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# Long Undersea Tunnels: Recognizing and Overcoming the Logistics of Operation and Construction

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ABSTRACT

Long undersea tunnels, and particularly those that are built for transportation purposes, are not commonplace infrastructure. Although their planning and construction take a considerable amount of time, they form important fixed links once in operation. The fact that these tunnels are located under the sea generally involves unique challenges including complex issues with construction and operations, which relate to the lack of intermediate access points along the final route of the tunnel. Similar issues are associated with long under-land tunnels, such as those under mountain ranges such as the Alps. This paper identifies the key issues related to the design and construction of such tunnels, and suggests a potential solution using proven technology from another engineering discipline.

## 1. Background to the issues

Compared with their under-land counterparts, the construction and operations of undersea tunnels that are used for transportation purposes have their own unique challenges and constraints—particularly for the longer tunnels. The Channel Tunnel between the UK and France is the longest undersea crossing in the world and provides a link between the high-speed rail network in the UK and that of France and the mainland of Europe. The overall tunnel is approximately 50 km in length, with the undersea portion being 38 km long. In Japan, the Seikan Tunnel has a total length of 53.8 km, with the undersea portion being 23.3 km. The layout of the overall Channel Tunnel is shown in Fig. 1.

For the trans-alpine tunnels that have been built or are under construction, the fact that the tunnel is located under a mountainous region similarly limits of the positioning intermediate access points, such as shafts and adits, along the length of the route. The Gotthard Base Tunnel of the AlpTransit project between Italy and Switzerland has a total length of 57 km.

Other long transportation tunnels are being considered around the world, both undersea and under land, including the Fehmarn Belt Tunnel between Germany and Denmark (18 km undersea), the Lyon–Turin Tunnel between France and Italy (57 km under land), Jeju Undersea Tunnel in Korea (79 km undersea), Bohai Strait Tunnel in China (up to 110 km undersea) and, potentially, Taiwan Strait Tunnel in China (150 km undersea).

As described in the following sections, it would be advantageous for these fixed links to have intermediate access points along the length of the tunnel for both construction and operational purposes. Such access points would facilitate multiple facets of the construction of the tunnel, and would provide emergency egress points for the evacuation of passengers in the event of an incident. However, such facilities would be difficult to provide for an undersea tunnel, unless it were to pass below a series of islands, whether natural or man-made, which is unlikely to be the case in deep-sea conditions.

## 2. Construction logistics

When considering the longest tunnels mentioned above as examples—that is, the Channel Tunnel, Seikan Tunnel, and Gotthard Base Tunnel—it is recognized that all three projects were built using multiple tunnel drives. Although the overall length of the Channel Tunnel is approximately 50 km in length, the longest tunnel drive was 22 km. This was the drive that extended from the UK shoreline to connect with the French tunnel boring machine (TBM) drives at a meeting point under the English Channel. The shorter drives extended from the shorelines back to the portals at each terminal.

For the Gotthard Base Tunnel, a number of adits and shafts were formed along the length of the route in order to subdivide

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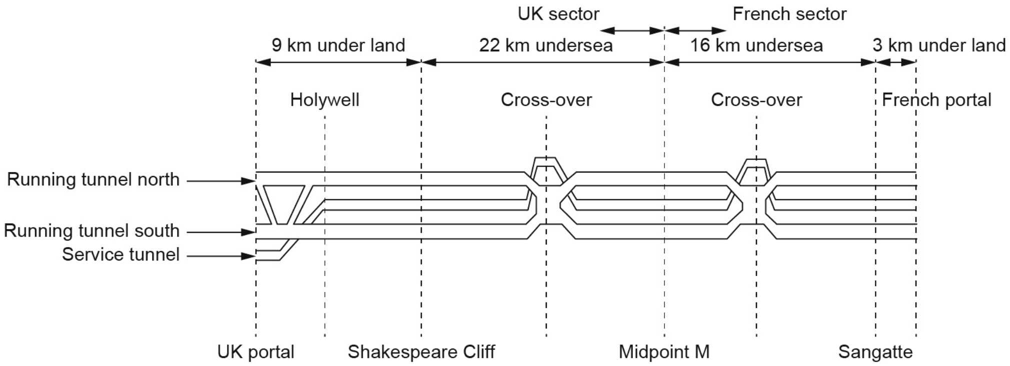


