-value curve lie the furthest from each other are variables 2 and 5, fire occurrence rate and percentage of HGVs carrying flammable load, see Figure 17 and Figure 18 below.

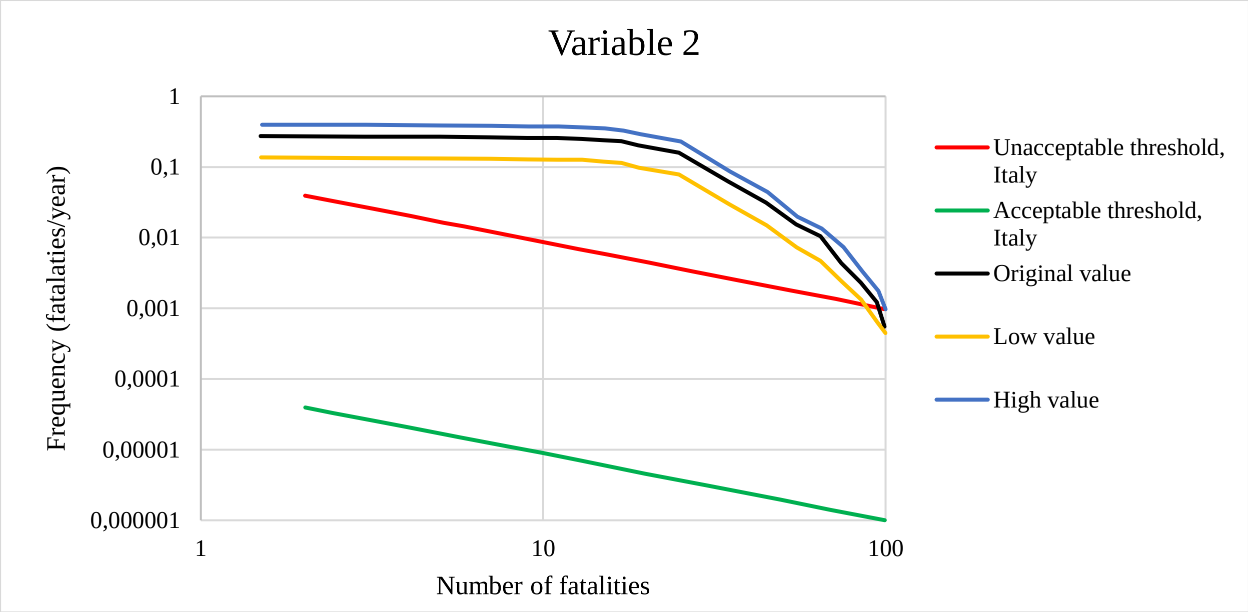

Figure 17. FN-curves with different fire occurrence rates. Original value gives the black line, yellow and blue lines are from low and high values.

