Inherent fire safety engineering in complex road tunnels – learning between industries in safety management

Lene Østrem
Gassco AS
Department of Asset Technology
Haugesund, Norway
leos@gassco.no

Morten Sommer
Western Norway University of Applied Science (HVL)
Department of Fire Safety and HSE engineering
Haugesund, Norway
Morten.Sommer@hvl.no

Keywords: inherent safety, fire safety design, complex road tunnels, lesson learned, risk hierarchy

ABSTRACT

Road tunnels in Norway are becoming increasingly complex, and several long subsea tunnels are either under construction or planned for the near future. The Office of the Auditor General in Norway recently stated that there is a need to improve fire safety in road tunnels. By systematically examining safety management in an industry dealing with high risks daily and combining this with knowledge gained through investigations of tunnel fire accidents and existing research on tunnel fires, this paper is aimed at identifying some areas for improvement in the fire safety engineering of complex road tunnels. The 'inherently safer' philosophy is used as a starting point for safety management, and there appears to be some potential for improvement within tunnel fire safety engineering when taking into account parameters and uncertainties regarding fire growth, heat release rates, smoke stratification and toxicity, and time available to escape with different ventilation strategies.

INTRODUCTION

Several large tunnel fires have occurred in Norway in recent years; Skatestraum Tunnel, July 2015 [1]; Gudvanga Tunnel, August 2013 and 2015 [2]; and Oslofjord Tunnel, June 2011 [3]. These accidents have all been investigated by the Accident Investigation Board Norway (AIBN), which concluded that, under slightly altered circumstances, each of these fires could have resulted in casualties [1], [2], [3]. In 2017, fires broke out in heavy goods vehicles both in Fjærland Tunnel [4] and in the Oslofjord Tunnel [5]. The fire in the Oslofjord Tunnel in 2017 bore several similarities to the 2011 fire. In the Oslofjord Tunnel alone, there has been one major fire every year since its opening in 2000 [3]. It is in this context that the Office of the Auditor General in Norway recently stated that there is a need to improve fire safety in road tunnels [6].

Road tunnels in Norway are becoming increasingly complex, and several long subsea tunnels are under construction or planned for the near future. A complex system is a system composed of many components that interact with each other [7]. One could argue that a tunnel represents a complex system because it depends on several stakeholders to achieve an acceptable fire safety design and to maintain that safety level once it enters the operational phase. The tunnel owner, project leader, technical entrepreneurs, fire brigade, road traffic centre, road users and government are all involved in the project's life cycle at some stage. Ensuring a high level of safety in any construction project is a multidisciplinary task. Traditional fire safety science based on natural science principles alone is severely limited when considering safety in complex constructions [8]. Achieving and maintaining an acceptable fire safety design to reduce the risk of the occurrence of a major fire leading to loss of life, as was the case with the 1999 fire in the Mont Blanc Tunnel [9], is critical but could be challenging when several stakeholders are involved.

One industry that has experienced several major accidents is the oil and gas industry. The Alexander L. Kielland accident [10] on 27 March 1980, which killed 123 people, became the starting point for developing the safety regulations in place within the Norwegian oil and gas industry today. Complex organisations in high-risk industries are dealing with different types of risk on a daily basis, and substantial effort is extended on managing risk to achieve safer systems. These organisations prioritise safety, performance and shared goals. The focus is on learning from accidents, incidents and near misses in order to improve the safety culture and safety performance. In the Norwegian oil and gas industry, inherent safety in design is a strong risk reduction principle [11]. This principle is a foundational consideration in every construction project. Furthermore, measures reducing the probability of an accident occurring are prioritised over measures reducing the consequences of the same accident. The purpose of this paper is thus to compare the fire safety design process and current legislative framework used when designing road tunnels with the inherent safety design process employed in the oil and gas industry.

THE PRINCIPLE OF INHERENTLY SAFER DESIGN

Inherently safer design is a philosophy in which the focus is on eliminating hazards or reducing their magnitude, rather than on attempting to control the hazard [12]. This is not a new approach; engineers working with a wide range of technologies have employed the principle for many years without recognising it as a common approach. In the late 1970s, the British chemical engineer Trevor Kletz [13] recognised this common approach and termed it ‘inherently safer design’. Kletz then developed a specific set of approaches to provide engineers in the chemical process industry with a common toolbox to systematise this way of thinking when designing processes and plants [13], with a view towards making these inherently safe.

