Uncertainties related to fire smoke toxicity in tunnels

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ABSTRACT: The research focus in this article has been to evaluate how risk analysis on Norwegian tunnels considers the uncertainties related to the fire smoke toxicity when evaluating the risk picture. A random selection of risk analysis from all over Norway have been assessed up against present knowledge of tunnel fires and smoke toxicity. It has also been assessed whether the analysis fulfils their intended role as expected by the associated regulations and standards. The conclusion is that the prevailing risk analysis on Norwegian tunnels do not take into consideration the uncertainties related to fire smoke toxicity in tunnels. It is recommended to further study empirical models used when assessing fire smoke toxicity, and further look into how to manage risk and uncertainties in the design phase regarding exposure to smoke during evacuation and continuously strive for an inherent safer tunnel design in Norway.

KEYWORDS: Fire smoke toxicity, fire hazards, performance-based design, risk analysis

INTRODUCTION

The main cause of injury and death in fires is exposure to toxic fire smoke and gases [1]. In fire safety engineering of complex structures, such as tunnels, a risk analysis is required as basis for the decision making [2]. The aim with risk analysis is to map and describe the risk for an object [3] when constructions and buildings do not fit the prescriptive regulations. The road authority can make an exception from the requirement of having emergency exits if the tunnel is shorter than 10 km and the average annual daily traffic (AADT) is below 4000 cars pr. lane, if a risk analysis can demonstrate that equal or better safety is achieved with alternative measures.

Fire science is chemistry, physics, computer modelling, engineering and human behaviour. Understanding the fire dynamics in tunnels and how the fire interacts with its surroundings is important when evaluating the fire safety design in tunnels [4]. The components present in the fire smoke from a larger fire will be a result of the goods carried by the heavy goods vehicles (HGV), how different components interact with each other when exposed to (extreme) heat loads, supply of air and combustible materials. Thus, the uncertainties regarding the composition of toxins involved are high. The fire smoke toxicity constitutes the major part of the risk picture in a tunnel. Currently there are very few restrictions regarding materials that are travelling through the Norwegian tunnels. New type of vehicles, technologies and fuels are integrated in fast pace in the transport systems.

In this study we question the design practices and the quality of existing risk analysis, based upon existing knowledge regarding smoke toxicity. Shortcomings in risk management have been evident in the investigations and national audits [5]. 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. As of today, there is no acceptance criteria or design requirement regarding smoke obscuration in Norwegian tunnels, even though this is a major component and uncertainty factor in prevailing risk analysis.

STUDY APPROACH

Tunnels can be seen as a complex structure [6], because it involves a large number of various stakeholders, which influences the tunnel designs and operations in a way that makes scenarios difficult to predict, involving complex interactions and tights couplings. A major fire in a steep subsea or onshore tunnel without emergency exits can be catastrophic. In Norway there are several tunnels where this could become a scenario [7]. This study explores the basic assumptions seen in a random selection of existing risk analysis performed in Norwegian tunnels. Based on knowledge gained through experiments of fire dynamics in tunnels and fire toxicity, we explored uncertainties regarding fire smoke toxicity. To which extent are these uncertainties managed in prevailing risk analyses? Based on our comprehension of the risk concept and the expectations to related safety levels interpreted from the tunnel safety regulation, current practices for risk analysis are investigated to see how such analyses fulfil their intended purposes. We assessed relevant literature on smoke toxicity, in order to reveal basic assumptions seen in the tunnel safety work.

FIRE HAZARD AND TOXICITY

Fire toxicity is most important in areas where escape is restricted, such as in several of the Norwegian tunnels. The toxic hazards associated with a fire and the inability to escape from fire atmosphere could be considered in terms of major hazard factors such as heat, smoke and toxic combustion products. [1]. Each of these factors could at some point effect the escape behaviour. The time available for escape is the interval between the time of ignition and the time after which conditions become untenable, resulting in that occupants can no longer take effective action to accomplish their own escape. This could be as a result from exposure to radiant and convection heat, visual obscuration due to smoke, inhalation of asphyxiant gases and/or exposure to sensory/upper-respiratory irritants [1]. Predicting the composition of fire smoke in a combustion environment can be extremely complex since it is depending on a large number of variables, such as the nature of the fuels involved (chemical composition, structure and formulation), the stage of combustion (smouldering, flaming or post-flashover), the temperature of the combustion and the available oxygen and ventilation in the vicinity of the fire [8]. Products formed from the most organic materials can be divided into two main categories based on their toxicity: components that have asphyxiant properties and oxygen depletion due to the fire itself, and thereby cause hypoxia and lead to loss of consciousness and death. The other category is smoke components that cause irritations, either as sensory irritants or as pulmonary irritants (affecting lungs), leading to immediate incapacitation or long-term effects [1]. Most likely sensory and pulmonary irritation will be present at the same time.

