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State-of-the-practice on tunnel fire safety management

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ABSTRACT: A survey was carried out to identify the strategies for tunnel fire safety used in different countries, with a focus on the combination of life safety and asset management for existing structures. This paper brings together the data that is gathered from contacting tunnel fire safety experts and asset owners in various countries. Contributions from Belgium, Germany, Norway, Sweden, Finland and the United Arab Emirates have been collected. The responses have been analyzed, similarities between the different countries were noted down, and the particularities of each country have been briefly summarized. The answers indicate that the structural assessment of existing tunnels subjected to fire loading is not much addressed, and that the use of nonlinear finite element modelling for this question is not used in other countries, indicating the novelty of the tunnel fire safety management strategies developed in the Netherlands.

1 INTRODUCTION

With major infrastructure disasters related to fire in tunnels, tunnel fire safety is an important topic for the safety of the traveling public. Some notable tunnel fire incidents include the Nihonzaka tunnel fire in 1979, the Caldecott tunnel fire in 1982, the Chunnel fires in 1996 and 2008, the Mont Blanc tunnel fire in 1999, the Daegu Municipal Subway fire in 2003, the Köningshainer Berge tunnel fire in 2013, the Rannersdorf tunnel fire in 2019 (Lantsoght et al. 2026), and the Brattli Tunnel fire in 2013 (Njå and Svela 2018). In the Netherlands, two major tunnel fires are noted: the Velser Tunnel fire in 1978 (Nelisse and Vrouwenvelder 2016) and the Heinenoord Tunnel fire in 2014 (Bongers 2020). The Velser Tunnel fire was caused by an accident with one heavy goods vehicle and four cars, resulting in a fire of 30 minutes with a maximum temperature of 800 °C and a Heat Release Rate (HRR) estimated afterward of 40 – 50 MW. After the fire, 15 mm of the concrete cover (of 70 – 80 mm) was observed to have spalled off. The Heinenoord Tunnel fire was caused by an accident with a heavy goods vehicle and a passenger car, resulting in a fire of 31 minutes with a maximum HRR estimated as 58 MW during 18 minutes. The Heinenoord Tunnel has fire protection panels on the roof and tiles on the walls. The damage after the fire included spalling of 25 mm of the concrete cover.

To improve the safety of tunnels in the Netherlands, and in particular of land tunnels, a research project was initiated in the Netherlands that focuses on the assessment of the capacity of land tunnels subjected to fire, with a focus on nonlinear finite element modeling (Díaz et al. 2024a, Díaz et al. 2024b, Sanabria Diaz et al. 2024). To link these technical insights to

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infrastructure management practices, information has been collected on the state-of-the-practice of fire safety management in tunnels in a number of countries. The goal of collecting the data was to compare the methodologies and requirements in the Netherlands to those used internationally, to see if the methods used in the Netherlands can be considered state-of-the-art, to check if the methods for fire proofing of structures using fire protection plates is commonly used, and to check if the asset management requirements for the tunnels in the Netherlands aligns with other countries.

2 METHODOLOGY

Fire safety in tunnels is a critical aspect of the operations of the transportation network and requires attention to both measures to safeguard tunnel users (human lives) and asset management. To develop the international state-of-the-practice in tunnel fire safety, written interviews with specialists across six countries outside the Netherlands were carried out. The questions for the survey were designed together with the asset owner in the Netherlands, to make sure that the information aligns with the needs of the tunnel owner and the required information on tunnel fire safety from the human life safety and asset management perspectives. The interviews were structured around the following questions:

1. Which type or types of fire protection is used in tunnels?
2. Are there additional requirements for asset protection (in addition to requirements for human safety)? Do the regulations distinguish between asset protection and safety of tunnel users?
3. Which temperature-time curve is used for assessment?
4. Are there any additional national requirements for the fire safety of the tunnel structure that go beyond the Eurocode requirements?
5. Is there a legal framework regarding the tunnel safety?

The respondents include specialized engineers and researchers in the topic from Sweden, Norway, Belgium, Finland, Germany, and the United Arab Emirates. The contacts were obtained through our professional network.

3 RESULTS

3.1 *Common practices across countries*

Despite the differences between the various countries, a number of shared strategies across various countries are identified. The first common strategy is the addition of Polypropylene (PP) fibers to concrete tunnel lining mixes for new tunnels (Mitchell 2007). PP fibers are widely used in structural tunnel fire protection. Typically dosed at 2 kg/m^3, these fibers prevent spalling under fire exposure by melting, followed by releasing moisture as vapor and reducing internal pore pressure. Germany, Norway, and Sweden all report using PP fibers in either sprayed concrete linings or cast elements. This technique is considered cost-effective and easy to implement for both new construction and retrofitting.

