DEVELOPMENT OF CONCEPTUAL RISK AND SAFETY STRATEGIES FOR THE FEHMARNBELT FIXED LINK TUNNEL

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ABSTRACT

The design of tunnels presents interesting and exciting safety and ventilation challenges. For the proposed world's longest combined road and rail sub-sea tunnel the challenges are even greater. This paper presents a case study of the proposed Fehmarnbelt Fixed Link tunnel and focuses on the risk and safety strategies and the derived impact on design and installation required to keep the tunnel operational and protect users and emergency responders in the event of an incident. The proposed tunnel stretches to 18km long, with a vast proportion of these 18km under water, and at its deepest point the Fehmarnbelt Fixed Link tunnel is 40m below sea level. The overall risk and safety philosophy is presented together with the risk acceptance criteria. The implications of applying the safety philosophy and meeting the acceptance criteria on the design are discussed and these include presentation of possible ventilation strategies including whether provision should be made for construction of a ventilation “island” at the mid-point of the tunnel. At critical locations, and for occurrence of critical events, it may be necessary to introduce risk reducing measures in order to maintain the risk at an acceptable level. In the Fehmarnbelt Fixed Link tunnel these measures are both in the form of physical installations and also operational rules and procedures. Examples are given on such measures including the installation of a suppression system. The paper debates the advantages and disadvantages of different suppression systems and considers how these can have a substantial impact on fire life safety and property protection.

1. INTRODUCTION

The Fehmarnbelt Fixed Link is a proposed permanent and direct connection between Scandinavia and continental Europe. The Fehmarnbelt Fixed Link will specifically connect Rødbyhavn in Denmark to Puttgarten in Germany and is expected to bring economic benefits to the entire region around the Fehmarnbelt.

The opening of the Fehmarnbelt Fixed Link will significantly reduce the travel time between continental Europe and Scandinavia. Instead of a 45-minute transit with the ferry, the trip by car over the Fehmarnbelt will only require about a quarter of an hour in future. Moreover, the time spent waiting for ferries and embarking and disembarking will also be eliminated.

With the opening of the Fehmarnbelt Fixed Link a good hour's travel time will be saved on the rail trip from Hamburg to Copenhagen. Rail freight traffic, which must currently be routed through Jutland and the Great Belt, will be routed directly through the Fehmarnbelt thanks to the Fehmarnbelt Fixed Link, thus saving about 160 kilometres on the Hamburg to Copenhagen stretch. This will create a strong transport corridor between the Øresund region and Hamburg.

At the time of writing a number of technical solutions are currently being investigated for the Fehmarnbelt Fixed Link in accordance with the treaty between Germany and Denmark governing the project. The two leading technical solutions are a cable-stayed bridge and an immersed tunnel. Both options present engineering challenges due to the scale of the project. This paper focuses on the tunnel option and specifically the risk and safety strategies and their derived impact on the design and installation.
2. FEHMARNBELT FIXED LINK TUNNEL DESCRIPTION

The proposed Fehmarnbelt Fixed Link tunnel if constructed will be the longest, combined road and rail immersed tunnel in the world. The tunnel will stretch 18km from Denmark to Germany and at its deepest point will be approximately 40m below sea level. The conceptual design for the tunnel contains four independent tubes and a central gallery as shown in Figure 1 allowing for uni-directional traffic in both directions for road and rail. The road tubes comprise two traffic lanes in addition to an emergency lane running continuously along the length of the tunnel. Each rail tube contains a single rail line subdivided into a number of block sections and there are no cross-overs within the tunnel.