The main idea of inherently safer design is that it is better to reduce the hazard early on in the design phase rather than to attempt to control it at a later stage by adding safety systems. Inherent safety is thus considered the most basic way of achieving a safer design in a cost-effective way. Generally, an inherently safer design is considered applicable to the consequences of a given risk, but could also apply to its likelihood of occurrence. An inherently safer design can reduce the magnitude of a potential incident arising from a particular risk or accident, or make the occurrence of an accident highly unlikely or even impossible [12].

An inherently safer design is, however, relative. A design solution can only be described as inherently safer when compared to another design solution. In the design process, one must therefore consider the entire project life cycle and compare the design with other possible design solutions. The principle of inherent safety has become a fundamental component of risk management in several industries over the years, not just at chemical plants. For instance, it is employed widely throughout engineering via the UK Construction, Design and Management (CDM) Regulations [14], which applies to the entire construction process, from concept to completion, in all construction projects in the UK.

Safety is generally understood as a condition in which nothing goes wrong and from which accidents are absent [15], [16]. Hollnagel calls this perspective Safety-I, because the focus is on avoiding things going wrong [17]. Safety-II, on the other hand, is defined by Hollnagel as a condition in which as much as possible goes right and in which the potential for success is as high as possible [17]. Safety management, correspondingly, can also be divided into two approaches. From a Safety-I perspective, one assumes that things that go right and things that go wrong happen in different ways – an activity either succeeds or fails. When something fails, the response is to find the cause and then develop appropriate barriers. This response is reactive. Safety-II, however, assumes that both outcomes basically occur in the same way. Safety management from this perspective should therefore focus on how to succeed. It presupposes a proactive approach by continuously attempting to foresee what can happen and then providing the means and conditions necessary for people to succeed [17]. The principle of inherently safer design will more or less fall into the Safety-II category, because there is a proactive attempt to anticipate events and developments early on in the design phase and then to reduce the risks accordingly.

STUDY APPROACH

In Norway, the oil and gas industries are regulated by the Petroleum Safety Authority, while the Norwegian Public Roads Administration (NPRA) plans, builds, operates and maintains roads and tunnels in Norway. The prevailing requirements in relation to safety in road tunnels are set out in the Tunnel Safety Regulation [18]. The NPRA is updated on all risks, dangers and vulnerabilities related to public roads [19], and it strives to ensure that everyone who uses the roads in one way or another reaches their destination safely [20]. The NPRA’s role in respect of road tunnels is therefore more or less the same as the role fulfilled by the Petroleum Authority in the oil and gas industry. However, the principle of safety management regarding fire risk and safety used in the oil and gas industry is not necessarily the same as that used in other sectors, including in the construction of buildings and roads.

By employing both the Safety-I and Safety-II approaches within safety management, the aim of this paper is to map whether the fire engineering of complex road tunnels can be improved by using the inherently safer philosophy in safety management. This is a qualitative study based on a review of the legislative framework relevant to the design process. Also, safety measures and lessons learned from tunnel fires in Norway have been systemized, and a case study within an industry that has been extensive experience of risk and safety management, the oil and gas industry, has been conducted. The study approach is as follows:

1. Identify how safety management is regulated and carried out in a project in the oil and gas industry in Norway by reviewing legislation and company-specific design documents. An interview was also conducted with the discipline responsible for technical safety.
2. Identify how safety management is regulated and carried out in a tunnel project by reviewing legislation and manuals issued by the NPRA related to road tunnels.
3. Compare and systematise safety measures and lessons learnt from previous tunnel fires in Norway. This was done to establish whether there are commonalities and to map potential barriers that might be present in a tunnel fire.
4. Compare legislation within the different industries with regard to safety and risk management.
5. Based on the results obtained via the steps above, make recommendations for improving the design process in order to create inherently safer tunnels.

To study the mechanisms governing an inherently safer design process in the oil and gas industry, a case study was performed on a new gas plant terminal. The terminal was built to increase the safety and capacity of an existing receiving terminal. The design of the new receiving terminal was scenario based, and the inherent safety philosophy was used together with safety performance-based design criteria. A review of all design documentation, as well as an interview of the person responsible for technical safety in the project, was conducted.

To study the approach to fire safety used when designing road tunnels, the NPRA’s official website was systematically searched for documents related to planning, building, operating and maintaining tunnels. Here, the N500 Road Tunnels manual [21], V520 Tunnel Guidance document [22] and R511 Safety

Management of Road Tunnels, Part 1 guideline [23] were found to be relevant and studied in detail.

Previous tunnel fires in Norway have been thoroughly scrutinised by the AIBN. The AIBN investigation reports on all tunnel fires occurring in the last few years [1], [2], [3], [4], [5], [24], [25] were studied and systematised, focusing on the safety recommendations made by the AIBN. The aim was to map potential areas for improvement in the tunnel design process.