Most countries focus on human life protection over asset management for tunnel structures. Tunnel fire safety strategies consistently distinguish between the protection of human life and the performance and post-incident continued use of infrastructure. Human safety measures focus on fire detection, alarm systems, emergency lighting, evacuation routes, and ventilation. Asset protection includes structural fire resistance, temperature control to prevent reinforcement loss and excessive concrete cover loss, and fire-resistant linings. Most countries separate these aspects in their regulations or adopt complementary standards to address each separately. Not all countries (for example, UAE and Belgium) focus on aspects related to asset management.

All designs of tunnel linings subjected to fire are based on standard temperature-time curves. Temperature-time curves provide a basis for assessing the fire performance of tunnel linings and structures. The hydrocarbon (HC) curve and Rijkswaterstaat (RWS) curve are most commonly used. Norway and Sweden apply the HC curve by default, with Norway using the RWS curve in high-consequence scenarios. The UAE uses the ISO 834 curve for railway tunnels and the RWS curve for road tunnels; similarly, in Belgium the choice of temperature-time curve depends on the asset owner. Germany employs a modified ZTV-ING curve, which includes a decay phase to simulate realistic fire scenarios.

All countries from which responses were obtained, have to fulfil requirements stipulated in a formal legal framework that mandates tunnel fire safety requirements. In Europe, the EU Directive 2004/54/EC (Thamm 2004) establishes minimum safety requirements, which forms the basis of the national regulations in Germany, Norway, Sweden, and Finland. The UAE applies the NFPA 130 and 502 standards alongside its national Fire and Life Safety Code (Jun, Kang 2006). These frameworks typically define minimum fire resistance levels, evacuation design, equipment specifications, and maintenance protocols.

In terms of strategies for the assessment of existing tunnels subjected to fire, only few countries have procedures to address this. Germany requires small- and large-scale fire testing for polypropylene fiber concrete. Norway refers to the full-scale Runehamar tests (Ingason et al. 2015). Finland requires third-party fire testing with a ten-year validity period, and Sweden allows testing or calculations, though field testing is uncommon. In Belgium, mobile furnaces have been used for tunnel renovation, but only in a limited number of instances. The UAE relies primarily on code compliance rather than explicit testing.

3.2 *Overview of findings*

In total, the responses representing the state-of-the-practice in six countries were obtained. Table 1 provides an overview of the main findings.

Table 1. Overview of main findings.

	Germany	**Norway**	**Sweden**	**Finland**	**UAE**	**Belgium**
Fire curve	ZTV-ING curve (custom German curve)	HC (default), RWS (critical)	HC curve 180 min	Up to 600°C requirement, focus on insulation performance	ISO 834 (rail), RWS (road)	ISO 834 or RWS, depending on the tunnel manager
Design	Eurocode + national additions; analytical verification in some cases	Regulation-based, no calculations	More general; design and calculation-based	Comprehensive strategy including ventilation, evacuation, monitoring	Prescriptive code compliance (NFPA + UAE code)	Follows the calculation approach of Eurocode
Legal aspects	RE-ING, EABT 80/100 + EU directive	EU directive + Handbook N400/N500	EU directive + national extensions	Traficom and Väylävirasto agency requirements	UAE Fire & Life Safety Code + NFPA	European tunnel directive
Assessment	Analytical calculations	Not much ongoing assessment	Assessment via calculations	Not much ongoing assessment	Not much ongoing assessment	Eurocode methods
Testing	Small- and large-scale fire testing for material compliance	Full-scale testing (Runehamar) data is used for reference	Limited material testing, no field testing of existing tunnels	Mandatory third-party tests, valid for 10 yrs	No standard testing	Furnace testing is the only option for new construction. Mobile furnaces have been used for tunnel

(*Continued*)

Table 1. (*Continued*)

	Germany	Norway	Sweden	Finland	UAE	Belgium
						renovation, but no broader societal requirement.
Asset protection	In separate regulations	Focus on preventing ignition/spread, limited to protecting PE foam and structure	Regulation distinguishes between user and asset safety (NFPA)	Structural survival prioritized: no collapse, removable insulation	Asset protection typically incidental unless client-specific	No additional requirements beyond human safety

3.3 *National differences*

Just like some general common practices have been identified in the past section, this section focuses on national particularities that are interesting to highlight. Figure 1 highlights the different temperature-time curve that are mentioned in this section.