![Figure 1: Fehmarnbelt Fixed Link tunnel cross section](image)

3. SAFETY AND RISK STRATEGY APPROACH

The overall safety goals for Fehmarnbelt Fixed Link are to provide a design that has sufficient and appropriate facilities that allow all incidents to be managed in a manner that provides adequate safety in terms of:

- Life safety to road users.
- Life safety to rail users, including train crew
- Life safety to third parties not directly involved in using the Fehmarnbelt Fixed Link
- Operational interruption, that might cause the use of other less safe alternative routes or forms of transport
- Life safety to maintenance and inspection personnel
- Life safety of emergency services personnel

In order to meet these goals the safety strategy adopts an integrated, holistic, risk based approach which links design, maintenance and operations. The designs for the construction of the tunnels and all the road and rail installations in addition to the portals and ramps, and all associated facilities, have been based on the following priorities for safety:

- The primary objective is to provide a design that will prevent accidents and other emergency situations occurring (prevention)
- The secondary objective of the design is to minimize the frequency and consequences of accidents and emergency situations if they cannot be prevented, i.e. to control incidents and provide facilities for self-rescue (control, self-rescue)
- The tertiary objective is to provide sufficient safety systems and management procedures to ensure that accidents and emergency situations can be handled with adequate safety by the rescue services (response).
In addition to the safety goals, there are societal and economic objectives which include:

- Asset protection
- Continuity of operations
- Minimization of monetary losses
- Protection of the environment

4. HAZARD ANALYSIS

The overall safety level for a tunnel is in part a function of the traffic volumes which statistically govern the likelihood of an accident occurring in addition to impacting on the consequences as a result of the number of people affected.

For the road tunnels, the design speed is 110 km/h, the operational speed is 90 km/h and the predictive design values for the traffic volumes at the opening year of 2018, the year 2030 and also for the year 2038 are shown in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>2018</th>
<th>2030</th>
<th>2038</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cars</td>
<td>8156</td>
<td>9822</td>
<td>11117</td>
</tr>
<tr>
<td>Trucks</td>
<td>1354</td>
<td>1934</td>
<td>2454</td>
</tr>
<tr>
<td>Buses</td>
<td>134</td>
<td>156</td>
<td>173</td>
</tr>
<tr>
<td>Total</td>
<td>9644</td>
<td>11912</td>
<td>13744</td>
</tr>
</tbody>
</table>

The calculated full lane capacity for the Fehmarnbelt Fixed Link is 1800 PCU’s (Person Car Units)/lane/h, which means the traffic volumes for 2030 are much lower than for many other road tunnels and particular urban tunnels with high traffic volumes during morning and evening rush hours. Statistically this should mean less accidents and an improved level of safety for tunnels which, in essence, are rural tunnels with low traffic volumes.

For the rail tunnels, the maximum conceptual design speed is 160 km/h with provision for future operations at 200 km/h in addition to the 250 km/h being investigated. The design values for rail traffic volumes (no. of trains per day) are set out in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>2018</th>
<th>2030</th>
<th>2038</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger</td>
<td>40</td>
<td>41</td>
<td>42</td>
</tr>
<tr>
<td>Freight</td>
<td>47</td>
<td>70</td>
<td>91</td>
</tr>
<tr>
<td>Total</td>
<td>87</td>
<td>111</td>
<td>133</td>
</tr>
</tbody>
</table>

In accordance with current practice for most railway tunnels a train on fire should make all attempts to leave the tunnel and this practice will be initiated across the Fehmarnbelt Fixed Link. The block sections for the railway and the timetabling is not yet concluded. However in the opening year the low rail traffic volumes indicate that it is unlikely that more than one train will be present in the tunnel at any one time. Of course for future growth and flexibility it is expected that the tunnel will incorporate a number of block sections in order to not reduce capacity and therefore the possibility of multiple trains within the tunnel must be considered.

For both road and rail tunnels based on past experiences of tunnel fires and the predictive traffic volumes and composition it is possible to identify relevant fire hazards. For the road
tunnel the most probable fire hazards will arise from the vehicles using the tunnel, the materials from which they are manufactured and the materials they are transporting. Another potential source of fire hazard comes from failures of equipment in the road tunnels or any plant and equipment room which, although fire separated from the tunnel, may still impact on the operation.

For the rail tunnel the hazards are in general similar although they will be heavily dependent on whether the rolling stock is for passengers or freight and whether they are pulled by electric or diesel engines.