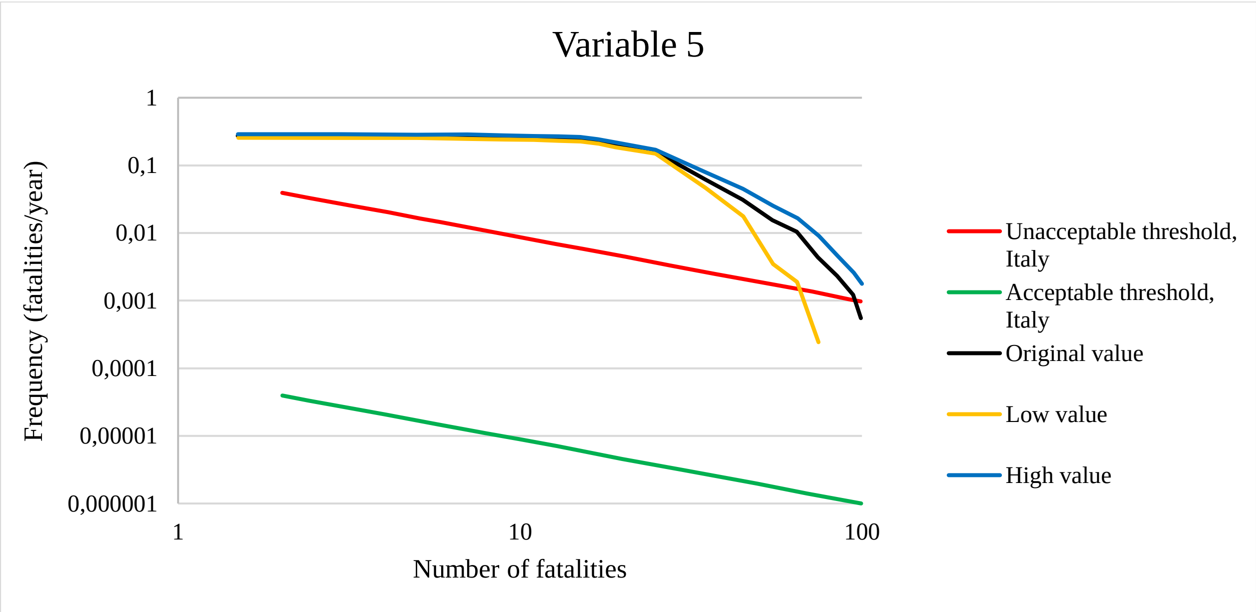

Figure 18. FN-curves with different percentage of HGVs with flammable load. Original value gives the black line, yellow and blue lines are from low and high values.

The variable with the lowest impact, where the curves are most equal, is variable 3, probability of standstill traffic, as shown in Figure 19 below.

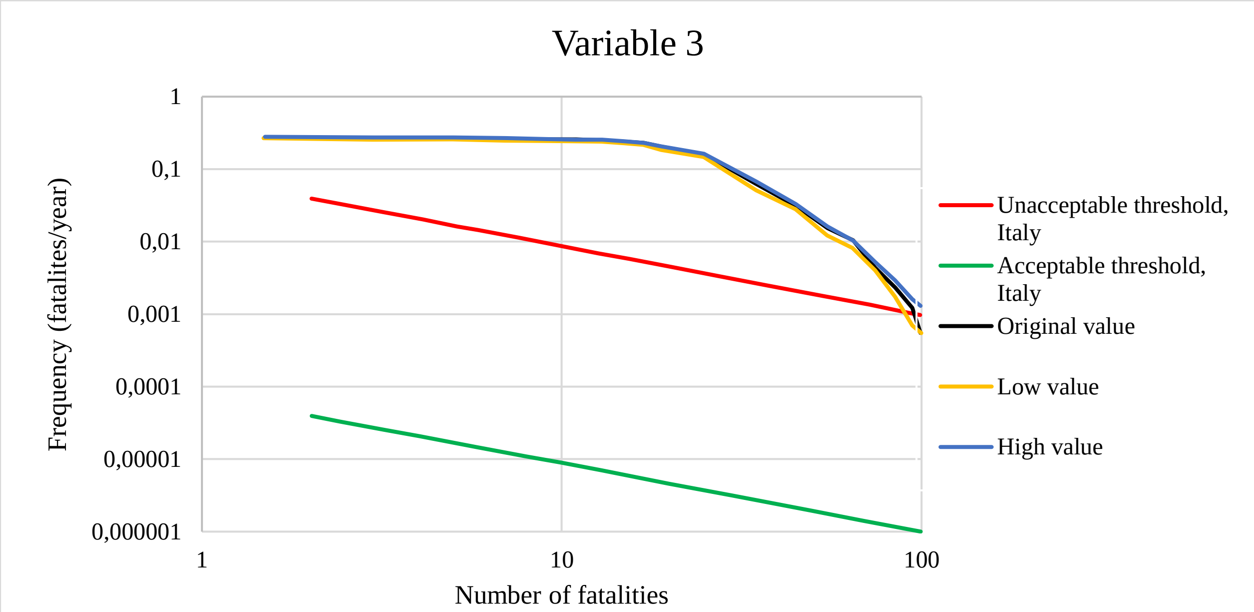

Figure 19. FN-curves with different probability of standstill traffic. Original value gives the black line, yellow and blue lines are from low and high values.