ACHIEVING AN INHERENTLY SAFER DESIGN PROCESS AT A GAS RECEIVING TERMINAL

Technical safety management in the project development and design processes comprises activities aimed at identifying risks and developing safety strategies and performance requirements for safety systems and barriers. In concept optimisation and design development, priority is given to preventive measures or the exposure of barriers and inherently safer design principles. The objectives with risk reduction principles and inherent safety design are to [11]:

- Reduce potential hazards
- Reduce the probability of unwanted events
- Reduce inventory and damage potential,
- Strive for simplicity and reliability
- Prevent escalation, for instance by implementing safety barriers.

The project owner must comply with a company governing document called the Safety Performance Standard [26]. The objective of the Safety Performance Standard is to add any supplemental safety requirements other than those specified by the authority's requirements and standards. The document confirms that the barriers, safety systems and functions are suitable, have sufficient capacity and availability, and are suitable for all operating conditions. The safety barriers are identified through risk analyses and lessons learnt from previous accidents in the industry [11]. This is followed by the development of a safety strategy [27]. This is an important document for the design phase. The objective of the safety strategy is to document the fire and explosion strategy and emergency preparedness strategy for the project and to verify the protection measures required to limit the risks to construction and personnel associated with fires and explosions. The main topics covered in the safety strategy document are [27]:

- Fire and explosion protection philosophy
- Identification of fire and explosion hazards
- Analysis of the fire and explosion risks
- Determination of the necessary fire and explosion protection measures
- Emergency preparedness and response.

The safety strategy is developed to ensure that the requirements of the Safety Performance Standard are fulfilled. The safety philosophy is strongly based on the integrity of the process design for the prevention of hydrocarbon release and the ignition of hydrocarbons if released. The objective is to maximise the safety of personnel under all circumstances. The philosophy for managing the fire and explosion hazards is based on the following order of priorities [27]:

1. Prevention of a loss of containment through adequate design (inherently safe), operations and maintenance
2. Effective detection or warning and escape of personnel
3. Prevention of ignition in the event of a containment failure, by control of ignition sources
4. Limitation of the released inventory in case of a containment failure by emergency isolation and blowdown to a safe location
5. Mitigation of the consequences of fire and explosion by means of adequate spacing and/or a fire and explosion protection system.

Having functional performance requirements in regard to safety leads to a scenario-based terminal design. All hazards are identified and modelled so that adequate barriers can be identified and implemented. For instance, an important barrier preventing the escalation of a fire and explosion scenario is the layout of the terminal. The new terminal was designed to be inherently safer than the old one by removing via design the possibility of an accident escalating. This was achieved by using a larger distance between the process trains than at the original terminal. By simulating different types of fire and explosion scenarios, it was possible to identify a distance at which it would no longer be possible for the fire to escalate before the process itself was shut down (i.e., no more flammable content in the pipelines). It was also possible to locate potential leakage points (e.g. valves) at a height at which they would not contribute to fire spread by enhancing the flame due to the Coanda effect [28] (flame will stick to the ground; see figure 1).

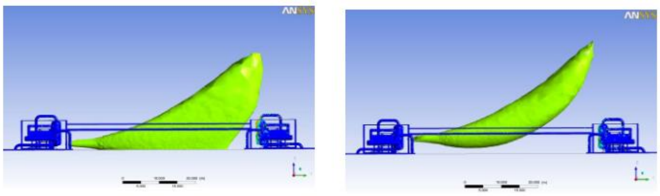

Figure 1. Simulation of a jet flame [29]

Using simulation tools (CFD modelling) and knowledge of fire dynamics [30] to map how different design solutions will affect fire development is a good way to achieve an inherently safer design of the terminal. In this case it was also cost-saving, due to a reduced need for passive fire protection and the associated increased maintenance cost due to the risk of corrosion underneath the isolation. Achieving this design solution requires knowledge about fire as a phenomenon and a good safety management strategy. The technical safety responsible person in the project is responsible for ensuring that the design process reflects the project scope and that the results from analyses and reviews are properly documented for timely input in the design and procurement process. The main elements related to technical safety design in projects in the oil and gas industry are illustrated in figure 2 [11].