Germany separates fire protection strategies for new and existing tunnels. New tunnels require PP fibers in the concrete mix, while older tunnels are retrofitted with fire protection boards or plaster, provided the reinforcement has a small concrete cover, c_{nom} = 60 mm. The ZTV-ING fire curve is used (Schmidt et al. 2013, 2015). The Eurocode uses the standard temperature-time curve or the hydrocarbon fire curve for the fire exposure. In contrast to this, the German approach stipulates that after the temperature rise and a fully developed fire phase, the fire subsides and the temperature effect decreases again. Design for new tunnels follows the Eurocode methods. These measures are designed to ensure that the temperature in the reinforcement does not exceed 300 °C in the event of a fire. If an analytical verification is carried out in the case of cut-and-cover, it is done in accordance with the specifications of the Eurocode. A thickness-dependent, linear temperature gradient with full stiffness of the concrete cross-section is considered, and the load-bearing capacity for the combination of exceptional design situations must be verified according to DIN EN 1990 (CEN 2002). For new tunnels, the construction is accompanied with material fire testing. A small-scale fire test is required as a suitability test when complying with the regulations for polypropylene fiber concrete. Three test specimens with minimum dimensions of 85 cm × 70 cm ×30 cm are produced for each concrete mix that needs to be validated. If a mix is used that deviates from the regulations for PP fiber concrete, a fire test on two statically loaded large-scale test specimens with minimum dimensions of 340 cm × 150 cm × 35 cm is required, using the RABT-ZTV curve for roadway tunnels. During refurbishment, the products used are subjected to a suitability test in advance. To protect tunnel users, tunnels in Germany are equipped with fire alarm systems, portable fire extinguishers, a water supply for the fire department and, in individual cases, a fixed-fire-fighting system. These requirements are outlined in RE-ING Teil3 and EABT 80/100. These regulations set requirements concerning both organizational and technical aspects of user safety in tunnels, as well as specifications for structural fire protection. There are different regulations between the requirements for the structure (and asset protection) and the tunnel equipment for user safety (and human life protection).

Norwegian tunnels, particularly rock tunnels, incorporate an inner lining for water and frost protection anchored to the wall with rock bolts. The linings are made of either prefabricated concrete elements or sprayed concrete, both with wire mesh protecting the insulation materials. These are fire protected by adding 2 kg/m^3 of polypropylene microfibers (18 μm, 6 mm) to the concrete mix. The minimum cover thickness of the lining is 80 mm in a PP fiber concrete layer of typically 300 mm. In this perspective, Norwegian tunnels differ significantly from tunnels in the Netherlands, as the soil conditions are different. For tunnels where collapse with significant impact on the surroundings or flooding could occur due to a fire, stricter fire resistance (using the RWS curve for two hours and 300 MW design fire load instead of the HC curve) and fire protection panels are installed. The design lifetime for the permanent rock support is 100 years and 50 years for the inner tunnel lining (water-and-frost protection). The “self-rescue principle” is used for user safety, with escape routes spaced according to the European directive. The fire protection criterium in the rock tunnels (concrete) is to limit the temperature rise on the backside to 250 °C to ensure that the PE-foam is not ignited and cannot spread any harmful gases to the escaping people. This requirement also serves to limit the fire damage in general. Fire resistance is based on the Runehamar test data (Ingason et al. 2015) and in normal situation, no calculations or simulations are used to determine the fire resistance of the tunnel. New materials are tested per ISO 9705-1 (International Organization for Standardization 2016). Moreover, the fire safety of tunnels is outlined in Handbook N500 (Trafikksiden 2005).