6. Discussion

This work aimed at verifying and validating the ARTU tool by checking its different parts/modules and the overall FN curves produced. This is important to establish, firstly to know whether the tool can be used in real tunnel projects and secondly to determine whether a margin of safety should be recommended and how large it should be. The comparison between ARTU and other models and experiments is in turn affected by uncertainties and issues with how different factors are measured by different models and experiments. The thesis also aims at determining which variables affect tunnel fires and how these can be implemented in risk analysis tools, see Chapter 4 for a description of these variables and recommendations for input values where possible.

To validate the tool, the different parts have been analysed one by one and its overall result (the FN curve) has been evaluated. The verification tests conducted for evacuation and toxicity assessment gave an estimation of uncertainty, which is discussed in Chapter 6.3. For the fluid-dynamics part, the results imply that there is a difference between experimental data and 1D fluid dynamics, possible reasons for this are discussed in Chapter 6.1. To examine these differences further, FDS simulations were made for all cases, see Chapters 5.1.2 and 6.2.

To validate the results from the complete tool result (the FN-curve), future studies could identify an FN-curve for a real tunnel and make the same case in ARTU to determine if there are some discrepancies between the curves. In dialogue with Cantene and the supervisors, 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 their own issues that are not explained, a fair comparison is difficult to make. Therefore, a hand calculation where the process of making the FN-curve was verified and a sensitivity analysis of some input variables was conducted as mentioned earlier. The verification of the FN-curve gives an estimate of uncertainty that is within +2 %, which makes the output from ARTU slightly conservative (this is most likely due to the truncation adopted in the calculations).

The different parts of ARTU have been validated or verified as discussed above and an estimation of their uncertainties has been made. Therefore, it can be assumed that the output of ARTU, the FN-curve, gives reasonable results if the different sub-parts do, bearing in mind the uncertainties of the different parts. Uncertainties when doing risk analyses in tunnels are discussed in Chapter 6.4.

Since this is the first version of ARTU, some improvements can be made. Proposals for development are given in Chapter 6.5. Finally, possible future research topics within the area of tunnel fires are discussed in Chapter 6.6.

6.1Discussion about 1D fluid dynamics

Validation of the 1D fluid dynamics software was somewhat difficult because the software is closed source and the authors did not know all assumptions adopted by the software. The results show varying levels of agreement between the software and the experiments. Some comparisons show large differences, but in general, the tool is conservative in comparison with the experimental results with the exception of carbon monoxide concentration (see discussion in Chapter 5.1), results can be found in Chapter 5.1.

The differences between experimental data and 1D fluid dynamics results can be explained by a couple of issues. First and foremost, one factor which has an impact on the differences between experimental data and 1D simulations is the fact that the 1D tool only gives one value for each variable at a set distance from the fire, instead of temperatures at different heights at a specific distance, this makes the temperature curves hard to compare. For this reason, FDS simulations were made with measurements in the same ways and places as in both the experiments and in the 1D tool.

It can be argued that measuring temperature using a 1D tool is not the optimal way in fires, since the temperature differs a lot between the ceiling and the floor level due to the smoke layer, with the temperature being much higher in the smoke layer than in the fresh air below. Far from the fire, the differences can be smaller because there has been a mixture of hot smoke and fresh air, and the smoke layer is not so clearly defined. The same goes for toxic species that go with the smoke in the tunnel.

Another factor is how the HRR is measured in an experiment which has an impact on the temperature-time curves and the velocity obtained, which means that the comparison with simulations, both 1D and 3D (FDS) can differ. As discussed in Chapter 3.3, HRR can be measured in different ways. Ingason, Li and Lönnermark (2015), gives an approximation of the measurement error for HRR in full-scale experiment that is in the order of ±15–25 %. This leads to an epistemic uncertainty that needs to be taken into consideration when analysing results.

