Kim Smedegaard Andersen, M. Sc., Technical Deputy Director, Femern A/S, Kopenhagen (DK)
Wolfgang Baltzer, Prof. Dr.-Ing., Managing Director, BUNG GmbH, Heidelberg (D)

Fehmarnbelt Fixed Link: Safety Concepts and Strategies for a Combined Road and Railway Tunnel – Legal Aspects, Ventilation Concept, User Safety, Accessibility for Emergency Services, Evacuation Scenarios

The Fehmarn Belt Fixed Link connects Scandinavia to Central Europe by the shortest route. The tunnel will connect the Danish island of Lolland and the German island of Fehmarn with a twin-track railway and a four-lane motorway. The construction of the tunnel with a total length of approx. 18 km will be the world's longest immersed tunnel for combined railway and road traffic to date. The project is required to comply with two principal European sets of regulations for tunnel safety on roads and railways in the European transport network and the relevant national legislation of both countries. The tunnel is designed in such a way that dangerous goods can be transported safely in compliance with international and national laws and rules. Comprehensive safety documentation with extensive risk analyses for the operation of the tunnel is being prepared. The approaches of the safety concept, the safety equipment and the opportunities for evacuation are presented.

Feste Fehrmarnbeltquerung: Sicherheitskonzepte und -strategien für einen kombinierten Straßen- und Bahntunnel – Rechtliche Aspekte, Lüftungskonzept, Nutzersicherheit, Zugänglichkeit für Rettungsdienste, Entfluchtungsszenarien

Die Feste Fehrmarnbeltquerung verbindet Skandinavien und Mitteleuropa entlang der kürzesten Strecke. Der Tunnel wird die dänische Insel Lolland und die deutsche Insel Fehmarn über eine zweigleisige Bahnstrecke und eine vierspurige Autobahn miteinander verbinden. Mit einer Gesamtlänge von rund 18 km wird der Tunnelbau der weltweit bislang längste Absenktunnel für den kombinierten Schienen- und Straßenverkehr sein. Das Projekt muss zwei zentrale europäische Regelwerke für die Sicherheit von Straßen- und Schienentunneln im europäischen Transportnetz sowie die einschlägigen nationalen Rechtsvorschriften beider Länder erfüllen. Der Tunnel ist so geplant, dass Gefahrguttransporte unter Einhaltung der nationalen und internationalen Gesetze und Vorschriften sicher durchgeführt werden können. Es wird eine ausführliche Sicherheitsdokumentation mit umfangreichen Risikoanalysen ausgearbeitet. Im Artikel werden die Ansätze des Sicherheitskonzepts, die Sicherheitsausrüstung und die Evakuierungsmöglichkeiten beschrieben.

1 Introduction

Safety of tunnel users is decisively influenced by the interaction between tunnel geometry and construction, the operational and traffic engineering planning, tunnelling elements as well as traffic and emergency management planning.

In principle, the safety equipment should enable persons involved in an accident to get themselves to a safe area before the arrival of the emergency services.

2 Fixtures and technical equipment

2.1 Construction and geometry

The geometry of the Fehmarn Belt Tunnel in itself constitutes an important preventive safety element. The tunnel comprises four separate tubes, one for each direction of travel and type of traffic. There is also a fifth tube in the form of a gallery between the road tubes to ensure that technical equipment in the tunnel can be inspected and serviced without disrupting traffic and to improve the working environment.

The tunnel is designed and constructed in such a way that it is protected against flooding and damage from sinking ships, anchors, etc. It will also be forbidden to drop anchor in the tunnel area. The tunnel cross-section of the fixed link is illustrated in Figure 1.

Both the road and railway tunnel tubes are connected to emergency exits at least every 110 m. This distance is considerably shorter than the standard requirement of the European Union (EU), which specifies a distance of 500 m between emergency exits.

The road and railway tunnel tubes are also lined with fire protection cladding to resist fire at temperatures of up to 1,350 °C for 3 h.

Figure 1 Tunnel cross-section

The restrictive Dutch fire curve RWS was chosen as the baseline requirement for the Fehmarn Belt Tunnel. Most tunnels are designed to resist fires of 50 or 100 MW for a specific period of time, whereas the Fehmarn Belt Tunnel is designed to resist fires of up to as much as 200 MW for three hours. For comparison, a fire in a standard car can develop a power of approx. 5 MW, depending on the circumstances.