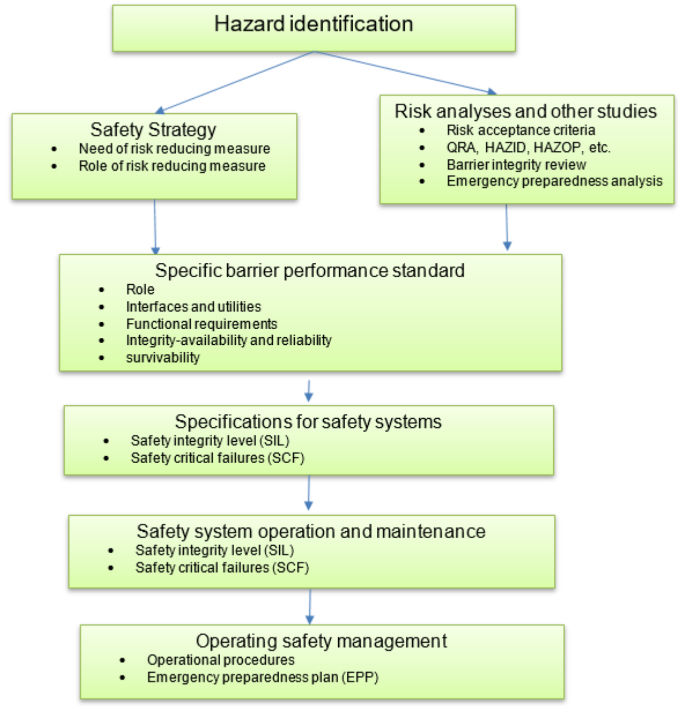

Figure 2. Main elements of technical safety design in the oil and gas industry [11]

The company's approach is a structured way to mitigate the fire risk and implement an inherently safer philosophy. It uses safety performance requirements to reduce fire and explosion risks, followed by an obligation to always reduce the risk as much as possible. This is a common approach to managing risk in the oil and gas industry during the development of projects. It is also a requirement of the Petroleum Authority in Norway to have in place risk reduction principles and barriers [31], [32].

Safety management during start-up and operation is defined in the overall corporation management systems and specific commissioning and operating procedures. Regular maintenance is carried out, together with frequent inspections and reviews, to ensure that the safety level is maintained. Important safety barriers are tagged as critical safety equipment in the maintenance system and have stricter requirements for follow-up than other equipment. Reviews that examine safety barriers and verify them against validation activities covering design, condition and operations are carried out at regular intervals during operation. Risk and barrier management form an integral part of corporate governance (figure 3).

Figure 3. Corporate governance structure [33]

REQUIREMENTS WHEN DESIGNING ROAD TUNNELS

When planning and designing a tunnel, the applicable governance document is N500 Road Tunnels, published by the NRPA [21]. The requirements listed in the manual are applicable during both the planning and engineering phases of projects. Planning and engineering a tunnel are based on estimated lifetime, estimated operation time, vulnerability and safety assessments, and operation and maintenance considerations. Tunnel profiles are based on the tunnel length and the expected AADT (yearly number of cars passing by a given location, divided by 365) 20 years after completion. Significant uncertainty regarding traffic growth requires special consideration based on a risk analysis. The tunnel class determines the safety level and equipment in tunnels longer than 500 m (i.e., the number of roadways, emergency exits, safety equipment, and breakdown and turnaround slots). Tunnels longer than 10 km require special considerations. The R511 manual provides guidelines regarding how to satisfy the tunnel safety regulations [23]. It contains a requirement to have a safety representative who coordinates all preventive safety measurements to ensure the safety of road users and operation personnel. It also contains requirements regarding safety documentation. The requirements for obtaining a safety approval and opening the tunnel to traffic are [23]:

1. Description of the tunnel's construction.
2. Planned preventive measurements, including portal design, ramps, lighting, traffic prognosis, risk analysis for hazardous cargo, and sidewalk for evacuation.
3. Road conditions: driving width, height and curvature, both horizontal and vertical.
4. Preventive measures for traffic users and workers in the tunnel: emergency telephones, fire extinguishers, fire water, emergency exits, evacuation lights, backup electricity, special provision for disabled persons, emergency communication tools and other measures.
5. Operations: what shall be monitored and managed.
6. Risk assessment: an assessment of the possible accidents that can occur and a description of potential hazards and consequences throughout the tunnel's lifetime. The assessment must emphasise and justify measurements that are conducted to reduce the probability and consequences of accidents.
7. A statement regarding safety from an expert.

Prior to opening, the following must be in place:

8. Description of the organisational, human and material resources and instructions necessary to maintain operation and maintenance of the tunnel.
9. An emergency preparedness plan, prepared in collaboration with the fire rescue organisation, which takes into consideration disabled persons.
10. A description of how events and accidents will be recorded and analysed.

Operational requirements:

11. Reports on and analysis of significant events and accidents that have occurred.
12. A list of emergency response exercises and lessons learnt.

The manual applies to all tunnels exceeding 500 m in length. The main elements of the safety design of road tunnels are illustrated in figure 4.