To analyse differences between the experimental results and results from the software, a comparison based on functional analysis operators was conducted as described in Chapter 5.1. This analysis, with calculations of ERD values for all comparisons, are used to investigate how far the results are from each other and gives a quantitative statement. The calculated values of ERD, in these series of tests, show that ARTU in most cases is conservative, which is somewhat positive for the developer and future users of the tool.

6.2 Discussion about FDS

FDS simulations were made to deduce the reasons behind the differences in the experimental results and the results from the 1D software. One important point is that the comparison between the 1D software and FDS is merely a comparison between different tools with different uncertainties, not validation. The comparison between FDS and experiments is a form of validation of FDS and if the results are satisfactory it is more valid to compare another tool with FDS which is validated for these sets of experiments. The use of FDS as a complement to the experimental validation study greatly helped in the validation of the fluid dynamics part of the tool by filling in the gaps where the experimental results were lacking or difficult to use for reasons discussed below.

One issue with comparing experimental results of for example temperature at specific heights, with FDS-results, is that only a small difference in the height of the smoke layer can make a big difference in the comparison. If the FDS measurement is in the smoke layer and the experimental measurement is just slightly below, the FDS results will be much higher than the experimental results. Vice versa is true if the experimental measurement is in the smoke layer and the FDS measurement is slightly below. For this reason, the temperature was measured at 1, 2, 3, 4 and 5 m in FDS instead of just 1 and 2 m as in most of the experiments, to see how far off the smoke layer in FDS is compared to in the experiments.

The issue with numerical instability due to pressure and velocity spikes is known by the creators of FDS as discussed in Chapter 5.1.2. Only the 5 MW case (test 7) could be run with a higher number of pressure iterations which creates some uncertainty in the other simulations.

A temperature comparison was made between FDS and the experiments as this is the most interesting value to see whether FDS can simulate correctly. The comparison shows a good agreement between the experimental results and the FDS simulations (except in test 9). The smoke layer is lower in the experiments than in FDS which leads to FDS giving lower temperatures than the experiments.

A comparison was made between ARTU and FDS to make a more fair comparison than what was possible using only the available experimental results. The results show that ARTU gives conservative results in almost all cases, especially for cases without ventilation where the results from ARTU are highly conservative. This can be partly explained by ARTU giving lower velocities due to buoyancy than FDS does, hence giving higher temperatures and build-up of smoke.

6.3Discussion about sub-models within evacuation modelling

Verification of the evacuation and toxicity assessment was a straightforward process since the authors of the thesis had access to the exact equations and assumptions made by the tool, see Chapter 4.4 for further descriptions.

The margin of error has been calculated for all the verification tests, as presented in Chapter 0. These are also summarised in Table 32 below.

Table 32. Margin of error of evacuation sub-models Δt= 5 s.

Sub-model	Margin of error, low (%)	Margin of error, high (%)
Walking speed vs visibility	- 5	+ 3.75
Walking speed vs density	- 13	+ 11
Flow through doors vs density[12]	0	+ 22
Chemical FED	+ 2	+ 21
Thermal FED	+ 0.2	+ 3

As can be seen in the table above, the results from ARTU have a margin of error of between -13 % and + 22 %. Thermal FED is the most accurate and flow through doors versus density and walking speed vs density is the least accurate. For most sub-models, the tool gives reasonable and conservative results that are slightly higher than experimental results. All sub-models have a relatively low margin of error.

The differences between where truncation is made gives a difference in the results, as shown in Chapter 5.2.1-5.2.3. The user of the tool needs to be aware of this and decide where truncation is best done in that specific case. The values given in Table 32 are with a time-step of five seconds and decimeters.