In both road and rail there is the potential for dangerous goods to be transported across the Fehmarnbelt Fixed Link and of course the hazards presented by the transportation of such goods should be considered. Typically for large infrastructure projects a dangerous goods policy will be developed which places restrictions on the time during which dangerous goods may be transported, in order to avoid peak hours, and the quantities of dangerous goods that may be transported in one shipment, to minimize consequences in the event of an incident.

For the Fehmarnbelt Fixed Link the policy relating to dangerous goods shall be driven during design stage by the operational risk assessment (ORA). Initially the ORA has been developed conservatively on the basis of no restriction on dangerous goods transportation either with respect to time or quantity. The relative impact of placing no restriction on dangerous goods shall be assessed in the context of the overall risk level and appropriate design decision shall be made on this basis.

In practice it is expected that the ORA will identify that the contribution to the risk level as a result of dangerous goods will be very small predominantly as a result of the low frequency of such incidents. However, for a number of reasons, this does not necessarily dictate that when the Fehmarnbelt Fixed Link is operational that there will not be restriction on dangerous goods. For example, within the ORA the probability of events involving dangerous goods is calculated based on limited statistical data and therefore must be addressed within the error bounds of the calculation.

Furthermore, the consequences of an incident involving dangerous goods can be very severe involving potentially significant loss of life. Therefore, regardless of the mathematical risk it may be determined as a result of societal and political issues, and consideration of the concept of ‘as low as reasonably practicable’, that a dangerous goods policy should be implemented. This will likely be based on international guidance and similar policies governing, for example, the Øresund Link between Denmark and Sweden.

It should also be taken into account what the alternative solution may be should dangerous goods be restricted across the Fehmarnbelt Fixed Link. As an extreme example, by restricting dangerous goods, the alternative route may pass by crowded public areas, hospitals, shopping districts or schools. The total risk in this instance, and the consequences as a result of an incident, may be significantly more.

The hazards associated with dangerous goods, as previously discussed, have a relatively low impact on the overall level of safety and more typically regular road accidents and fire events impact more heavily. In dealing with fire events there are a number of safety features and installations which are incorporated into the tunnel in order to meet the safety goals of prevention, self rescue, control and emergency response. The remainder of this paper concentrates on two installations; namely the road tunnel ventilation system and suppression system.
5. ROAD TUNNEL VENTILATION

Generally when developing a tunnel ventilation system a review of the international standards and guidances is recommended. However, it should be noted that most international standards and guidance documents are typically generic and not tailored to specific tunnel scenarios and being generic they must cater for a wide range of alternative designs. Therefore it is often appropriate to introduce some level of performance based design to ensure that a suitable system is provided. This approach then considers emergency ventilation in context and within a fully integrated safety strategy for the complete tunnel.

The majority of international standards and guidance documents would recommend that a mechanical ventilation system (ranging from a non-ducted longitudinal ventilation system, to a fully ducted transverse ventilation system) should be incorporated for a road tunnel of an equivalent length to the Fehmarnbelt Fixed Link. The type of system would mainly depend on the type of tunnel (uni-directional or bi-directional) and the expected traffic capacity (i.e. non-congested or congested traffic).

The traffic data for Fehmarnbelt Fixed Link indicates a relatively low number of vehicles, and there will be a dedicated, intelligent traffic management system. It is therefore expected that under normal operation, congestion inside the tunnel will not occur and can be prevented, even during peak hours. On this basis the use of a longitudinal ventilation system for smoke control is proposed in the conceptual design.

A longitudinal ventilation system is designed to create airflow within the tunnel and push smoke in the direction of the moving traffic flow. This airflow will need to provide a minimum “critical” velocity in case of fire to ensure that the smoke is pushed downwind, and cannot “backlayer” moving upstream over vehicles stopped behind an incident.

In the event of a fire in the road tunnel it is assumed that the traffic in front of the fire will continue to drive through the tunnel and will be travelling faster than the flowing smoke layer. The traffic behind the fire will stop and the occupants of these vehicles will commence the evacuation upstream of the fire. The occupants will be notified via the dynamic signage and the alarm system to evacuate into the adjacent road tube, via into the central gallery until the non-incident tube is clear, through appropriately spaced cross passages. Cross passages into the adjacent running tube will be spaced at intervals of 100m, significantly less than recommendations in international guidance, providing an increased level of life safety.