Already in 2004, an investigation by The Norwegian Directorate for Civil Protection (DSB) showed that transportation of dangerous goods, gases, explosive, pyrophoric and toxic gases and fluids were much larger than expected on Norwegian roads [9]. Transportation of corrosive, toxic and other dangerous substances crossing the mountain from east to west in Norway is significant. Probably the real volume is larger than given in the report, since not all companies were part of the survey. The survey was on classified dangerous goods, but in a fire seemingly harmless materials can become toxic. The variation of substances transported through tunnels is huge, it will vary from products to the aquaculture, refrigerated dairy products to upholstered furniture, building materials and electrical equipment. It is a common misconception that one can identify “toxicity” as a discrete property of specific substances such as wood or diesel [8]. In reality combustion products from fuels consist of a complex mixture, partly depending upon the elemental and molecular composition of the burning fuel, but as much upon the combustion conditions. During a fire development the combustion conditions change considerably, and the human exposure conditions further depend on the dynamics of air entrainment and plume dispersion [8].

When occupants become immersed in smoke, behavioural, sensory and physiological effects occur. Toxic fires effluents are responsible for most fire deaths and an increasingly large majority of fire injuries. Most fire deaths and injuries occur in residential fires, although assessment of fire toxicity is currently focused on areas where escape is restricted [8]. In the UK, and probably across Europe, most fire deaths result from small fires within the room of the fire origin, but with spread of toxic smoke to other areas [1]. In the US only 21 % of fire deaths occur in the room of origin of the fire and 67 % occur on another floor [1]. The main cause of deaths beyond the room of fire origin is exposure to toxic smoke. Fire safety in general has often focused on preventing ignition and reducing flame spread, and not so much focus has been given to the fire toxicity. It may render many questions, but an obvious one is that the fire safety engineering community is not multidisciplinary enough to include medical and physiological expertise or even psychological crisis response analytics. Risk analyses also seem to skip that kind of information in its consequence analyses.

Statistics from the UK indicate that 30 % of fire related deaths in the UK in 2017/18 were caused by the victim being overcome by gas, smoke or toxic fumes. The other dominant causes are burns alone (24 %) and combination of burns and being overcome by gas or fumes (15 %) [10]. In Norway the corresponding figures in the time period 2005-2014 shows that asphyxiation is the main cause of fire related deaths (57 %), followed by burns (15 %). The combination of asphyxiation and burns was concluded in 10 % cases [11]. However, asphyxiation may have many explanations, in which various toxins may contribute.

According to the tunnel safety regulation [2], tunnels with an incline larger than 3 % shall have extra and/or enhanced risk reducing measures based on findings from the corresponding risk analysis. In Norway there are at least 57 road tunnels with gradients larger than 5 %, which of 33 are subsea road tunnels. These represent approximately 5 % of the road tunnels in Norway, but experienced 42 % of the fires in the period 2008-2015 [12]. The recent years there have been several fires in Norwegian tunnels involving heavy goods vehicles (HGV) or buses. As of today, no road-user has been killed by the fires, which strengthens the arguments that the fire smoke can be controlled by the ventilation system in the tunnels. This fact seems now to cause a growing perception amongst tunnel owners (risk owners) and consultancies that the smoke has been non-toxic and can be controlled in cases of fires. This silently supports the choice of ventilation strategy, which is longitudinal instead of transverse ventilation [13] in all of the tunnels in Norway. The Norwegian argument is that transverse ventilation increases complexity and thus reduce reliability of smoke extraction in case of fires. This is critical seen in a societal safety perspective. It is stated in the tunnel safety regulation that longitudinal ventilation in tunnel is only allowed if the risk analysis demonstrates that it is acceptable [2]. This regulation, which came into force in 2007, do not have retroactive effect.

Smoke toxicity and escape

We know that smoke exposure delays or prevent escape for an extended period, and during this period fire conditions may become life threatening [1]. 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 ~ 500 m before collapsing due to lethal smoke compositions [14]. In the St. Gotthard Tunnel, 24 October 2001 two HGVs collided, and a fire broke out. After the fire was brought under control, the bodies of 11 people were found to the north of the incident location within approximately 1250 m. Ten died as a result of smoke inhalation [15]. In Kaprun November 2000, 155 tourists were killed in a ski train blaze. Several passengers ascending on foot were asphyxiated by the smoke [16]. Taken into account the tragedy and lessons learned from these accidents, we question the design approach used in Norwegian tunnels.

Usually the tunnel length and density of traffic (AADT) are the design parameters when deciding the safety level for a tunnel. In more advanced engineering designs of fire protection systems and escape routes, the heat release rate (HRR) of the vehicles using the tunnel is an important input. Heat release rate, or also called energy release rate, is defined as the energy the fire releases per unit time, usually given in kW (= kJ/s) [17]. The energy released in a fire depends on factors such as ignition source and vehicle type, their geometry and size, material type, the geometry of the tunnel and the ventilation conditions [4]. It is very hard to predict the dimensioning HRR for a given tunnel, because it depends on so many different factors. Thus, regarding HRR predictions designers and analysts should take into consideration the uncertainty when engineering the tunnel concept. Experience from large tunnel fires experiments show that HRR is the most important parameter for describing the development and consequences of a fire [4], and it should be a key parameter in engineering the design of ventilation, evacuation systems and the structural strength of a tunnel. This is not the practice when engineering tunnels. The tunnel regulation handbook N-500 [13] describes the design of a tunnel, mitigation measures and its requirements for technical equipment in tunnels longer than 500 m.