As discussed in Chapter 4.1.2 and 5.2.5, NFPA recommends reducing the time to reach the threshold value for thermal FED with 25 % in order to take uncertainty in the equations into account. This has not been done in either ARTU or the hand calculations that were used to

[12] Values from calculations using decreasing density is presented here as they are the ones used in the model.

verify ARTU, which means there is an inherent uncertainty in these results. To address this uncertainty, the calculations in the code could be reduced in accordance with NFPAs suggestions.

In the calculations regarding chemical FED, only high values of CO, CO_2 and low O_2 levels are considered. As discussed in Chapter 4.3.1, CO and CO_2 have been shown to be the most important toxic species produced by most fires, and therefore it is reasonable to take these into account. Other toxic species, e.g. hydrochloride and hydrogen cyanide, can, of course, affect evacuees but since previous studies have shown that CO and CO_2 are the most dangerous, the others are not considered. In special cases where the risk of fires producing, for example, large amounts of hydrogen cyanide is especially high, the toxic effects of the substance must be considered in some way and this tool might not be appropriate since this is not possible in this first version.

6.4 Discussion about uncertainties

One inherent difficulty with tunnel risk analysis is the great uncertainty in many variables which together can lead to the total risk being skewed from reality. Many assumptions must be made about factors like fire load and human behaviour and these present some challenges to the user of any tool. Variables with aleatory uncertainty can be handled by using statistical distributions to simulate the spread in possible values but sometimes it can be difficult to determine which distributions give reasonable results as discussed in Chapter 3.2. Variables with epistemic uncertainty are much more difficult to deal with since it can be reduced but it can be very costly and time-consuming to do so. It is preferable to reduce these uncertainties by gathering of more data but sometimes a better option might be to pick a conservative value or distribution instead of doing, for example, a full-scale test of human pre-movement time in a specific tunnel, this way a project developer at least can know they are on the safe side. A probabilistic risk assessment such as what ARTU uses can be a great tool to address the above mention difficulties. An important step to reducing uncertainties is to gather local data for the area where the specific tunnel is located since there can be large geographical differences.

The sensitivity analysis gives results as expected, with higher frequencies when the values are higher and lower frequencies for the lower values. Considering the analysed variables, the fire occurrence rate and the percentage of flammable load seems to be the two variables with the highest impact on the results. The probability of standstill traffic seems to be the variable with the lowest impact. The sensitivity analysis also shows that none of the chosen variables give a large difference in the FN-curve and level of risk. This is positive as it points at that no single variable has an extraordinarily large impact on the results and makes the tool less vulnerable to giving results which are very deviant just because of one uncertain variable. If one variable is highly uncertain and its input in the tool is deviant from reality due to lack of information, this single issue should not affect the total outcome and risk level, as it is many variables together that give the level of risk. However, to be sure that no pair of or group of variables together give highly different results, a more advanced sensitivity analysis could be made where more than one variable is changed at a time. A further sensitivity analysis can investigate possible synergistic effects and would add robustness and credibility to the results produced.

6.5 Further development of ARTU

As this is the first version of ARTU, things can be improved to involve more variables in the tool, thus improve it. This version does not account for fire spread to adjacent vehicles, i.e., only one vehicle at the time is burning. Knowledge from large, catastrophic fires in road tunnels indicate that the consequences became worse when the fire spread to adjacent vehicles, as discussed in Chapter 4.2.4. Therefore, an improvement of ARTU could be to take fire spread into consideration in order to include more possible scenarios. If the fire spreads from the initial vehicle this will lead to a different, probably higher HRR curve, which has not been considered in this version of ARTU. Cleary, a higher HRR curve will increase the probability of a higher number of fatalities. Also, different combinations of burning vehicles could be taken into consideration, e.g. an HRR curve for an initial fire in an HGV which then spreads to a light vehicle or an HRR curve for two light vehicles that both ignite after a collision.