The proposed Fehmarnbelt Fixed Link tunnel is an immersed tube structure and therefore the use of a ducted ventilation system significantly increases the cross sectional area and perhaps necessitates the need for a ventilation island in the middle of the Fehmarnbelt. Preliminary concept calculation have indicated that the required ventilation duct would be of the order of 20m² per road tube in order to overcome the pressure differences associated with ducting hot gases up to a distance of 9km. This duct area could be reduced by the introduction of a ventilation island in the middle of the tunnel thereby only requiring hot gases to be ducted a maximum of 4.5km. This would have the benefit of providing additional space for ventilation fan stations. However, introducing an island in the Femern Belt would have the recognisable drawback of increasing the risk for ship collisions with this island in the Strait.

A ducted system however has a number of other implications for the tunnel design over and above the longitudinal system. These include a reduced reliability and an increased risk to life safety due to more single points of failure, e.g. extract fan failure or fire damper failure, both of which have the potential to impact on the effectiveness system wide. Furthermore there are increased maintenance requirements, an increased construction time and increased costs.
Typically in tunnel fires the critical areas for life safety are within the vicinity of the fire and of the order of say a few hundred metres away, particularly downstream. At that distance away from the fire, visibility is likely to be lost however smoke temperatures will be reduced (especially with the inclusion of a suppression system) and toxicity often reduced below untenable conditions as a result of dilution. Within the Fehmarnbelt Fixed Link tunnel, exits are proposed every 100m which significantly improves the capability for self rescue. Any tunnel ventilation system with extract locations in excess of say 200m to 300m in essence result in a longitudinal system for occupants evacuating within the vicinity of the fire in respect to life safety. Thus in principle, tunnel length is not a risk factor.

Although technically a longitudinal system is feasible it represents a fairly significant departure from a standard code based approach for a tunnel of this length and is certainly not known to have a precedent with regard to length. Most tunnels over a few kilometres either have a transverse or semi-transverse ventilation system which often arises as a result of congested traffic being expected to occur on a regular basis.

Although there are no tunnels as long as the proposed Fehmarnbelt Fixed Link designed with a purely longitudinal system there is precedent for significant road tunnels using nonducted longitudinal ventilation system. The Westerscheldetunnel in the Netherlands is 6.6km long and is provided with a longitudinal system. The tunnel traffic load in 2008 was 16,600 vehicles per day in both directions combined in comparison to the Fehmarnbelt Fixed Link design volume of approximately 12,000 vehicles per day in both directions combined. Furthermore the Westerscheldetunnel has a greater spacing between cross passages of 250m, is not provided with emergency lanes and has no suppression system. Qualitatively the level of life safety in the Fehmarnbelt Fixed Link can therefore be considered greater than in Westerscheldetunnel.

Other examples include both the Øresund Link (4.0km) and the Cross City Tunnel in Sydney, Australia (2.2km). Both tunnels have a high traffic volume, a uni-directional pair of tunnels and a longitudinal ventilation system. The Cross City Tunnel has a deluge suppression system installed while the Øresund Link does not.

As the primary concern for life safety is within the vicinity of the fire, venting the smoke 2.2 km (Cross City Tunnel, Sydney), 4.0 km (Øresund Link), 6.6 km (Westerscheldetunnel, The Netherlands) or even 18 km (Fehmarnbelt Fixed Link) all represent a similar level of risk. Therefore, although there is no precedent for a longitudinal system in a tunnel of this length the principle of longitudinal ventilation is employed in a number of tunnels around the world.

6. SUPPRESSION

Until recently the general guidance with regard to suppression systems is that they should not be installed in tunnels, with many regulatory authorities citing a number of potential hazards that might be caused by such systems including concerns with flammable liquid fires and steam generation. These reasons have previously been included in guidance in a number of tunnel documents from organisations such as NFPA and PIARC and most of these claims have arisen in Europe and North America.