**Fig. 1.** Layout of the Channel Tunnel between the UK and France.

the overall tunnel into a number of sections and facilitate multiple drives. The schematic layout of the Gotthard Base Tunnel is shown in Fig. 2. Indeed, the deepest of these adits was 800 m, which is a substantially deep excavation; however, this meant that the longest tunnel drive was 14 km in length. It is therefore clear that the constructors of these schemes considered that the provision of intermediate construction points along the length of the tunnel would be beneficial to both cost and program.

### 2.1. Tunnel ventilation

Whether a tunnel is excavated by drill and blast or by TBM, there will be a need to ventilate the tunnel face with fresh air throughout the construction phase. This ventilation is provided by ducting, which generally runs along the soffit of the constructed tunnel. For longer tunnels, chillers may be needed at points along the length of the ducting to ensure cool air at the tunnel face for the health of the workforce. Although delivered at the tunnel face, the ventilation actually provides clean air for the entire length of the excavated tunnel. Clearly, the longer the tunnel drive is, the more air must be delivered, and the greater the size of the duct will be. For an extremely long tunnel, it is possible that the construction requirements—that is, the size of the duct and cooling equipment—could actually determine the diameter of the constructed tunnel. This would not be a cost-effective solution. It is therefore beneficial to divide the overall tunnel into a number of shorter sections.

### 2.2. Flexibility with converging drives

The use of multiple staging areas for construction, and tunnels driven in both directions from these locations, means that a certain amount of flexibility and assurance is provided for the construction logistics. If one TBM were to experience a breakdown, then the machine coming in the opposite direction could complete the overall tunnel. This would not be possible with a single heading, which relies on a single TBM completing the full length of tunneling. Again, multiple drives are advantageous in ensuring completion of the work within a reasonable timescale.

### 2.3. Access to the tunnel face

Access to the tunnel face for both the delivery of materials and the workforce is generally provided by locomotives that run along the completed tunnel. For the safety of the workers within the tunnel, the speed of these delivery trains is around 20–25 $\text{km}\cdot\text{h}^{-1}$. Considering that the longest drive of the Channel Tunnel was 22 km, it is clear that as the TBM neared the end of its drive, the TBM crew would spend an hour at the start of each shift (and a similar time at the end) just traveling to their workplace. Longer drives would take even more time. Labor costs could be a major issue for very long tunnels, if 20% of the working day is spent traveling to and from the tunnel face. Thus, the logic of dividing the tunnel into reasonable lengths, as demonstrated in the Gotthard Base Tunnel, can be seen as benefiting the overall cost.

## 3. Operational issues

Among the issues that need to be considered for the operational logistics of the completed tunnel are: air quality/ventilation, aerodynamics (particularly for a railway tunnel), temperature, drainage, and fire and life safety. In addressing these items, reference is given to the Channel Tunnel between the UK and France, including the studies that were conducted during the design of that project.