For all technical systems, there is a risk of it malfunctioning. Therefore, a failure rate factor could be implemented to address any system failure in e.g. the ventilation system. This is not implemented in this first version of ARTU, which contributes to uncertainty in the results. To include this in the tool, each specific system needs to be evaluated to be able to estimate the failure rate, together with already known statistics for technical components, as mentioned in Chapter 4.2.2.

6.6 Future research

As discussed in Chapter 4.2.1 one known difficulty with creating a realistic fire scenario is the lack of experimental fire data on modern vehicles. For buses, only three cases that could be used were found, and this makes it difficult to determine whether this is a typical appearance of a bus fire HRR curve. There was also a lack of fire tests using modern cars, especially with alternative fuels. Therefore, future research within the area of tunnel fires could consist of full-scale experiments with modern vehicles, especially electric vehicles. A future research subject could be further fire testing of different types of modern vehicles with different types of energy carriers and see which HRR curves, heat of combustion and combustion products they can produce.

Human behaviour is also a difficult subject and further experiments researching people’s behaviour in tunnel fires, for example, their pre-movement time, could be conducted. As discussed in Chapter 4.2.4, as fire spread can have a large impact on the outcome, future research should investigate how fire spread occurs during fires in tunnels and at which distance it occurs.

7. Conclusion

This work presents the verification and validation of a risk assessment tool for tunnel fire risk analysis. In addition, a review of key factors affecting road tunnel fire safety has been performed. The proposed values in this thesis can inform the selection of default values in ARTU and help future users which design values to pick. The verification of sub-models within evacuation modelling has shown that the tool gives reasonable results with a margin of error of -13 % and +22 %. The values of the margin of error can be used to recommend a certain safety margin. The verification of the probabilistic risk analysis shows that ARTU gives reliable results with a low margin of error, within +2 %.

A third party 1D fluid dynamics software is used in ARTU which has positive and negative effects on the results. The software is fast and gave conservative results in four out of five analysed cases, which was calculated with functional analysis. The 1D tool gave results with better agreement in cases with ventilation than in cases without ventilation which gave more conservative results. The use of FDS, which is a well-established and validated tool for fires in road tunnels, as a comparison when the experimental results were lacking or could not be compared to ARTU, facilitated the validation by filling in these gaps with simulated results.

Uncertainties when dealing with risk analyses in tunnels prove to be a central issue that needs to be handled. In this report it is addressed by the recommendation of gathering more information about uncertain variables, using statistical distributions when it is no longer possible to minimize spread in values and by doing a sensitivity analysis. The sensitivity analysis shows that the fire occurrence rate and the percentage of HGVs carrying flammable load have the largest impact on the FN-curve and level of risk when changed and analysed one by one. A further sensitivity analysis that takes possible synergistic effects into account by changing more than one variable at a time would add robustness and credibility to the results produced.

Overall, this report has concluded that ARTU should give conservative results for risk analyses in road tunnels. In order to confirm this even further, more validations could be conducted with different experiments.

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Appendix A - Input table for 1D fluid dynamics simulations

Removed for confidentially agreement.

Appendix B – Input table for the calculations to the FN-curve

Removed for confidentially agreement.

Appendix C - Experiments compared with 1D fluid dynamic software

Removed for confidentially agreement.

Appendix D - FDS compared with ARTU, Benelux test 6 (no mechanical ventilation)

Removed for confidentially agreement.

Appendix E - FDS compared with experiments, Benelux test 6 (1.5 m/s ventilation)

Removed for confidentially agreement.

Appendix G - FDS compared with ARTU, Benelux test 8 (no mechanical ventilation)

Removed for confidentially agreement.

Appendix H - FDS compared with experiments, Benelux test 8 (wind)

Removed for confidentially agreement.

Appendix I - FDS compared with experiments and ARTU, Benelux test 9

Removed for confidentially agreement.

Appendix J - FDS compared with ARTU, Benelux test 14 (no mechanical ventilation)

Removed for confidentially agreement.

Appendix K - FDS compared with experiment, Benelux test 14 (initial ventilation at 1 m/s)

Removed for confidentially agreement.