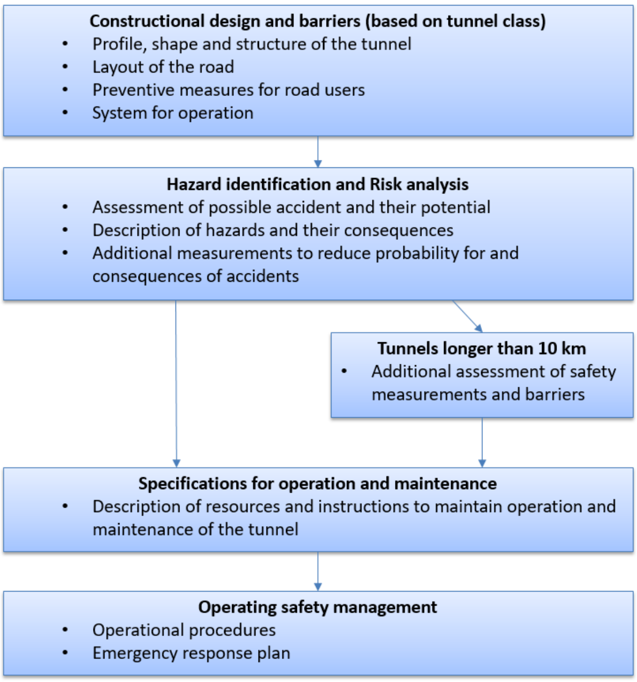

Figure 4. Design requirements for tunnels longer than 500 m

LESSONS LEARNED FROM NORWEGIAN TUNNEL FIRES

By studying the investigation reports and lessons learned from road tunnel accidents in Norway over recent years, there are several important lessons that should be included when assessing the risk level of a new tunnel. The AIBN has published investigative reports on several fires and has made a total of 23 safety recommendations [1], [2], [3], [24], [25]. These recommendations have a number of similarities and can be divided into four main groups:

- Understanding risks involved/safety management (six)
- Engineering recommendations (three)
- Preventive recommendations (nine)
- Reactive recommendations (five)

The recommendations are categorised as shown to make it easier to sort out the potential barrier or safety constraints [34] that can be used when designing a new tunnel. Within each of these categories, barriers that could have affected the fire development ave been identified.

An examination of the safety recommendations made by AIBN supports the notion of a tunnel as a complex system due to all the participants that must be involved to improve the safety level in a tunnel. There are several design elements that affected the fire development in the fires investigated. Moreover, it is worth mentioning that the ongoing investigation of the 2017 fire in the Oslofjord tunnel so far shows several similarities to the fire in 2011 [5]. The investigation of the fire in the Fjærland Tunnel [4], in which a heavy goods vehicle externally mounted with cleaning equipment caught alight, has shown that, despite the presence of an ongoing cleaning operation with traffic routing and an escort car, this did not prevent road users from being exposed to fire smoke after the fire ventilation started (13 persons were injured by the smoke). A common feature of heavy goods vehicle and bus fires inside tunnels is that such fires escalate rapidly. This is supported by research done by Haukur et al. [35]. In more or less every fire scenario in Norwegian tunnel fires, road users were exposed to fire smoke, resulting in a range of injuries, from minor to severe and even critical [1], [2], [3], [4], [5].

COMPARING REGULATIONS

A comparison of the Tunnel Safety Regulation [18] with the Framework HSE, Management and Technical and Operational Regulations [31,32] used in the petroleum industry reveals some differences in the handling of the expectations and responsibility for reducing risk. In the PSA regulation, there is a requirement to continuously reduce risk and to have safety barriers for all identified and known risks (Management Regulation §4, §5). In reducing the risk, the responsible party shall choose the technical, operational or organisational solutions that, according to an individual and overall evaluation of the potential harm and present and future use, offer the best results, provided the costs are not significantly disproportionate to the risk reduction achieved. Risk means the consequences of the activities, with associated uncertainty (§ 11 Framework Regulation).

In contrast, the Tunnel Safety Regulation states that, where certain structural requirements only can be satisfied through technical solutions which are either not feasible or can be achieved only at disproportionate cost, the administrative authority may accept the implementation of risk reduction measures as an alternative to the application of those requirements, provided that the alternative measures will result in equivalent or improved protection. The efficiency of these measures shall be demonstrated through a risk analysis.

Furthermore, risk analyses, where necessary, shall be carried out by a body that is functionally independent from the tunnel manager. The content and results of these risk analyses shall be included in the safety documentation submitted to the administrative authority. A risk analysis is an analysis of risks for a given tunnel, considering all design factors and traffic conditions that affect safety, notably, traffic characteristics and type, tunnel length and tunnel geometry, as well as the forecast number of heavy goods vehicles per day.