Despite these recommendations suppression systems have for many years been installed in a number of longer road tunnels in Japan and, during the last 20 years, in all road tunnels in Australia. Recently, following the major fires in the Mont Blanc, Tauern, Gotthard and Frejus tunnels in Europe, PIARC and the NFPA have both revised their recommendations concerning suppression systems to much more positive consideration, but clearly state that such systems should only be installed as a part of an overall safety approach.
The authors of this paper have conducted a study into suppression systems installed worldwide. The number of suppression systems (both water mist and deluge) installed in selected countries worldwide are shown in Figure 2 and although the study does not profess to cover all tunnels the trend clearly shows that European countries have significantly less experience of tunnel suppression systems.

![Figure 2: Number of road tunnels installed with a suppression system (water mist or deluge) per country](image)

The trend for railway tunnels is less defined as there are limited known rail tunnels internationally incorporating a suppression system. This may be for a number of reasons including that rail fires are less frequent than road tunnel fires and, that in the event of a fire, trains are designed to drive out of the tunnel and thereby further reduce the incidents of rolling stock fires in tunnels. On this basis the cost/benefit of the suppression system may not be perceived to be significant enough to warrant the initial investment.

In both road and rail tunnels with suppression installed the immediate effect will be to limit the fire size and control the fire growth. Fires occurring in vehicles may sometimes not be directly affected by a suppression system if the fire is shielded by the vehicle. Therefore in these instances, the suppression system is controlling the fire rather than suppressing or extinguishing a fire. By controlling the fire, the development of a catastrophic fire can be avoided and the tunnel structure protected, minimizing damage and repair time. If the fire is controlled, the chances of a successful evacuation will increase whilst aiding the emergency services ability to control the situation.

By minimising the frequency of development of a catastrophic fire the risk to life safety can be drastically reduced and furthermore the downtime as a result of a fire can be minimised. In the context of the ORA for the Fehmarnbelt Fixed Link tunnel these two aspects assist in ensuring that the risk level to tunnel users, operational revenue and reputation is as low as reasonably practicable. For this reason a deluge suppression system is to be installed in both the road and rail tubes of the Fehmarnbelt Fixed Link. The decision to install a suppression system in the road tunnel can be justified financially through a cost/benefit analysis. In
isolation the cost/benefit analysis for a suppression system in the rail tunnel may not be as credible. However, for the Fehmarnbelt Fixed Link, where the installation infrastructure is in place in the road tunnel, the decision is simplified. This suppression system is considered to represent the longest tunnel suppression system in the world and continues the general trend towards suppression for rail networks either on board rolling stock or in tunnels.

7. SUMMARY

The Fehmarnbelt Fixed Link is a significant infrastructure project proposed to connect Scandinavia with continental Europe. At the time of writing a number of technical solutions are being explored including a cable-stayed bridge and an immersed tunnel. All of the solutions have challenges due to the scale of the link. However for the tunnel it is expected that the safety strategies and the overall risk level when using the tunnel will play a significant role in the success or failure of the solution. To this extent, the safety and risk strategies have been developed as integrated, holistic, performance based strategies to ensure that the specific features of the tunnel are captured.

This paper aims to present a brief case study of the conceptual design for the Fehmarnbelt Fixed Link tunnel solution. Some of the anticipated hazards have been discussed particularly in relation to dangerous goods and key aspects of the design specifically addressing fire hazards have been explored. The length of the tunnel is unprecedented however the principle of using a longitudinal ventilation system is tried and tested in practice as a proven technology and the functionality is independent of tunnel length. The ventilation system is part of the overall safety and risk management strategy which includes a suppression system in the road and rail tunnels, a continuous emergency lane for both road tubes and significantly shorter exit spacings than recommended in many international standards, regulations and guidance documents. The complete safety strategy is considered to present a considerable investment in safety for the Fehmarnbelt Fixed Link tunnel solution and will be subject to scrutiny by authorities in both Denmark and Germany over the coming months and years.