In general, fires that escalate from a HGV to neighbouring vehicles are the typical catastrophic fires leading to several fatalities. Common for all of these are the significance of the vehicle type and position in relation to the portals and other vehicles, the ignition source and the effects of the ventilation on the fire growth rate. Further, the type and weight of load carried by the HGVs played an important role in determining the severity of the fire. The size and type of ignition source is important for the potential growth of the fire, and the variety of ignition source is tremendous [4]. It could be everything from electrical circuit failure, leaking fuels, overheated breaks and so on, introducing uncertainty on how fast the incipient period which can vary from tens of seconds to tens of minutes.

With the aid of longitudinal ventilation, the fire could spread very rapidly. The fire growth rate gives premises to how the fire scenario will develop and is one of the most important design parameters for tunnel safety. A linear trend between fire growth rate and ventilation conditions is observed from experiments [4]. Also, the tunnel ceiling height has a major effect on the outcome of the fire. The combination of low ceiling height and longitudinal ventilation could be devastating. Ventilation conditions are important for the chemical production and the hazards. An under-ventilated fire has greater yield of major toxicants than well ventilated fires. The ventilation is an important means to affect, and improve the conditions upstream the fire, making it possible for the rescue service to reach the fire. In Norway the ventilation system is often used as a part of the firefighting tactics, using the ventilation in a predefined direction. Two reasons are given for this methodology [4], firstly, the firefighters know in advance the ventilation direction and thereby which portal to enter and attack the fire from. Secondly, the conditions downstream of the fire are assumed to be of less danger to people being in this part of the tunnel due to dilution of the fire gases.

Test cases

The firefighting strategy in tunnels is partly based on the results from the experiments in the Byfjord tunnel in 1998 and the Bømlafjord tunnel in 2000, showing that downstream the car fires the concentrations of CO and NO_x were not life threatening [18]. Two cars were set on fire in each tunnel. These tunnels, both built in the mid-1990s, were longitudinally ventilated, with fire-ventilation velocity ~3 ms^{-1}. Information on approximate fire sizes and flame behaviour, temperatures, fire detection, smoke movement and toxicity were collected. The objectives were to investigate the emergency preparedness of the fire brigades/road authorities and to record temperatures, movement and visibility of the smoke plume in tunnel. Measurements of O_2-, NO_2-, CO-concentrations, wind speed at the lowest point in the tunnel and temperatures beneath tunnel ceiling above cars were obtained. During the test in the Byfjord tunnel (north of Stavanger) the prevailing wind direction was chosen as the ventilation direction. Very soon the ventilation system controlled the smoke movement. The whole tunnel cross section was filled with smoke 20 m downstream, and 25 min after the ignition, smoke filled the whole 3 km section of the tunnel from the burning cars and to the tunnel opening at Randaberg. For six years the Stavanger Fire Brigade and the road authorities, as a result of incomplete risk analysis, thought they could drive down the tunnel beneath or through the smoke plume in order to reach the fire. However, given the prevailing wind direction resulting in a draught 2-3 m/s towards Randaberg, it was demonstrated that the Fire Brigade could not reach the scene of these fires (5-10 MW) before the tunnel was filled with smoke of 1-2 m visibility. CO and NO_x concentrations were not life threatening and O_2 concentrations were measured to 19 % in the smoke layer downstream the fire [18].

Research done by Lönnermark and Blomqvist [19] shows that smoke gases from a passenger car can have potentially negative impact on humans. Three separate, full scale fire tests were carried out under a large-scale ("industry") calorimeter, a fire ignited in the engine compartment and two fires ignited inside the vehicle, one that was extinguished and one that was allowed to develop into a fully developed fire. Both the fire gases and run-off water were analysed. The emissions measured were HCL, SO_2, volatile organic compounds (e.g. benzene), polycyclic aromatic hydrocarbons (PAHs) and polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDDs/PCDFs). Aldehydes and isocyanates were also found in the smoke gases. Both these compounds have well-documented short-term and long-term effects on humans. Other toxic compounds were HCN and SO_2. These compounds have a direct effect on people and are of concern for rescue personal and others exposed to smoke from vehicle fires.

These components amongst others, were not measured as a part of the scope of work in the Byfjord and Bømlafjord tunnel full scale experiments done by Nilsen [18].

Toxicity and exposure

Tunnel users such as HGV and buses will introduce a larger variety of potential toxic compounds. It does not need to be classified as dangerous goods to contribute to large uncertainties when it comes to containing toxic components released in fires. Regardless of the ventilation condition, toxic compounds with direct effect on people, both short-term and long-term, will still be present in some kind of mixing ratio. Uncertainties are also associated with other gases that have not been analysed and might have unknown effects that could be important for the overall toxicity in fire situations. Technical equipment, such as cables from lighting and ventilation systems could be a source of toxic and irritant compounds in a tunnel fire. Studies of fire effluent toxicity is a multidisciplinary area, where both fuel chemistry and conditions of the complex processes of fire have significant influences [1]. The yields present will be scenario-based and depend on the contexts, materials and ventilation conditions. An important question is, how to select design scenarios deemed the acceptability range? The time-concentration curves of the toxic products depend on the mass burning of the fuel (kg/s), dispersal volume (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 [1]. The main dangers presented by smoke are obscurity (lack of visibility prevents people from fleeing), toxicity (which incapacitates) and temperature (which also incapacitates) [20].