2.1.1 Road tunnel tubes

Road tunnel tubes come with special requirements. For the road tunnel tubes of the Fehrmarn Belt Fixed Link the following was decided (Figure 2):

- One-way traffic prevents frontal collision and dazzle.
- Both road tunnel tubes have emergency lanes. As a result, stationary or stranded vehicles will not impede traffic flow.
- In the southbound road tube, separate parking areas are provided at regular intervals outside the emergency lane for service vehicles (in the so-called "special elements") so that they do not disrupt normal traffic.
- Specially designed step barriers are installed along the walls to reduce the likelihood of consequential accidents if a car hits the barrier. In the event of a collision, the vehicle direction is straightened when it hits the step barrier without entering a spin or changing direction out of control.
- Profile road markings (rumble strips) with haptic and acoustic warning effects will be used.
- There is very little overall gradient in the road tubes, which reduces the risk of brakes and turbochargers overheating in larger vehicles such as trucks and coaches.

2.1.2 Railway tubes

For the railway tubes the following was decided (Figure 3):

- There are no switches or crossovers in the tunnel or directly before and after the portals at the tunnel entrances. This limits the risk of derailment.
- The emergency walkways on each side of the track in both railway tubes are designed to stabilize the train and prevent mechanical impact on the tunnel wall in the event of derailment.

In general, all critical structural parts are projected against the action of fire, so that the load-bearing capacity of the structure is maintained in the event of fire. The structures are also designed to resist pressure impacts from an explosion.

2.2 Safety and technical equipment

The tunnel is equipped with an extensive system of sensors and measuring points to monitor its technical equipment, environment, air quality, and traffic use. Installations relevant to safety (fire detection, emergency lighting, emergency communication and other systems) are protected against damage, heat or fire. Most of the equipment is also duplicated and redundant. Consequently, if equipment is out of operation due to service or failure, data will still be available from corresponding equipment nearby.

Loudspeakers are installed in the road tunnel for announcements in the tunnel in several languages or direct announcements from the tunnel control centre. A corresponding system exists for radio. An interrupt function, similar to the familiar system for traffic news on the radio, can be used to give information to road users in the tunnel.

Figure 2 Drawing of the southbound (outer) road tunnel tube with safety and technical equipment

Figure 3 Drawing of the inner rail tunnel tube with safety and technical equipment

As an additional option, the variable traffic signs in the tunnel can be used to give information in the form of text, pictograms or animations to road users and/or evacuated persons in the tunnel. The information on signs can be zoned and written information can be displayed in several different languages, for example in a cycle.

The tunnel is equipped throughout with a distributed aerial system that permits the use of both Danish and German national emergency services radio, mobile telephony and mobile broadband. The railway tunnel tubes are also equipped with coverage for Global System for Mobile Communication – Rail (GSM-R).

Access to emergency services radio is further secured with redundancy. This ensures that radio coverage is not lost throughout the tunnel if, for example, a fire destroys the special longitudinal aerial cable in one location.

A permanent fire suppression system will be installed in the road tubes. The fire suppression system is controlled from Fehmarn Belt Fixed Link Control Center (LCC) in the event of fire.

A permanent fire suppression system will have several advantages. Depending on the extent of a fire, the system will be able to either suppress the fire or completely extinguish it. The system can also prevent the fire from spreading to other vehicles nearby and thus also reduces the risk of extreme temperatures developing. As a result of the system's fire suppression properties, it can also limit smoke generation, which improves rescue opportunities for the road users and working conditions for the emergency services.

The road tunnel, portals, ramps and access to technical areas are equipped with an extensive video monitoring system and an automatic incident detection system. Fixed cameras are primarily used in the road tunnel, while remote-controlled cameras that can pan, tilt and zoom are primarily used outside the tunnel. The system is integrated with the alarm log so that an alarm in LCC can be accompanied by images from the location, where possible.

The tunnel is also equipped with installations for controlling and adapting the flow of road traffic. This is done by an Intelligent Traffic Management System (ITS). For the Fehmarn Belt Tunnel, this comprises variable traffic signs every 450 m inside the tunnel and on sign gantries at selected locations outside.

The railway traffic in the Fehmarn Belt tunnel is monitored and directed from the Banedanmark train traffic control centre in Copenhagen (TCC), which monitors and directs train traffic both inside and outside the tunnel and is in constant contact with the driver of each train and the corresponding train control centre in Germany.