DISCUSSION AND CONCLUSION

In both industries, requirements regarding safety management are present, and there are similarities regarding risk reduction principles and requirements for risk analysis. However, the principles regarding how to set safety requirements appear to be somewhat different. The oil and gas industry appears to have a proactive risk hierarchy implemented in their governing documentation. On this basis, risk management strategies in the inherent and passive categories are more robust and reliable [12]. It seems as though the Norwegian Public Roads Administration has a more reactive approach to safety. When designing tunnels, the body requires that the profile, shape and structure of the tunnel, layout of the road, preventive measures for road users and operations systems be decided before hazards are identified and analysed. This makes it difficult to adopt a risk-based approach to design.

Some of the technical system requirements described in the N500 manual [21] play a significant role during a fire and need to be tailored accordingly, for instance, the drainage and ventilation systems. For example, the manual states that there must be a distance of 250 m between emergency exits (when required). Based on our knowledge of potential fire toxicity, smoke irritants, human behaviour in crises and an inherently safe design approach [36],[12], this requirement is not necessarily adequate in all fire scenarios. The functionality of the barriers present in a tunnel will determine whether or not it is possible to conduct a safe evacuation. Some recommendations can therefore be made to achieve an inherently safer design and safety management system. The safety management approach in the oil and gas industry has developed from the mechanisms of Safety-I. As a consequence of improved knowledge about safety management, the result of dealing with risk on a daily basis, the process plants have become inherently safer over the years, and now follow a Safety-II approach by focusing on foreseeing what can happen in terms of fires and how to succeed in preventing these fires from escalating into major fires or accidents. At present, safety management and barrier management are integral aspects of the corporate governance system, making it possible to conduct scenario-based design based on the results from risk analysis.

Currently, the N500 manual [21], which is used when designing tunnels in Norway, does not emphasise an inherently safer design regarding fire safety. Knowing that a large fire in a tunnel holds significant potential to create a major accident, one should aim to make tunnels inherently safer. In an inherently safer tunnel, the probability of a major fire occurring would be further reduced (hazards minimised). If the accident nevertheless occurs, the tunnel must be designed in such a way that it reduces the adverse consequences in a reliable and efficient way (limitation of effects), making it possible to reach a safe location without having to walk or drive long distances to escape the smoke. Consequently, one should enhance the present barriers when designing a tunnel and describe the safety functionality and reliability requirements early on in the project development process.

As stated in the N500 manual [21], the requirements set out in the manual are compliant with the Tunnel Safety Regulation [18]. When designing the ventilation system, the tunnel safety regulation states, among other things, that construction, building and operations shall maintain control of heat and smoke in case of fire. Mechanical ventilation shall be present in tunnels that exceeds a traffic volume larger than 2,000 vehicles in each direction, and in tunnels over 1 km in length [18]. When mechanical ventilation is required, transverse or semi-transverse ventilation shall be used. Lengthways ventilation is not permitted unless a risk analysis can document an adequate safety level. Safety measures, for instance, traffic regulation, short distances between emergency exits and smoke extraction at regular distances, shall be implemented accordingly. Chapter 9 of the N500 manual covers the ventilation system [21]. The chapter states that the ventilation system should be dimensioned for a possible fire, be reversible, and dimensioned to manage the smoke in the required direction. Further guidance is given on smoke management and how to choose a ventilation direction. However, this is not in accordance with the Tunnel Safety Regulation's requirement of a transverse or semi-transverse ventilation system as a starting point. The N500 manual [21], which is the prevailing project document, more or less states that the ventilation system should be longitudinal. This set of project requirements does not enhance safety barriers or their role in reducing the adverse consequences of a fire scenario.