Carbon monoxide is an asphyxiant gas and the toxic effect is due to its combination with haemoglobin in the blood to form carboxyhaemoglobin (COHb). This is well known, but CO can have other adverse effects, for example interruption of energy production of cells, interference of oxygen delivery and other cellular activities [21]. These effects are not as well understood or widely discussed in the literature. A concentration of 50 % COHb is often taken as a threshold for lethality [8], however a large variety can be expected in humans and the actual limit depends on the situation. A lower level over a longer time period can result in effects on the cellular processes and might lead to fatalities at lower levels of COHb, than if a person is subject to shorter and higher exposures. Exposure to HCN forms cyanide ions in the blood, and this is approximately 25 times more toxic than CO. The dynamics of HCN in the human body are, however, poorly understood and blood cyanide is not analysed as routinely as COHb [4]. CO_2 affects the time to incapacitation in two ways. At low concentrations CO_2 stimulates breathing, which increases the uptake of other toxic gases. At high concentrations (> 5 %) it becomes an asphyxiant, although not additive to the effects of CO and HCN. The main effect from irritant gases are important when evaluating the possibility for people to escape from a fire. Another effect is that the gases can cause oedema and inflammation in the lungs, leading to death 6 to 24 hours after exposure.

Effective dose and concentration levels are 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) [20]. 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. 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* [22], 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. Secondary combustion products will also be generated 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.

TNO suggests methods to clarify in which manner the formation of combustion products can be defined [21], but the guidelines should be considered as indications containing a relatively high degree of uncertainty. This is all based on materials and research results published in 1992, and the underlying studies are even older. TNO recommends for any future research on acute toxicity to obtain better definitions for these types of injuries that could arise consequently when exposed to smoke from a fire. They also state that the methodology established for inhalation by human beings represent no more than an indication, and that a lot of research is required to arrive at reliable dose-effect relationships [21].

Hull and Stec [8] claim that analytical chemistry has made tremendous advances over the last 20 years. Instrumental sensitivities have increased by several orders of magnitude. These improvements have occurred in a period when advances in combustion toxicity have been rather slow. Further, the regulatory focus has been to control the flammability and rate of heat release to control fire hazard, rather than focus on the toxicity. The range of components present in a fire effluent, and the lack of knowledge relating to the toxicity of all individual components, make quantification of fire toxicity expensive [8].

UNCERTAINTIES IN RISK MANAGEMENT

A major study was done by tunnel safety experts in the UN that led to the development of a new international tunnel fire guideline (UN/ECE 2001) [23]. After this study a new EN directive (Directive 2004/54/EC) [24] for fire safety in road tunnels was introduced in 2004. The new regulations did not just set a safety level for a tunnel through prescriptive regulations but also the requirements for how a safety level should be maintained during the whole tunnel lifetime. These new regulations are prescriptive in its form. If a tunnel deviates from the prescriptive solutions, risk analysis should be carried out to form the basis to decide if upgraded safety levels are necessary. To satisfy the requirements of risk analysis in the new regulations, risk analysis guidelines were developed. A study on risk guidelines published in 2004 [25] under the RISIT program founded by the National Research Council of Norway, pointed out the need for more scenario-based solutions. A more resent guideline focuses directly on the different risk analysis methods and when they should be applied [26].

In ISO 31000 [27] risk is defined as the "effect of uncertainties on objectives". Risk management is seen as coordinated activities to control an organisation with regards to risk. A risk analysis is an important part of mapping potential risks within an organisation, and in the ISO 31000 the term "uncertainty" is brought into play. There are several uncertainties related to fire risk in a tunnel, that must be addressed in risk analyses. The scrutiny of whether fire smoke in a tunnel fire is toxic is an important part of the analysis process.

We address ISO 31000, since tunnel fire safety is internationally regulated, and the standard is often referenced. The recommended risk management process is illustrated in figure 1:

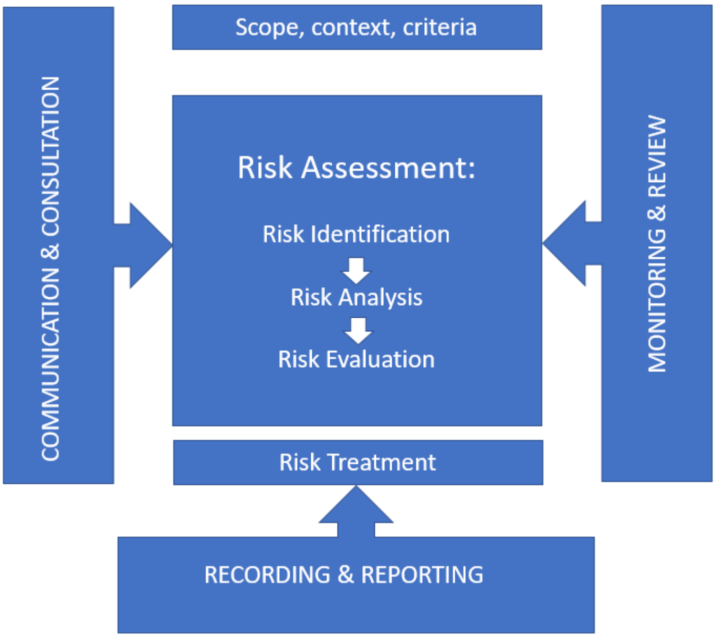

Figure 1: Risk management process according to ISO 31000 [27].