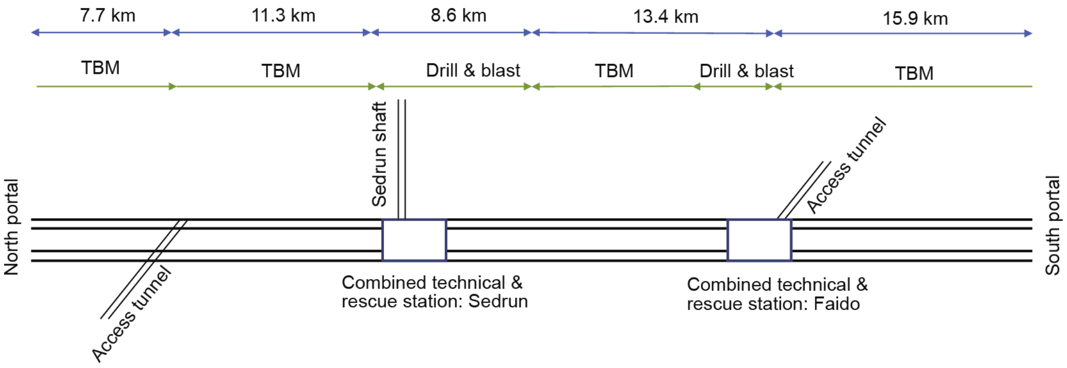


**Fig. 2.** The Gotthard Base Tunnel, between Italy and Switzerland.

### *3.1. Initial design considerations*

#### *3.1.1. Air quality and ventilation*

The layout of the Channel Tunnel actually comprises three parallel tunnels—two running tunnels and the central service tunnel which is used for access for maintenance crews and for emergency evacuation purposes, as shown on Fig. 3.

The Channel Tunnel has been a major success since coming into operation in 1994; in 2014, a record of 21 million passengers traveled through the tunnel. Up to 400 trains per day pass through the tunnel—200 in each direction—and the average daily traffic volumes are as follows:

- 58 000 passengers
- 6000 cars
- 180 coaches
- 54 000 t of freight

Normal ventilation of the running tunnel relies on train movements through the tunnel, supplemented by fans located on shorelines. Air is required for up to 20 000 people in the tunnel at any one time, at a rate of 26 $\text{m}^3$ per person—that is, at 144 $\text{m}^3 \cdot \text{s}^{-1}$ [1].

The central service tunnel is pressurized to ensure that it remains smoke-free in the event of a fire in the tunnel, and is partitioned from the running tunnels by air-tight doors. This is known as the normal ventilation system (NVS). A supplementary ventilation system (SVS) controls smoke in the tunnel in the event of a fire. In this situation, fans provide 300 $\text{m}^3 \cdot \text{s}^{-1}$ of air into each running tunnel. These fans are located on the French and UK shorelines, so they must ventilate a total length of 38 km between them.

#### *3.1.2. Aerodynamics*

Clearly, for cost reasons, the contractor required a minimum diameter to be identified for the tunnels. Thus, the tunnels were sized to accommodate the largest of the rolling stock that would use the tunnel—in this case, the shuttle wagons used for the transport of heavy goods vehicles (HGVs). The internal diameter of the running tunnels was set at 7.6 m. The blockage ratio in tunnel was 50% for this rolling stock [2].

It was determined [1] that trains traveling at high speed would displace 5000 t of air in the running tunnels, and the power requirements for the locomotives would be significantly affected by drag. A solution was needed to avoid pushing this column of air through the entire length of the tunnel; this was provided by the inclusion of piston relief ducts (PRDs) connecting the running tunnels along the length of the tunnel. These were built at 250 m intervals and allowed the pressure build-up within the tunnels to be transferred into the opposite tunnel.

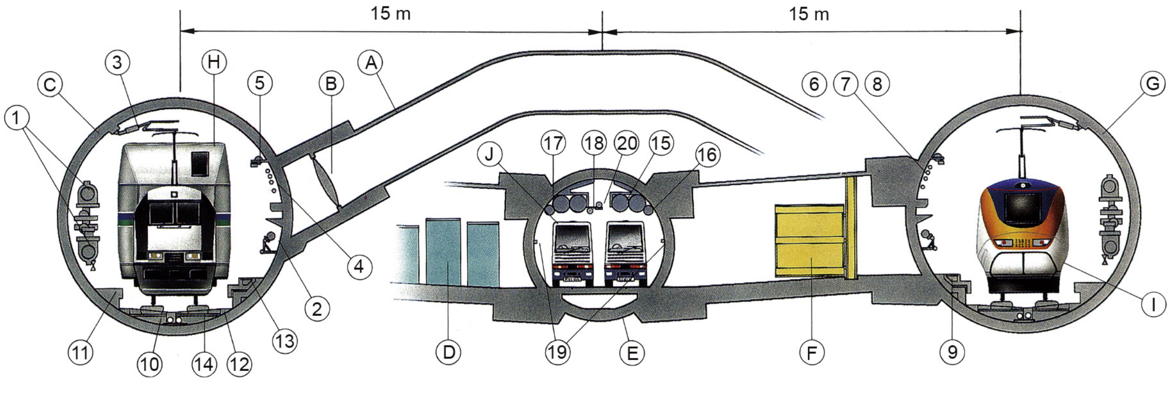
The design of the ventilation system and the diameter of the tunnel needed to be optimized during the design stage. Smaller tunnels would be easier to ventilate in the event of a fire, despite the need to account for friction forces caused by the segmental linings. Aerodynamics would be improved by enlarging the tunnels—but at the greater expense of construction and a significantly increased capacity of the ventilation fans to maintain the speed of airflow in the event of a fire. This is a particular issue for long tunnels with no intermediate shafts.