The Tunnel Safety Regulation [18] requires emergency exits for tunnels between 0.5 and 10 km in length with an AADT > 8,000 and for tunnels of more than 10 km in length and an AADT of more than 4,000. The robustness of this set of design criteria is questionable, since it is not based on the possible fire effect that could be present in the tunnel. The tunnels themselves are designed for a lifespan of 100 years, and the technical installations for a lifespan of 50 years [21]. The safety level, however, is determined on the basis of the expected traffic volume in 20 years [21]. This means that the engineering criteria take account of only the number of cars using the tunnel in 20 years, not the various types of vehicles. Instead, the possible fire effect, that is, the heat release rate (HRR) [35], should be used as a safety design criterion or constraint, rather than the traffic volume. This was also stated in the investigation report from AIBN [3], and is supported by several tunnel fire experiments and knowledge acquired in the field of tunnel fire dynamics [35]. If the AADT exceeds a given number after, for instance, 15 years, then the requirements for emergency exits suddenly apply. Upgrading the tunnel to comply with the new safety level would then come at a very high cost. Further, the Tunnel Safety Regulation [18] requires that, when heavy goods vehicles above 3.5 tons exceed 15% of the expected average traffic in a 24-hour period, or seasonal traffic significantly exceeds the average AADT, the increase in risk should be handled by increasing the tunnel's traffic volume (AADT) [18]. This represents yet another uncertainty factor that will change during the years of operation. At certain points in time, the requirement regarding emergency exits may apply. Several further uncertainties support the argument that the expected fire effect (HRR) over a period of 100 years should be an engineering criterion rather than related to traffic volume. Previous tunnel fires, as well as our knowledge about fire as a phenomenon, show that fire risk is connected to the inclination of the tunnel, the types of vehicles inside, and the ventilation strategy [1], [2], [3], [24] , [25], [35]. These parameters will affect the fire growth, heat release rate, smoke stratification and time available to escape. Fire smoke can be lethal [36]. It should therefore be a safety constraint regarding evacuation in smoke. At present, there are several uncertainties regarding the possible effect of evacuation in smoke. From a risk-based design perspective, where the strategy is to emphasise inherent and proactive measures [12], the current requirements of the N500 manual [21] appear to be somewhat inadequate when it comes to setting a framework for a robust fire safety design. It is possible to learn from other industries and tunnel fires already investigated in Norway to work on developing a risk hierarchy and design criteria for tunnel fires, aiming for an inherently safer fire safety design.

One way to achieve a more proactive approach to safety management could be to study the design process followed when designing a complex tunnel and to map how the risk analysis results are used to implement fire risk reduction measures. Will risk analyses take into consideration lessons learnt from previous tunnel fires? Furthermore, which barriers and safety constraints should be present, based on our knowledge of fire smoke toxicity?

From this starting point, it might be possible to develop barriers and safety constraints and thus implement them in the design process. By applying a Safety-II approach to safety management [17], the Norwegian Public Roads Administration could increase the fire safety level in road tunnels and move one step closer to fulfilling the ‘Zero Vision’ of nobody killed or seriously injured in traffic. The integration of a structured safety management process into the corporate governance system and design requirements could drive an inherently safer fire safety design in complex road tunnels over time.

This study has some limitations which should be taken into account by future research. Only Norwegian tunnels and design documents were studied. Other countries, especially those that have experienced major road tunnel accidents, might also have lessons to offer regarding safety management in the design process. Moreover, the legislation used for fire safety in buildings could be reviewed. This study selected the oil and gas industry because, in this industry, the regulations consist largely of risk- and performance-based requirements. They regulate important aspects of HSE for the industry in an integrated and coherent manner. On the other hand, the economics of these two industries are rather different. Still, there appear to be some transferable lessons regarding safety management. This conclusion are also supported by previous investigations of road tunnels, which have stated that their safety management and the understanding of risks require improvement.

REFERENCES

[1] Accident Investigation Board Norway (2016/5), *Report on fire in tank trailer in the Skatestraum tunnel in Sogn and Fjordane on 15 July 2015*, issued November 2016.

[2] Accident Investigation Board Norway (2013/05), *Report on fire in a heavy goods vehicle in the Gudvanga tunnel on the E16 road in Aurland on 5 August 2013*, issued March 2015.

[3] Accident Investigation Board Norway (2015/02), *Report on a fire in heavy goods vehicle on the RV23, Oslofjord tunnel, 23 June 2011*, issued October 2013.

[4] Investigation of fire in the Fjærlands tunnel, available online [read 22.04.18], https://www.aibn.no/Veitrafikk/Undersokelser/17-374

[5] Report on fire in heavy goods vehicle in the Oslofjord tunnel on national road 23 on 5 May 2017 available online [read 26.02.19], https://www.aibn.no/Veitrafikk/Undersokelser/17-369

[6] Authority General in Norway, Report 3:16 (2015-2016), *Investigation on work done by the Government to improve safety in road tunnels*, issued September 2016.

[7] Perrow, C. *Normal Accidents: Living with High Risk Technologies* (2nd ed.), Princeton, New Jersey: Princeton University Press, 1999.

[8] H. Bjelland, O. Njå, A.W. Heskestad, and G. S. Braut, ‘The concept of safety level and safety margins: Framework for fire safety design of novel buildings’, *Fire Safety Journal*, vol. 51, pp. 409-441, 2015.