The risk analysis techniques can be qualitative, quantitative or a combination of these. Amongst other, but not limited to, risk analysis should consider factors such as complexity and connectivity, time related factors and volatility, sensitivity and confidence levels. A challenge in any risk analysis is that it is influenced by divergence of opinions (subjectivity), biases, perceptions and judgements. To overcome such challenges the analysis process must include many stakeholders, traceability to data, models and assumptions employed, assessment of their credibility and trustworthiness as well as clarifying various sources of uncertainties.

Risk analysis is futuristic, but uncertainties involved relates to various topics, which we can relate to the timeline. Uncertainties related to historical recordings, for example mapping previous fires in tunnels and toxic compounds involved or establishing an overview of state of HGVs through tunnels, can be dealt with and reduced by improved data retrieval. It is a methodological problem. Uncertainties of the present, such as modelling toxins and their effect on humans in tunnel fires are epistemological. We have some knowledge, and we can improve the knowledge base and thus reduce uncertainties. However, there are still extrapolations, engineering judgements and expert opinions needed. We will still lack knowledge. In order to establish future fire scenarios and risks, we have major uncertainties. This uncertainty exists but cannot be reduced. We can change the tunnel system, but the future is uncertain per se [28].

Risk analysis cannot be without some kind of "valuation". Data is interpreted, subjective models of how reality works is made, and the analysis is influenced by social, cultural or philosophical matters. The models that collect data is subjective [29]. So-called expert risk analysis based on empirical data and scientific methods are important and necessary, but are they sufficient? The purpose of risk management, which risk analysis is an important piece in, is the creation and protection of value. The purpose is to improve performance, encourage innovation and support the achievement of objectives [27]. Human behaviour and culture significantly influence all aspects of risk management at each level and stage. It is important that risk management continually improves through learning and experience. Each organization should specify the amount and type of risk that they may or may not take, relative to objectives. In this way tunnel fire risk analysis and uncertainties regarding toxicity becomes a dialectical debate over safety, which is important for the decision-making processes.

Criteria are defined to evaluate the significant of risk and to support decision making processes. The risk criteria should reflect the organisations values, objectives and resources and be consistent with polices and statements. Such a risk criteria should be established at the beginning of a risk assessment process. When setting the criteria one should consider several things, such as the nature and type of uncertainties that can affect outcomes, how to define and measure consequences (positive and negative), time-related factors, consistency in the use of measurements and how the level of risk is to be determined. Combinations and sequences of multiple risks must also be considered, together with the organisation's capacity [27]. In Norway the road authorities have a philosophy of "zero killed" in the traffic [30]. Thus, developing operational functional requirements, addressing risk acceptance should be a natural part of this. Currently it is not, and the regulation is more prescriptive than functional, despite that risk and contingency analyses are mandatory. They become more compliance oriented than important tools in proactive safety management practices.