2.3 Ventilation system

To maintain adequate air quality and the required flow conditions for normal and fire events, the ceiling of the road tubes contains niches with groups of jet fans. The central gallery and the railway tubes are also ventilated from the portals with jet fans. The ventilation system installed in all tunnel tubes will not be in use in normal operation.

The piston effect of vehicles and trains will press the air in the tunnel out and suck fresh air in, thus ensuring good air quality. Natural ventilation can be supplemented everywhere by mechanical ventilation from the tunnel ventilation system, for example if the road traffic flows slowly or comes to a standstill.

The ventilation system can be used to control the air flow in the tunnel in one direction or the other. If an incident with a fire is registered in a rail tube, the staff at LCC will immediately activate the ventilation system to produce positive pressure in the tubes not affected by the incident. This pressure difference prevents any smoke from the incident tube spreading to the evacuation route and to the safe area in the road tunnel tube.

In addition to limiting a fire, it is important to be able to control the generation and propagation of smoke or fumes. The ventilation system ensures that the smoke can be blown in the desired direction in a controlled manner, typically in the direction of travel, and that positive pressure can be created in the other tunnel tubes at the same time so that smoke does not enter the tubes unaffected by the accident.

The choice of the ventilation system was based on the EU Tunnel Directive [1], which recommends the arrangement of a mechanical ventilation system for tunnels over 1.000 m. In national transpositions such as the German RABT (*Richtlinien für die Ausstattung und den Betrieb von Straßentunneln*) [2], smoke extraction systems are additionally required in large tunnels with lengths such as in the present case.

In addition to the requirements of the EU Tunnel Directive, the decision of the ventilation system was made because the construction of a smoke extraction system could not take place without significant environmental impacts. This would degrade the environmental compatibility advantages for the selection of the immersed tunnel.

To increase the level of safety, it was for example decided to reduce the distances between emergency exits significantly and to ensure a high monitoring level in combination with information systems such as variable traffic signs.

3 Link Control Centre

The Link Control Centre (LCC) will be the primary centre for control and monitoring of the entire tunnel. LCC has operator functions to manage and monitor road traffic, toll plazas and maintenance. LCC is staffed 24 h/d. The monitoring ensures that irregularities in the tunnel are quickly detected and managed. Femern A/S operating staff takes care of both day-to-day control of road traffic and continuous monitoring of all technical installations.

The control room system will also feature an option to give outside parties such as the emergency services remote access to the system. Remote access can be used to display images from the video system, the current status of traffic flow (for example a sign plan), ventilation, environmental parameters, etc. The system will be available in a building at the portal on Fehmarn and from the emergency services control centres in both countries.

Figure 4 shows an example of a control centre on the basis of the Øresund Bridge.

4 Compliance with safety requirements

Compliance with external safety requirements for the railway and road tunnel can be summarized in four general pillars. Examples of safety-related measures are subsequently given under each pillar.

4.1 Prevention of accidents and incidents

The most important measure to ensure a high level of safety in a traffic tunnel is to prevent any accidents and incidents from happening at all. In connection with the Fehmarn Belt Tunnel, great efforts have been made to prevent and thus limit these

Figure 4 Example of a control centre (Øresund Bridge)

risks, partly through measures in the technical design and partly through requirements and procedures for monitoring, control and traffic management in the built tunnel. There are systems for control of road traffic flow and communication systems for internal use and contact with police and emergency services on both sides of the Fehmarn Belt. In the event of abnormal situations that may lead to an accident, e. g. stationary vehicles or people in the road, the system immediately issues an alarm so that the operators can immediately react and take the necessary measures. There will be procedures for the management of different incidents, and there will always be rapid intervention when an incident could lead to an accident.

Femern A/S service staff will continuously patrol the road tunnel in cars. The staffs are trained to provide first aid and roadside assistance and to perform basic firefighting in connection with incidents in the road tunnel tubes. They can also support the operators in the LCC by inspecting technical equipment in the tunnel.

The monitoring systems in the tunnel will automatically register abnormal situations, e. g. if traffic is moving more slowly, if a vehicle or train is stationary, or if there is a fire or an increased level of air pollution. Other monitoring systems located outside the tunnel register over-height vehicles and for the railway traffic, overheated axle bearings and wheels are detected before a train enters the railway tubes.

