Toxicity Limit States in Tunnel Fire Safety Designs

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Abstract. The Mont Blanc tunnel fire March 1999 killed 39 persons, of which most died within 15 min due to intoxication. In Norway there have been several fires the recent seven years. No single road-user has died from intoxication in those fires, in spite of being engulfed with smoke for more than 1.5 h. The tunnel safety discourse amongst tunnel owners and researchers turns towards questioning whether current longitudinal ventilation strategies can be used to design the tunnel system to meet the self-rescue principle. Smoke control would then be the design criterion. The Norwegian Public Roads Administration could in this perspective re-duce its effort to invest in safety measures ensuring safe havens for road users trapped in smoke and other fire preventive measures. We are very critical to such a development of tunnel fire safety. This paper raises questions about predictability of smoke dispersions in case of tunnel fires as well as human tolerability of toxic gases from fires. We conclude with issuing designs of research studies to reduce the gaps of knowledge revealed in the literature.

1 Introduction

In Norway there is approximately 1100 road tunnels, and 33 of them are below sea level. Several new tunnels are being planned and many are under construction. In the last 10 years there has been an increasing focus in the Norwegian community on fire safety related to tunnels. This is due to an increase in the number of tunnel fires in Europe and Norway, but also because the society in general has an increased focus in risk analyses and safety. Designs are getting more and more complex within several industries, including the transportation sector, increasing the need for credibility of acceptance criteria based on human tenability when the possibility to escape is restricted. This paper is a first step to raise questions about current engineering practices when it comes to human tenability limits.

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2 Discussing the Norwegian Statistics

A review of Norwegian tunnel fires in the period 2008–2015 (Nævestad et al. 2016) reveals that larger vehicles are overrepresented in tunnel fires in Norway. Tunnels with steep incline is overrepresented; 5% of the tunnels in Norway represented 42% of the fires. 40% of these fires involved heavy goods vehicles, which is a lot taken into account that they only measure 14% of the traffic load on Norwegian roads (Nævestad et al. 2016). Tunnel design in Norway has an increasing degree of complexity, resulting in a need for a performance-based design.

The NPRA has an ambition to develop a model for fire risk that can predict probability and severity of fires in the Norwegian tunnels. Such modelling work will hardly reflect all major factors and system characteristics and thus, the use could be counterproductive. "Though the primary goal of stochastic modelling is to provide insights and not numbers, numerical answers are often indispensable for gaining system knowledge" (Tijms 1994). Tijms' basic text book concludes in its beginning on what is important with quantitative analyses. The interpretation of the results of stochastic models is of no value unless we know the models and data material supporting them. Nævestad et al. (2016) shows that the average occurrence of fires in the entire Norwegian population of tunnels are 24 per year (min 17 - max 34), which of rather few occurred in heavy vehicles (>3,5 t). Distributed over the NPRA-regions the fires that somehow included heavy vehicles were:

Region East – 17 fires in 8 years, of which 5 in the Opera tunnel, 5 in the Oslofjord tunnel and 2 in the Tåsen tunnel, while the last 5 occurred in five different tunnels.
Region South – 4 fires in 8 years, all in different tunnels.
Region West – 24 fires in 8 years, of which 3 in the Mastrafjord tunnel, 2 in the Bømlafjord tunnel, 2 in the Gudvanga tunnel, and 17 fires in different tunnels.
Region Mid Norway – 11 fires in 8 years, of which 4 in the Hitra tunnel, 2 in the Stavsjøfjell tunnel, 2 in the Eiksund tunnel, and 3 in different tunnels.
Region North – 7 in 8 years all in different tunnels.

Major fire loads have been reported in the two fires in the Gudvanga tunnel, the Brattli tunnel, the Follo tunnel, the Skatestraum tunnel and in two fires in the Oslofjord tunnel. The fire in the Follo tunnel killed the HGV-driver. No other fires have killed road-users due to intoxication, but in the same period 5 road-users have been killed in tunnel-accidents which have also included fires. We scrutinized the major accidents (major injuries to people) and found:

- In 2009 a person was killed in a head on collision between a private car and a HGV in the Stavsjø tunnel (mid night before Saturday – the private car came over into the HGV's lane). The young male driver (in the 20-ies) was killed. A fire in the private car was put out immediately.
- In 2010 a head on collision in the Hordvik tunnel also between a HGV and a private car implied death of the driver of the private car. Both vehicles caught fires but were immediately extinguished.