Sweden uses different fire protection technical systems in its tunnels: fire detection, fire alarm, ventilation, fire suppression, evacuation (way-finding, emergency lighting, etc.), and structural protection. Structural design uses the HC curve (180 minutes, outlined in EN 1363-1 (CEN 2020) and EN 1363-2 (CEN 1999)), which differs from the 60 minutes HC curve used in Norway. It was stressed that one of the main advantages of the HC curve is that it can be represented with a single mathematical expression, whereas the other curves are defined piecewise. Fire resistance is checked using temperature limit calculations. National tunnel safety guidelines are extensions of EU frameworks and they also refer to NFPA 502, in which asset protection and safety of tunnel users are clearly distinguished. The temperature limit of 300 °C for the reinforcement that is stated in NFPA 520 is also used in Sweden. Sprayed concrete is a common measure to protect the tunnel structure in the Nordic countries. There are usually requirements on thickness of sprayed concrete for different classes of tunnels, such as in the Norwegian regulation N500. To determine the fire resistance of tunnels, testing and calculations are both acceptable. There is usually no specific calculation method specified in regulations. Common methods can be used with proper material properties. It is not common for contractors to do field testing of fire resistance of new construction and renovation tunnels. In general, the assessment of the fire resistance of tunnel structure relies more on design and calculations.

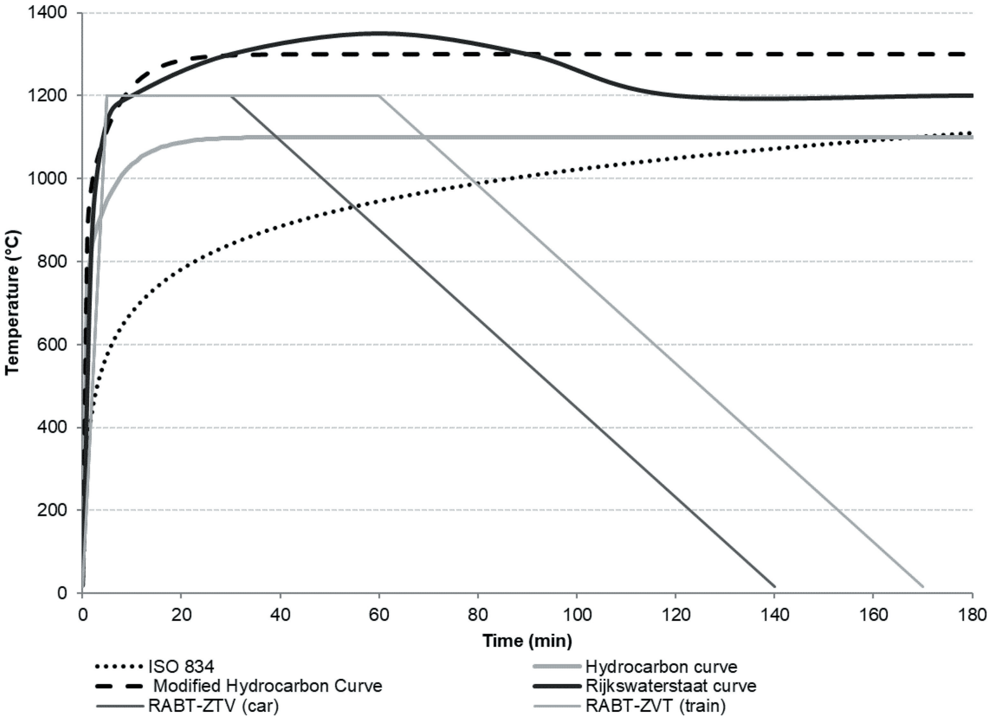

Figure 1. Temperature-time curves used in different countries.

Finland emphasizes integrated tunnel safety systems. Structural integrity is prioritized, requiring load-bearing components to survive fire without the need for replacement. Tunnel structures are designed to prevent continuous collapse during a fire. Fire protection materials must withstand temperatures up to 600°C and ensure no harmful smoke, gas, or liquid is released from insulation materials within 60 minutes of a fire. The fire protection materials be removable for inspection and must not adhere permanently to the concrete structure. Fire resistance must be demonstrated through standardized fire tests conducted by neutral third parties. The results are valid for ten years if the product remains unchanged. Ventilation is calibrated for smoke control, and evacuation lighting is placed at low levels for visibility in smoke. The Traficom and Väylävirasto agencies enforce national requirements based on tunnel length and usage for safety planning. In particular, the Finnish Transport and Communications Agency (Traficom) sets minimum safety requirements for tunnels longer than 100 meters on public roads and 500 meters on the TEN-T network. These regulations cover emergency exits, evacuation routes, emergency stations, evacuation lighting, and monitoring and communication systems. Specific guidelines for the structural and fire protection design of road tunnels are provided by the Finnish Transport Infrastructure Agency (Väylävirasto), ensuring that safety systems are integrated into the overall tunnel design. In specific projects like the Rantatunneli in Tampere (Lehtonen and Ylönen 2016), extensive planning and coordination ensured that fire safety measures were integrated into the tunnel's design and construction. This included the use of advanced fire protection materials, careful planning of evacuation routes, and thorough testing and calibration of ventilation and smoke control systems. These measures collectively ensure that tunnels in Finland are designed to withstand fires, facilitate safe evacuations, and support efficient emergency responses, thereby enhancing the overall safety of tunnel users.