A safety distance of one block length is normally applied in the Danish railway network. For the railway tunnel, the safety distance has been increased to two block lengths, equivalent to a minimum distance of 3.6 km between trains, as an additional safety measure included in the safety concept.

Exemplary illustrations of the tunnel safety equipment and equipment for prevention of incidents are shown in Figure 5.

4.2 Limitation of accidents and incidents

The Fehmarn Belt Tunnel has been fundamentally designed to minimize the risk of accidents occurring and to minimize their consequences if they do occur.

If, despite the preventive measures taken, an incident or accident does occur, the tunnel has a number of measures to prevent the incident or accident from spreading or endangering other tunnel users. The Fehmarn Belt Tunnel will be equipped with a number of technical facilities and systems designed to limit the consequences of such events (Figure 6).

The fundamental measure in this context is separate tunnel tubes for each type of traffic and direction of travel. Consequently, an incident will generally only affect one of the four traffic tubes, after which the other tunnel tubes can function as a safe area for evacuated persons and as an access route for the emergency services.

4.3 Escape to safe areas

Femern A/S has optimized the tunnel design to make escape (self-rescue) simple, fast and efficient. Road users, passengers and train crew in the Fehmarn Belt Tunnel can easily reach a safe area in the event of an accident until the emergency services arrive and provide assistance.

The most important factor affecting fast escape is the distance to the nearest emergency exit. The emergency exits that provide access between the tunnel tubes will be located at a maximum interval of approx. 110 m, which is much shorter than authorities as well as standards normally require.

4.3.1 Road tunnel

In the road tunnel tubes, road users will be given information by signage, variable information boards, loudspeakers and radio. Should a serious situation arise in one tunnel tube, everyone who is affected by the incident and is prevented from driving out of the tunnel themselves will be requested to leave their vehicle and evacuate via the nearest emergency exit. The emergency exits lead to a safe area in the adjacent road tunnel tube (Figure 7), where they can remain safely until the emergency services arrive.

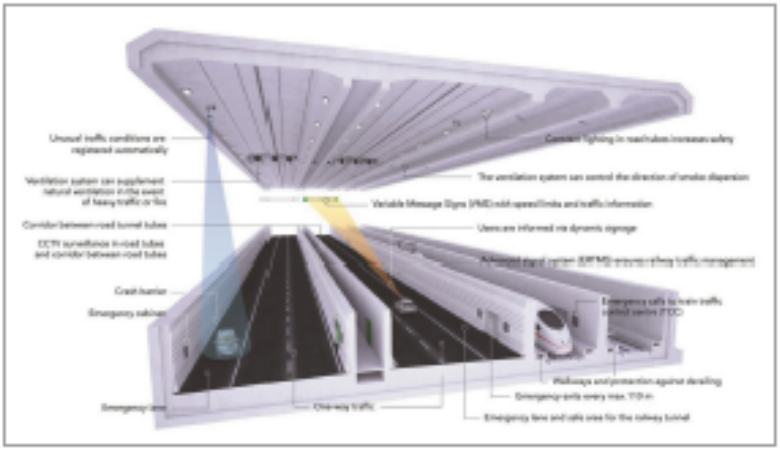

Figure 5 Tunnel safety equipment and equipment for prevention of incidents

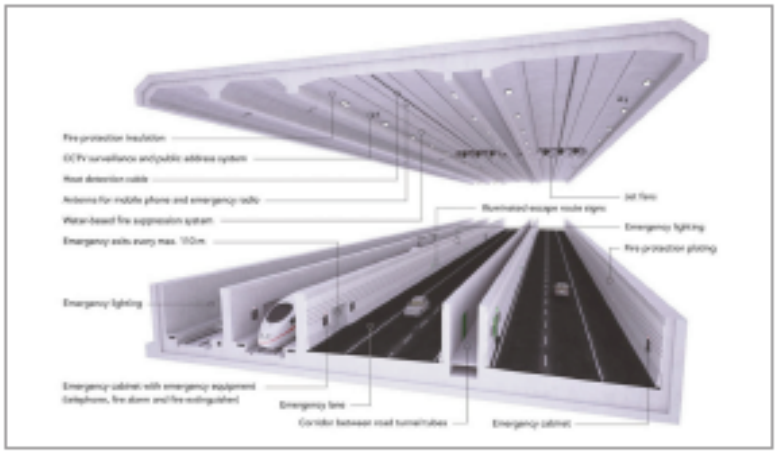

Figure 6 Tunnel installations to limit the consequences of critical incidents

4.3.2 Railway tunnel

In the event of a fire in a train in the tunnel, the passengers will be asked to seek safety in the train carriages not affected by the fire. The train will continue travelling out of the tunnel directly to the so-called firefighting point just outside the tunnel on open land. From this point, the passengers can safely leave the train using evacuation paths that lead to a rescue site in the open land.