- In 2010 a Lithuanian driver of a HGV died due to mechanical injuries and smoke inhalation from the collision with the Follo tunnel portal and the tunnel wall in the entrance zone.
- In 2011 a fire occurred in a Polish HGV in the Oslofjord tunnel, which implied major smoke inhalation injuries for several road-users (Njå and Kuran 2015). The data material from Statistics Norway and the study made by Institute of Transport Economics (Nævestad et al. 2016) described the consequences as minor, which is an error.
- In 2011 two persons were killed in a head on collision between a bus and a private car. The accident occurred outside the Vassenda tunnel. Smoke was seen from the private car, but no fire occurred in any of the vehicles. The event is part of the official tunnel fire statistics, but this could be questioned.
- In 2012 a fire started in the rear tires of a HGV-trailer in the Mastrafjord tunnel. Two persons were reported with small injuries from smoke inhalation (ref. a local newspaper), but the information from Statistics Norway described it as serious injuries.
- In 2013 a head on collision between a private car and a HGV in the Storesand tunnel killed the driver of the private car. The HGV caught fire, but was extinguished rapidly.
- In 2013 a motorcycle driver was killed in a collision with a lorry in the Naustdal tunnel. A minor fire was immediately extinguished.
- The fire in the Gudvanga tunnel included many intoxicated patients, of which many were seriously injured.
- In 2015 the second Gudvanga fire included a bus. It implied five injured persons from smoke inhalation.

The largest HRRs were observed in two other fires that luckily included no persons still in those tunnels when the fires developed (Skatestraum and Brattli tunnels). The fact that no road-users were in the tunnels were not subjected to any system safety measures, but “pure luck”. In the work with tunnel safety, it is acknowledged that there are major uncertainties about the consequences of exposing people to fire smoke over a longer period. Research shows that design of the tunnel will affect the fire growth and development (Ingason et al. 2014), hence the possibility to ensure safe evacuation.

3 Fire Toxicity in Norwegian Tunnels

The main cause of injury and death in fires is exposure to toxic fire smoke and gases (Stec and Hull 2010). In the event of a fire, fire safety depend upon the outcome of two parallel timelines: the time from ignition of the fire to the development of incapacitating conditions (ASET) and the time required for occupants to reach a place of safety (RSET) (Hurley 2016, chapter 63, p. 2308–2428). When occupants become immersed in smoke, behavioural, sensory and physiological effects occur. Toxic fires effluents are responsible for the majority of fire deaths and an increasingly large majority of fire injuries (Stec and

Hull 2010). Fire safety in general has often focused on preventing ignition and reducing flame spread, and not so much focus have been given to the fire toxicity.

Since no one have been killed by the smoke in a tunnel fires in Norway, a perception seems to emerge amongst tunnel owners that the smoke has been non-toxic. As of today there is no acceptance criteria or design requirement regarding smoke obscuration in Norwegian tunnels (SVV 2016). This silently supports the choice of ventilation strategy, which is longitudinal instead of transverse ventilation (SVV 2016). Smoke exposure can however delay or prevent escape for an extended period, during which fire conditions may become life threatening (Stec and Hull 2010). Major accidents worldwide have had devastating consequences. On 24 March 1999 a Belgian truck with a refrigerated trailer carrying margarine and flour caught fire in the Mount Blanc tunnel and resulted in 39 deaths, and major complexities in the fire and rescue work. Those who tried to escape managed to make only 100 $\sim$ 500 m before collapsing due to lethal smoke compositions (Duffé and Marec 1999). In the St Gotthard Tunnel, 24 October 2001 two HGVs collided and a fire broke out. The fire spread rapidly, and even though the fire brigade managed to enter the tunnel in less than 7 min, the fire burned for approximately 24 h. After the fire was brought under control, the bodies of 11 people were found to the north of the incident location within a distance of approximately 1250 m. Some were inside their vehicles, other were on the road way. Ten died as a result of smoke inhalation (Carvel and Beard 2005). In Kaprun November 2000 155 tourist were killed in a ski train blaze. Several passengers ascending on foot, as well as the train conductor, were asphyxiated by the smoke and then burned by the fire (Sempio 2013).