[9] Task force for technical investigation of the 24 March 1999 fire in the Mont Blanc vehicular tunnel, Report of 30 June 1999, Minister of the Interior, Ministry of Equipment, Transportation and Housing – 30 June 1999.

[10] Available online [read 23.04.2018], http://www.ptil.no/artikler-i-sikkerhet-status-og-signaler-2012-2013/alexander-l-kielland-det-svarte-dognet-article9135-1094.html

[11] NORSOK Standard, *Technical safety S-001* (4th ed.), Standards Norway, 2008.

[12] S. Mannan, *Lee’s Loss Prevention in the Process Industries: Hazard Identification, Assessment and Control* (vol. 2, 4th ed.), Butterworth-Heinemann: Elsvier, pp. 2346-2368, 2012.

[13] T. Kletz, and A. P. Amyotte, *Process Plants: A Handbook for Inherently Safer Design* (2nd ed.), Boca Raton: CRC Press, 2010.

[14] Health and Safety Executive UK, *Health and Safety in Construction* (3rd ed.), HSG150, 2006 (Available online, 25.01.2018 http://www.hse.gov.uk/pubns/books/hsg150.htmhttp)

[15] T. Aven, ‘What is safety science?’, *Safety Science*, vol. 67, pp. 15-20, 2014.

[16] E. Hollnagel, ‘Is safety a subject for science?’, *Safety Science*, vol. 67, pp. 21-24, 2014.

[17] E. Hollnagel, *Safety-I and Safety-II: The past and future of safety management*, Surrey: Ashgate, 2014.

[18] Forskrift om minimum sikkerhetskrav til visse vegtunneler (tunnelsikkerhetsforskriften), Lovdata, available online [read 05.05.2018], https://lovdata.no/dokument/SF/forskrift/2007-05-15-517

[19] Information available online, Government.no [read 08.05.2018], https://www.regjeringen.no/no/dep/sd/org/underliggende-etater/statens-vegvesen/id443412/

[20] Information available online, Road Authority home page [read 08.05.2018], https://www.vegvesen.no/en/the-npra/about-us

[21] Statens vegvesen, ‘Håndbok N500 Vegtunneler’, available online [read 05.05.2017], https://www.vegvesen.no/fag/teknologi/tunneler/handboker

[22] Statens vegvesen, 'Håndbok V520 Tunnelveiledning', available online [read 05.05.2017], https://www.vegvesen.no/fag/teknologi/tunneler/handboker

[23] Statens vegvesen, 'Håndbok R511 Sikkerhetsforvaltning av vegtunneler', del 1, available online [read 05.05.2017], https://www.vegvesen.no/fag/teknologi/tunneler/handboker

[24] Accident Investigation Board Norway, (2017/07), *Report on a fire in heavy goods vehicle on the RV 7, in Måbøtunnel 19 May 2016*, issued December 2017.

[25] Accident Investigation Board Norway, (2017/04), *Report on a fire in gas driven bus in Trondheim 17 December 2016 and 23 November 2016*, issued September 2017.

[26] Company governing documents, *Safety performance standard, HSE-141*, Rev. 05, 06.04.2017.

[27] Company project documentation, *Safety strategy*, Doc. No. 1372-E-000-S-RD-0112, Rev. 5, Issued for design, 16.10.2014.

[28] D. J. Tritton, *Physical Fluid Dynamics* (2nd ed.), Oxford Science Publications, 1988.

[29] Company project documentation, *Fire and explosion hazard analysis (FEHA)*, Doc. No. 1372-E-076-S-RS-0104', Rev. 6, Issued for design, 11.05.2012.

[30] D. Drysdal, *An Introduction to Fire Dynamics* (2nd ed.), Chichester: Wiley, 1998.

[31] Petroleum Safety Authority, *Framework HSE regulation*, §11, available online [read 23.04.2018], http://www.ptil.no/framework-hse/category403.html

[32] Petroleum Safety Authority, *Management regulation*, §5, available online [read 23.04.2018], http://www.ptil.no/management/category401.html

[33] Petroleum Safety Authority, *Principles for barrier management in the petroleum industry*, *Barrier memorandum 2017*, available online [read 05.05.2017], http://www.ptil.no/news/barrier-memorandum-new-version-2017-article12697-878.html

[34] N. G. Leveson, *Engineering a Safer World: System Thinking Applied to Safety*, Cambridge, MA: The MIT Press, 2011.

[35] H. Ingason, Y. Z. Li, and A. Lönnermark, *Tunnel Fire Dynamics*, New York: Springer, 2015.

[36] A. Stec and R. Hull, *Fire toxicity*, Oxford: CRC Press, 2010.