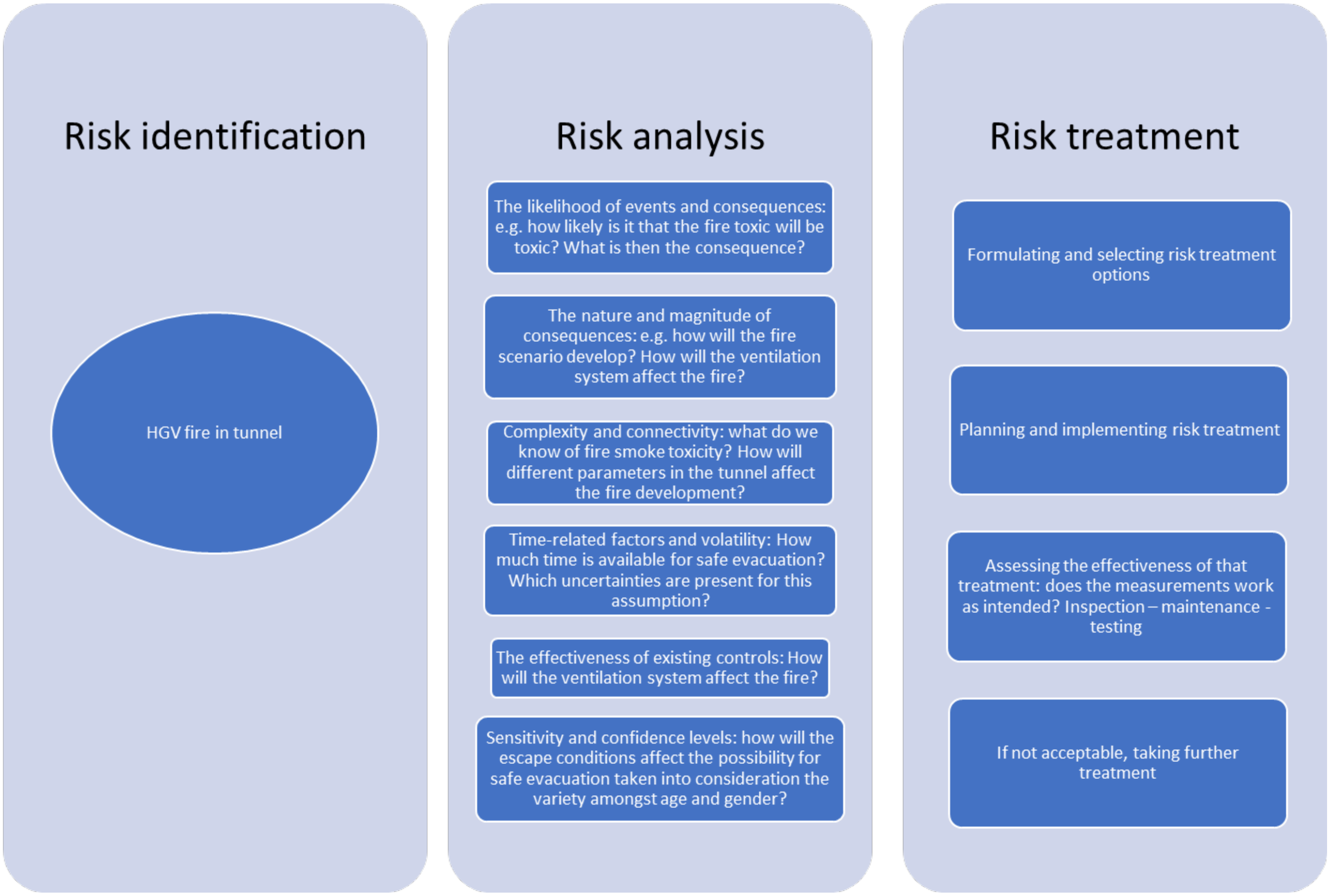

Figure 2: Risk assessment process for fire in a HGV in tunnel illustrated with the ISO 31000 [2] model

Taking the intention from the ISO 31000, the purpose of risk identification is to find, recognize and describe risks that prevent the organization to achieve its goal (no fatal fires from HGVs). The quality of information used will influence the assumptions and exclusions made, limitations of the techniques and how they are executed. All these influences should be considered, documented and communicated to decision makers. Justification for risk treatment is broader than solely economic considerations and should take into account all of the organisation's obligations, voluntary commitments and stakeholder views. Transforming normative risk management strategies into practices are complicated and can only be reviewed by in depth studies of the tunnel systems [6].

FIRE AS A HAZARD IN EXISTING NORWEGIAN TUNNEL RISK ANALYSIS

A random selection of 40 risk analyses carried out for tunnels longer than 500 m in the west, south, east and middle of Norway have been assessed. The aim was to map how the so called "highly uncertain events" were treated. In a tunnel this would typical be if a HGV fire developed into a large fire, producing toxic gases. An overview of the distribution of some of the answers to questions raised when looking into in the prevailing risk analysis is presented in figure 3 below.