Taken into account the tragedy and lesson learned from these accidents, we question the design approach used in Norwegian tunnels. Understanding the fire dynamics in tunnels and how the fire interacts with its surroundings is important factors when evaluating fire safety design in tunnels (Ingason et al 2014). The components present in the fire smoke is a result of the goods carried by the HGVs, and how different components interact with each other when exposed to extreme heat load. Currently there are very few restrictions. New type of vehicles, technologies and fuels are integrated in fast pace in the transport systems. The tunnel regulator uses performance based rules, but we questions the design practices. These shortcomings have been evident in the investigations and national audits. There is a need for design requirements to keep up with the technological development, resulting in a more functional and performance based legislation that challenge existing practices.

There is a need for informed expert decision making for professional management regarding safety in tunnels, taking into account the uncertainties regarding the fire smoke toxicity. It is important to understand that the yields present will be scenario based dependent on the contexts, materials and ventilation conditions. The time-concentration curves of the toxic products depend on the mass burning of the fuel (kg/s), dispersal volume (to give kg/m3) and the yields of each toxic product (kg/kg). The yields at different stages will depend upon fuel substances, fuel/air equivalence ratio, temperature and oxygen concentration in the flame zone (Stec and Hull 2010). The main dangers presented by smoke are obscurity (lack of visibility prevents people from fleeing), toxicity (which incapacitates) and temperature (which also incapacitates) (Hurley 2016, chapter 63, p. 2308–2428).

3.1 Regulation

The EU Road Tunnel directive (Directive 2004/54/EC) is prevailing in Norway. The effect of the Directive is to constitute what is regarded as a minimum European level of safety in road tunnels. However, the obligation of engineers to exercise professional care remains even if there are directives in place. The EU directive and the N500 tunnel code require risk assessment to demonstrate acceptable safety levels during evacuation in special circumstances. We raise the question; what is acceptable safety level during evacuation? Why is it possible for a tunnel owner to direct the self-evacuation principle, when road-users do not know what it mean?

Further, a comparative analysis of safety standards for road and rail tunnels performed by Arnold Dix (2004) assessed the regulatory frameworks in Germany, Austria and Switzerland against the EU Road Tunnel directive, and furthermore Japan's approach. The comparison demonstrates a vast range of designs and operational conditions when it comes to underground transportation safety. Dix concluded that the great variation in key safety parameters such as ventilation, lightning, emergency evacuation, control systems and pedestrian ways, require expert engineering in design and operation. In the US the NFPA (National Fire Protection Association) standards are highly recognised and used for fire safety. NFPA 502 is the standard for road tunnels, bridges, and other limited access highways. When it comes to means of egress from a road tunnel it is stated that a tenability level shall be provided in the means of egress during the evacuation phase in accordance with the emergency response plan. A criteria for tenability and time of tenability should also be established (NFPA 2017, ch. 7.16.2). Further reference is given to NFPA 101, Life Safety Code, which is the most widely used source for strategies to protect people from the hazardous exposure from fires (NFPA 2018). The NFPA codes used in fire safety design are moving away from being prescriptive to become more performance-based or scenario-based. For instance in Hong Kong, the fire safety strategies optimize fire protection and fire prevention measures to attain specified fire-safety objectives. Fire safety systems must be defined clearly and include at least three parts: detection and alarm system, fire control system and air and smoke control system (Miclea et al. 2007). Keeping the thermal and toxic effects under acceptable and tenable limits are considered extremely important and tenability limits are stated, amongst other on CO_2 concentration levels.

Effective dose and concentration levels are more commonly used to provide an indication of lethality and incapacitation, from the cumulative effect of the most noxious fire effluents, expressed as fractional effective dose or concentration (FED or FEC) (Hurley 2016, chapter 63, p. 2308–2428). ISO 13344:2015 states that pyrolysis or combustion of every combustible material produces a fire effluent atmosphere, which, in sufficiently high concentration, is toxic (ISO 2015). The standard provides means for estimating the lethal toxic potency of fire effluent produced during a fire. The lethal toxic potential are related to the fire model selected, the exposure scenario and the material evaluated. Lethal toxicity values associated with 30-min exposures of rats are predicted, using calculations. The intended use of fire safety engineering calculations is for life-safety prediction for people and is most frequently for time intervals somewhat shorter than 30 min. It must be kept in mind that the importance of considered engineering decision making and evaluation of risk and uncertainties underlies all standards and guidelines.