In the UAE, tunnel fire safety is governed by the UAE Fire and Life Safety Code of Practice (Dubai Civil Defence 2017), which supplements NFPA standards 130 for railway tunnels and 502 for roadway tunnels. Structural fire protection focuses on compliance with prescriptive requirements, including forced fire-fighting systems (FFFS) for tunnels over 1 km, emergency detection, and power backup systems. The use of FFFS is an enhancement to the NFPA approach and supports the protection of the asset as well as protection of the attending fire team. The general requirements focus on means of egress for passengers and access for fire fighters, fire-fighting systems, emergency lighting and signage, structural fire rating for the tunnel linings and associated structures, fire compartmentation and separation, and smoke management systems. Tunnels over 90 m require CCTV and tunnels over 240 m require a fire detection system, a wet riser system, a TVS system, emergency lighting and backup power to emergency systems. Additional requirements specific to asset protection are not generally specified unless they are driven by the client. The RWS curve is applied for road tunnels, while the ISO 834 curve is used for railway tunnels. No tests are done on materials or existing tunnels and no specific calculation methods are identified for determining the fire resistance rating required for tunnels.

Belgium uses fire protection panels for tunnels and the ISO or RWS temperature-time curve. No additional requirements for asset protection are taken in addition to the requirements for human safety. The calculation approach from the Eurocode is used for the design of new tunnels and in principle also for the assessment of existing tunnels, and the governing legal framework is the European tunnel directive. In terms of testing methods, furnace testing is the only option for new construction. Mobile furnaces have been used for tunnel renovation, but no broader societal requirement is in place.

4 DISCUSSION

As can be seen from the overview of results in the previous sections, there are general consistencies in the international state-of-the-practice in tunnel fire safety. One of the main aspects is that all reviewed countries have approaches for human safety and for structural safety in terms of asset management, as expected. The use of PP fibers in concrete tunnel lining mixes is becoming more standard as evidenced from the answers. Different fire curves are used in different countries, but the differences between the fire curves tends to be limited. A main difference here can be observed with the German curves (Figure 1), which explicitly take the cooling stage into account.

Testing using a mobile furnace is not very widespread. In Germany, the focus is on material testing to check the performance of the concrete mixes with PP fibers. In Norway, experience with full-scale testing at the Runehamar site has informed the national practices. As all European countries have to comply with EU regulations, there are similarities in the basis aspects between the European countries, whereas the UAE leans more towards approaches as used in the United States.

The approach used in the Netherlands which centers around the use of nonlinear finite element modelling to assess the structural performance of tunnel sections subjected to fire is unique: none of the interviewees mentioned this approach as standard in their country. As such, the Dutch approach is state-of-the-art and may inform future assessment practices internationally.

5 SUMMARY AND CONCLUSIONS

This paper summarizes the findings of a state-of-the-practice review on tunnel fire safety in six countries: Sweden, Norway, Finland, Germany, Belgium, and the United Arab Emirates. The review was carried out using written interviews, using a set of five standard questions that focus on human life safety, national regulations, assessment practices (if any) including testing, and design requirements.

The main conclusions from this review are:

- The main requirements in Europe are aligned, as these are all based on the European directive 2004/54/EC on road tunnel safety.
- Most design requirements relate to limiting the temperature in the reinforcement layer during fire to a maximum value, which is in line with the Eurocode provisions.
- Human life safety is, as expected, the governing goal over asset management and protection. From this perspective, regulatory documents focus on the spacing between emergency routes, ventilation, sprinkler systems, and other systems for firefighting, tunnel control, and more.
- Assessment of the tunnel linings for their structural performance during a fire is not common practice. Moreover, assessment using nonlinear finite element analysis, the method which is pioneered in the Netherlands, is a novel approach.
- Testing using mobile ovens, or testing of specimens to check the performance of the concrete mix under fire, is used only in exceptional cases.

The state-of-the-practice that is compiled in this work lies a basis for the development of methodologies for the assessment of existing tunnel linings of land tunnels subjected to fire in the Netherlands.

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