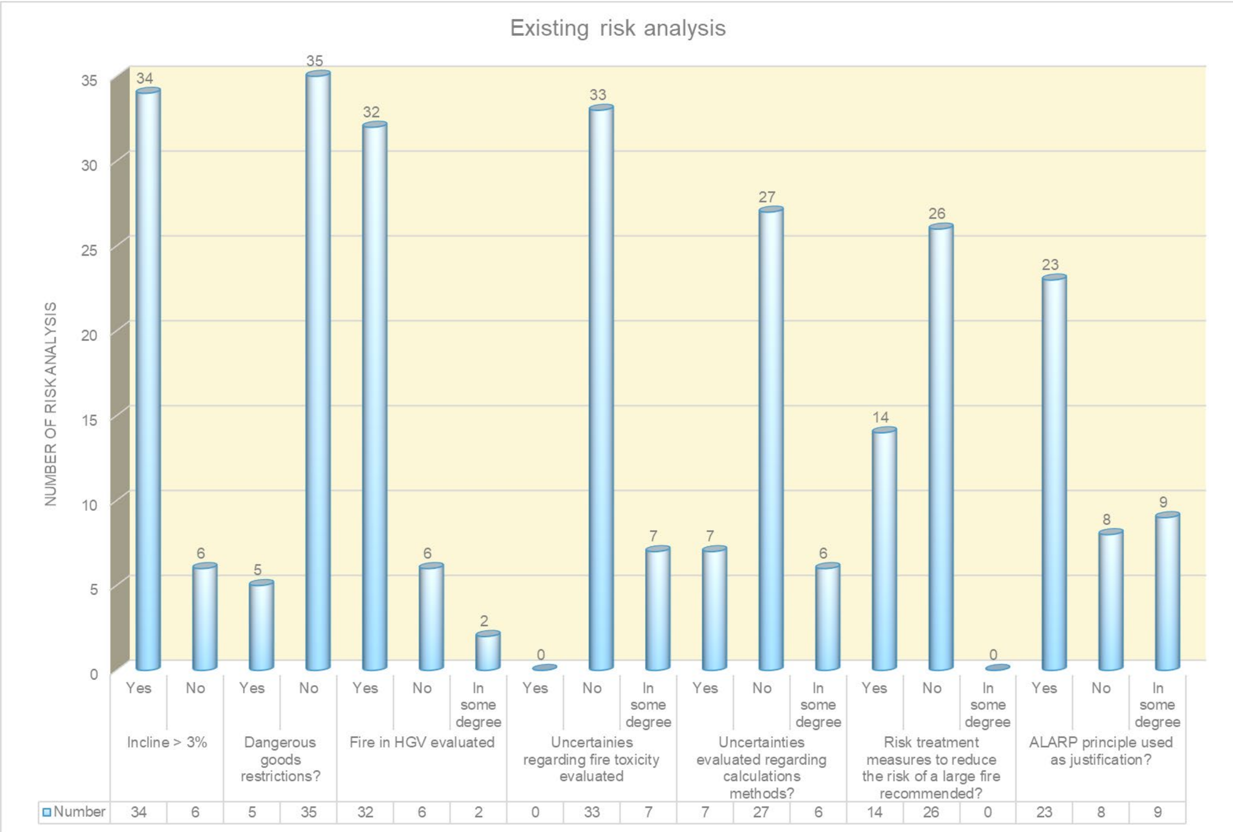

Figure 3: Coarse analysis of a random selection of existing risk analysis

In each of the selected risk analysis it was investigated whether the incline was above 3 % - then the requirement of having extra and/or reinforced measurements based on a risk analysis is prevailing. Further the potential variation of different types of goods were explored (restrictions to dangerous goods?). Whether or not fire toxicity was mentioned as a hazard, or if it was registered as an uncertainty, was also investigated. Several of the risk analysis had quantitative calculations to represent the probability of something going wrong in the tunnel. So whether or not uncertainty/lack of knowledge regarding calculations were mentioned was also looked into. Risk analysis is meant to give input on how we should deal with the risk. Whether or not risk reducing measures regarding potential larger accidents were suggested, and whether they were recommended solely based on cost, was also looked into. Thus, we assessed the use of the ALARP-principle.

Escape routes besides entrances were not present in 39 of the 40 tunnels. Only one risk analysis stated that there was a need to improve the evacuation possibilities. The rest of the analyses stated that it did not reduce the risk level enough to make it acceptable as a measure from an economical point of view. When reviewing the risk analyses, we got the impression that most of the risk analyses were calculation exercises for probabilities based on, as mentioned in several of the analyses, figures from a database that had several uncertain elements.

Arguments used for accepting risks in the performed risk analysis were that the smoke was controlled by the ventilation system and would not constitute a large risk for the occupants. We question this approach towards safety for the occupants based on the huge uncertainties involved. The existing knowledge of fire smoke toxicity and the uncertainties involved in a HGV fire scenario in a tunnel are scarcely treated in all analyses. Since the fire scenarios involving heavy goods vehicles are infrequent events, it seemed that the fire toxicity and the related uncertainty was not treated in the risk analyses.

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. We question the quality of the risk analyses performed for Norwegian road tunnels and exemplify it with the quote:

"An evacuation tunnel would just increase the level of felt safety, but it would in little degree improve the safety level. It would only be beneficial in larger tunnel fires with large releases of dangerous gases or liquids. It is uncertain how many people that would actually use the escape way, because for many it would be natural to turn the vehicle around and drive out or escape by foot in the driving lane. In the St. Gotthard tunnel (2001) 11 people lost their lives even though the tunnel had escape exits. Also, experiments in the Netherlands shows that passive and insecure actions of people in a fire situation reduces the effect of emergency exits. This uncertainty regarding human behaviour makes it impossible to calculate the risk reducing effect of an emergency tunnel. It is also impossible to calculate that alternative measurements gives equal or better effect".

The subsea bi-directional tunnel, 8900 km of length, 7,4 % incline and built in 2013, was built without emergency exits/tunnel. The strategy is that longitudinal ventilation will control a fire and make it possible to evacuate. We question the intention behind the risk analysis, when this approach to map risk reducing measures is used. The example regarding the St. Gotthard tunnel, where 11 people lost their lives even though the tunnel had escape exits, is wrongly used. First, in the St. Gotthard tunnel the scenario was escalation between HGVs and private cars. A fire scenario involving escalation have not been reflected upon in the majority of the Norwegian risk analysis studied. The fire in the St. Gotthard tunnel demonstrates that the smoke very fast will reduce visibility and make the possibility to escape very limited. The victims tried to escape, but some of them could not open the sliding doors. There are challenges with allocating signs and systems to ensure safe egress to emergency exits. Using lack of rationalities amongst road-users as argument against emergency exits are superficial, easy and it certainly lacks justifications. We interpret the quote above as an argument for a decision already made.

The analyses shall be carried out to identify and assess what can contribute to reduce the major accident risk, thus increase safety performance. The performance assessments need to be justified in knowledge, and that is one of the major reflections from risk analysis. All statements must be assessed upon its knowledge base.

The risk analyses reviewed in this study were not consistent in their approach to predicting risk levels, probabilities and acceptance criteria. It varied substantially amongst the companies performing the analyses (in total 6 different companies).