3.2 Fire Toxicity

From the 1970s until the early 1990s fire toxicity was recognised as a serious problem and some high quality research was undertaken (Stec and Hull 2010). It was then discovered that real fires had a much higher level of toxicity than small-scale laboratory tests. The difficulties of replicating real fires on a bench scale could be one of the reason for diminution of research into fire toxicity. The focus of fire safety research changed towards reducing peak heat release rates. Recent years there have been a resurgence of interest in fire toxicity, mainly due to performance-based design approaches to fire safety engineering in several industries.

In forensic investigations fire toxicity has played an important role and blood samples are routinely analysed for carbon monoxide to ensure whether or not the victim was alive after the fire started (Stec and Hull 2010). This has however led to the assumption that because the carbon monoxide levels were easily quantified in the blood, this is the only important toxicant, which is not the case. Most of the fire models used today is based on 30–50 years old experiments (Stec and Hull 2010). Studies of fire effluent toxicity is a multidisciplinary area where both fuel chemistry and conditions of the complex process of fire have significant influences (Stec and Hull 2010). It requires understanding of the stages of fire growth – from ignition to ventilation controlled burning, the behaviour of a fire in different scales combined with the effect of the interactions with the surrounding environment (air supply, walls, ceiling etc.), the product formation from flaming polymer pyrolysates, the behaviour of the aerosol particulates and the response from the human body to the components present, the chemical quantification of those fire effluents and the toxicity of these (Stec and Hull 2010). Proper investigations of fires and victims involved have also been scarce, mostly directed towards liability investigations.

Assessing the fire safety in a road tunnel, thus, requires application of detailed knowledge of fire development and smoke toxicity combined with the understanding of risk management. When introducing the concept of risk assessment to decide upon acceptable levels of risk in a tunnel, the situation may easily arise where the analyst do not see the full scope of the choices that are made. We questions the outcomes of risk management strategies, especially when we take into account the limitations in the knowledge regarding tenability limits and the large variance of human behaviour in fires. The effects of fire on occupant's can be divided into three phases (Hurley 2016, chapter 63, p. 2308–2428):

- Phase 1: The fire is growing but the occupants are not affected by heat or smoke.
- Phase 2: Occupants are exposed to smoke, heat and toxic products. At this stage irritancy and asphyxiation will affect their escape capability. At this point in time, factors such as the toxicity of the fire smoke and the dynamics of their production become critically important when trying to escape.
- Phase 3: This phase is the terminal phase of victims as a result of the fire.

The toxic effects of the fire product are important in the second and third phase. However, most studies of fire toxicity have been regarding lethality, for instance the Strathclyde study in the United Kingdom. The lethality, in terms of the LC_{50} on laboratory animals, have been focused on individual fire products such as carbon monoxide (CO) or hydrogen chloride (HCL) or a mixture of thermal decomposition products from materials (Hurley 2016, chapter 63, p. 2308–2428, chapter 63, p. 2308–2428). The phase with incapacitation in fires can be studied either by animal experimentation or by investigations of the circumstances surrounding real fire casualties, particularly survivors of serious smoke exposure. This crucial area of toxicity has been largely neglected. Research performed by TNO (The Netherlands Organisation of Applied Scientific Research) published in the coloured books; *Methods for the determination of possible damage to people and objects resulting from release of hazardous materials* (CPR 1992), states that the combustion products that theoretically can appear in a fire are mainly determined by the chemical composition of the substance. If for instance hetro-atoms are present, such as chlorine and sulphur, in addition to carbon and hydrogen, then next to CO, CO_2 and H_20 also CL_2, HCL, $COCL_2$, $S0_2$ and COS will appear. This will typically be called primary combustion products. But in addition to this also secondary combustion products will be generated (CPR 1992), as a result of mutual reactions between the combustion products that are formed. Generally there are very little data available with regard to secondary combustion products. However there are some exceptions, for instance combustion of polychlorinated aromats polychlorodibenzo-p-dioxins (PCDD), which are products of incomplete combustion of organic materials.