If a fire occurs in a train and cannot be suppressed with the fire suppression equipment carried by the train, and the train is unable to leave the tunnel, it will be necessary to evacuate the train. The train crew is trained for such situations and will immediately initiate evacuation by instructing and guiding the passengers to follow the signage of the escape route, and to go to the safe area in the emergency lane in the inner road tunnel tube via the emergency walkways and emergency exits (Figure 8).

4.4 Deployment of the emergency services

In the event of an incident in the Fehmarn Belt Tunnel, the emergency services have to be able to reach the area as quickly as possible. Short response times and well-established cooperation procedures with clear division of tasks and responsibilities are essential in such critical situations.

The Danish and German emergency authorities have the ultimate responsibility for approving the safety concept for the construction and operation phases.

As is the case for all other road and railway tunnel structures, there will be continuous evaluation and optimization of all safety-related matters in all phases of the project.

The authorities will perform regular inspections in the operation phase and there will be continuous training activities and test exercises to ensure that the emergency services personnel can be deployed in the best possible manner in the event of incidents and accidents.

5 Overall safety assessment

The design and dimensioning of the tunnel are based on an extensive Operational Risk Analysis (ORA) [3]. The risk calculations in the ORA include the following scenarios with their death tolls, traffic interruptions and repair costs:

- Vehicle collisions,
- Collision of vehicles with persons/objects,
- Vehicle fires,
- Fires caused by hazardous substances,
- Fires in slow-moving traffic,
- Transformer area fires,
- Explosion,
- Release of poisonous substances,
- Flooding,

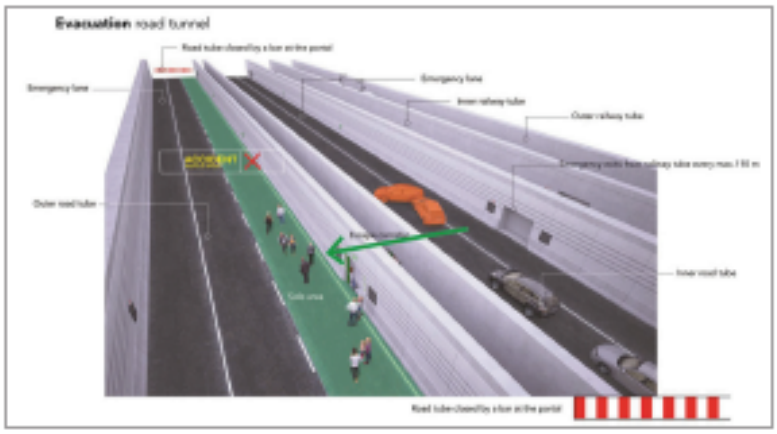

Figure 7 Escape concept for the road tunnel

Figure 8 Escape concept for the railway tunnel to the inner road tunnel tube

- Casting of anchors,
- Sunken ship,
- Ship running aground.

Based on data from Danish accident statistics, the ORA calculates that over 99 % of the risk to users of the road link in the Fehmarn Belt Tunnel will arise as a result of an accident without involvement of fire.

Overall, the results of ORA calculations show that the safety level of the Fehmarn Belt Tunnel is very high and that the tunnel will be at least as safe to use as similar stretches of road or railway in the open countryside in Denmark.

References

[1] European Tunnel Directive 2004/54/EC of the European Parliament and of the Council of 29. April 2004 on minimum safety requirements for tunnels in the Trans-European Road Network

[2] Forschungsgesellschaft für Straßen- und Verkehrswesen (FGSV): Richtlinien für die Ausstattung und den Betrieb von Straßentunneln – RABT 2006; Köln, 2006

[3] *Pedersen, J.; Sørensen, F.; Sunde, E.; Glibbery, K.*: Fehmarn Belt Fixed Link – Tunnel Design Services; Operational Risk Analysis, 8. Revision; Nr. RAT 64233-002, ATR RAT75-KSA-569; 03.06.2016