DISCUSSION

Quantitative risk analysis is a heritage from the nuclear and oil and gas industry. As a comparison, the Petroleum Safety Authorities states in the management regulation § 17 that necessary assessments shall be carried out of sensitivity and uncertainty [31]. Risk analyses shall be carried out and form part of the basis for making decisions when, amongst other (not limited to) identifying the need for and function of necessary barriers, identifying specific performance requirements of barrier functions, including accident loads used as basis for designing and operating. It is made clear that risk analyses are only a tool for identifying barriers, operational constraints etc.

The most important in this study was to demonstrate that there are several uncertainties regarding toxicity from the fire smoke in tunnels, and that this is important knowledge to include when mapping the risk picture for existing and new tunnels. Products formed during combustion processes can vary substantially depending upon the materials involved, and each individual fire scenario should ideally be viewed on a case by case basis due to the large number of variables affecting the products formed [8]. For instance, polymeric materials (plastic, resins, fibres and foams) are likely to produce high quantities of carbon monoxide upon combustion. Nylons, polyurethanes and polyacrylonitriles are polymers that contain large quantities of nitrogen and are likely to yield significant amounts of hydrogen cyanide (HCN), nitrogen oxides (NOx) and ammonia.

It is important to address uncertainties regarding the toxicity potential in fire smoke in the decision-making process for the stakeholders involved, and to highlight that risk needs to be understood and managed. Risk is not a static term, it is dynamic, and it will vary. It may be important to visualise the range from the most expected cases to the worst case in order to show that there may exist more than one outcome of a tunnel fire, than discussed in the prevailing risk analyses. Lessons learned from large tunnel fires are many, and they need to be implemented when designing new tunnels. The way uncertainty is treated in a randomly selected sample of analyses seems to be insufficient. The majority of the analyses concluded that larger fires were highly unlikely, and it was too costly to introduce risk reducing measures.

However, what seems to be an acceptable probability for a large fire and who to use the ALARP principle varied. There are no stated acceptance criteria for risk in the selected risk analyses. The term reference tunnel is often used (comparing against a new tunnel), but it is also mentioned that it is impossible to calculate the risk reducing effect of an escape tunnel. We conclude that many of the risk analyses are demonstrations of a calculation exercise.

The road authorities in Norway have the vision zero philosophy as a traffic safety ambition. The sample of risk analyses in this study does not reflect this statement. The risk analyses seem to be about documenting that the risk level is acceptable, and not to find potential barriers that will contribute to reduce the risk level. Increasing the knowledge of what is important factors when it comes to smoke toxicity and how we can reduce it by introducing barriers, would be a much more useful approach to reduce the societal risk.

Further, if there are technical barriers introduced, they need to have a certain level of reliability for functioning when needed. The probability of failure of ventilation, used as an important barrier, was not mentioned in one of the risk analyses assessed. To determine safety integrity level for existing barriers or potential new one would be a step in the right direction. Fire safety risk needs to be understood and managed, not just calculated and accepted. Trying to manage and reduce risk require risk reducing measures, described as technical, operational and organizational barriers. Barriers shall be established that always can:

1. identify conditions that can lead to failures, hazard and accident situations,
2. reduce the possibility of failures, hazard and accident situations occurring and developing, and
3. limit possible harm and inconveniences. Where more than one barrier is necessary, there shall be sufficient independence between barriers.

In 2006 there was a fire in a heavy goods vehicle driving through the Mastrafjord tunnel in Rogaland [32]. The HGV was loaded with car tyres. The smoke filled the entire tunnel portal, and inside the tunnel there was a road tanker filled with propane and a bus filled with passengers, coming from the ferry from north going south towards Stavanger. All in all, there were 30 cars stuck in the tunnel. This accident was a thought-provoking accident, and it shows the potential in such an accident. Lesson learnt from previous tunnel fires tragedies requires attention. Stronger attention should be given to smoke toxicity in the design phase. Which barriers are possible to introduce to reduce the fire risk in a tunnel? Questions that needs to be explored in the tunnel design and the human aspects:

1. What are the current experiments and knowledge base for the empirical models used in fire safety when it comes to fire smoke toxicity?
2. How to manage risk and uncertainties in the design phase regarding exposure to smoke during evacuation, to continuously strive for an inherently safer tunnel design?
3. Is it possible to develop methods to determine different level of incapacitation when exposed to fire smoke?
4. Is the use of human tenability limits beneficial in risk analysis, considering what is adequate from a safety perspective often is a political and/or industry question?

The questions above are important aspects to consider in fire safety engineering. There is a gap of knowledge when it comes to incapacitation and long terms effect of being exposed to fire smoke during evacuation. Long tunnels with limited possibilities for escape introduces challenges. Modelling fires and allowing development of fire scenarios in risk analysis, introduces a need for tenability limits and risk acceptance criteria to make decisions. But there is also a need to demonstrate that human tenability limits and risk acceptance criteria 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.

The risk analysis processes should be improved. The analyses must not be the tool for addressing compliance and legitimizing tunnel designs that are based on interests of single parties. Toxicity is a vital question, uncertainty must be addressed and discussed amongst the wider span of stakeholders.

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