3.3 Modelling Fire Toxicity

TNO suggests methods to help making it clearer in which manner the formation of combustion products can be defined (CPR 1992), but the guidelines should be considered as an indications containing a relatively high degree of uncertainty. The "green book" establishes a methodology, for a number of substances, acute toxicity data, which are applicable for the inhalation by human beings. Data available (mostly from animals), with the help of an extrapolation model, a 30 min LC_{50} value for human being was derived. An LC value is the concentration at which a given percentage of exposed population will die. In this case 50%. The calculation of LC_{50} for human is based on the known LC_{50} for animals. The latter are converted to values corresponding to a 30 min exposure duration. Thereafter extrapolation is made by the help of an extrapolation factor. The methodology contains several uncertain factors. The parameters used in the method are also only valid for lethal injury. Proper values of the parameter for other types of injures, for instance lung damage, respiratory system and alimentary canal disturbance, does not seem to available. TNO recommends for future research on acute toxicity to try and obtain better definitions for these type of injuries that could arise as a consequence when exposed to smoke from a fire. They also states that the probit constants for human beings represent no more than an indication, and that a lot of research is required to arrive at really reliable dose-effect relationships (CPR 1992). Newer standards and guidelines are often based on the coloured books, which are based on old studies and experiments.

The models present in the "green book" is for use in quantitative risk analysis. The uncertainty in the models must be considered within the framework of, sometimes, other relatively large uncertainties, that could be effect models, probability models, population data, etc. Still, when assessing risk analysis for road tunnels, a risk analysis containing results from these methods are used when making decisions regarding fire safety. In order to evaluate toxic conditions for people in fires, one needs to determine physiological and pathological effects of exposure to toxic smoke and how they impair escape, cause incapacitation and death. When evaluating the risk of fire toxicity present in a road tunnel it is necessary to identify the main toxic species responsible for these effects amongst the hundreds of chemical species known to occur in fire effluents and combinations that might occur. This is to say at least a rather complex task. In tunnels transportation of a large variety of non-hazardous and hazardous goods will be present.

4 Recommendation and Conclusions

The design phase for complex tunnel structures with limitations in escape routes introduces gaps in how to work with risk factors. When looking at the uncertainties present in models and knowledge regarding tenability of humans exposed to smoke, it is a big surprise to us that analyses of toxins and human responses are often neglected in tunnel designs. The fire safety engineering practise moving towards a performance based approach to fire safety design has not improved this situation.

Incapacitation in tunnel fires, and how these products affect the capability of escape during fire, is a crucial area containing several uncertainties that has been neglected. Some of these uncertainties regarding fire risk in tunnels have been reflected on in this paper. Regulatory variations globally demonstrates the importance of professional expert engineering decision in the design phase. Lesson learnt from previous tunnel fires tragedies requires attention. Stronger attention should be given to smoke toxicity in the design phase. Some questions that needs to be further explored are:

Design phase:

1. What are the experiments and knowledge base for the empirical models used in fire safety today when it comes to fire smoke toxicity?
2. How manage risk and uncertainties in the design phase regarding exposure to smoke during evacuating, to continuously strive for an inherently safer tunnel design?
3. To which degree is the uncertainty regarding fire smoke toxicity reflected when modelling fire in risk analysis for road tunnels?

Human aspect:

1. Is it possible to develop methods to determine different level of incapacitation when exposed to fire smoke?
2. Is the use of human tenability limits beneficial, considering that what is adequate from a safety perspective often is a political and/or industry question?

All questions above (but not limited to), are important aspects to consider in fire safety engineering. There is a need to increase the understanding of the experiments and empirical models used, when introducing human tenability as a risk acceptance criteria. Empirical models are often used in fire safety engineering, but there is a gap of knowledge when it comes to incapacitation and long terms effect of being exposed to fire smoke during evacuation. Especial long tunnels with very limited possibility for escape introduces challenges. Using human tenability limit in design, knowledge regarding combustion chemistry and human biological and psychological effects on people are just as important as the fire development itself. Modelling fires and allowing development of fire scenarios, introduces a need for tenability limits and risk acceptance criteria`s to make decisions. But there is a need to demonstrate that human tenability limits and risk acceptance criteria's regarding fire toxicity are beneficial, or if it only introduces a perceived level of safety for the asset owner making decisions regarding fire safety in public transportation systems.

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