#### *3.1.3. Temperature*

The average level of heat generated by trains traveling through the running tunnels of the Channel Tunnel is 80 $\text{MW} \cdot \text{d}^{-1}$. It was determined that air temperatures could reach 50 °C after 2–3 months—and this is in the temperate climate of Northern Europe. The tunnels therefore needed to be cooled; this was done by circulating 3 °C water in 400 mm diameter pipes located on the tunnel walls. Longer tunnels would need more cooling pipes to control the temperature, and it is conceivable that for very long tunnels, these could affect the actual diameter of the tunnel.

#### *3.1.4. Drainage*

Due to the nature of the relatively impermeable ground through which the tunnel was driven, groundwater flows were permitted through joints of tunnel segments to reduce the build-up of



A Piston relief duct at 250 m intervals
B Piston relief damper
C Running tunnel
D Typical technical room
E Service tunnel
F Typical cross-passage with bulkhead door
G Running tunnel
H Eurotunnel Le Shuttle
I British Rail train
J Service tunnel transport system

Running tunnels

1 Cooling water pipes flow and return
2 Firemain 100 NB (125 m each side of cross-passage)
3 Catenary equipment (every 27 m)
4 Leaky feeders
5 Main lighting
6 2 × 20 kV cables
7 1 × 3.3 kV cables
8 Low voltage cables
9 Signalling cables
10 Phase 1 track concrete and drainage
11 Maintenance walkway concrete
12 Phase 2 trackbase concrete
13 Evacuation walkway precast units
14 Track support

Service tunnel

15 Drainage pipes 400 NB (3 No + 1 future)
16 Firemain
17 Firemain 250 NB (future)
18 Leaky feeders
19 Main lighting push buttons
20 Main lighting

**Fig. 3.** Configuration of the Channel Tunnel, between the UK and France.

hydrostatic pressures acting on the tunnel lining. However, the drainage water needs to be collected in sumps and be transported back to the surface. This is performed by four 400 mm diameter pipes that are located in the service tunnel. The space provision for these pipes has a significant impact on the size of the service tunnel and, regarding temperature considerations, it is possible that a longer tunnel would have necessitated a larger diameter facility.

#### *3.1.5. Fire and life safety*

For emergency evacuation purposes, cross passages are located at 375 m centers along the length of the route. These provide connections from each running tunnel into the central service tunnel, which provides a place of safety in the event of an emergency.

The "First Line of Response" team patrols the service tunnel on a 24-hour basis, and is at hand in the event of any incident within the tunnel. The full-time emergency services crew is based at the Sangatte Terminal on the French side of the tunnel. It is thus possible that the emergency services crew could be 40 km away from an incident in the tunnel if one were to occur near the UK coastline.

A number of fires have occurred in the Channel Tunnel during the first 20 years of operation, and the policies and procedures that were set in place at the outset have since been modified.

### *3.2. Lessons learned*

When the Channel Tunnel first opened for operations, the initial policy, in the event of a fire being detected on a train, was to run the train through the tunnel to the opposite portal and extinguish the fire in the open space. There have now been a total of four fires that have occurred in the tunnel during the 20 years of operation, and that initial policy has now been amended. All four incidents have been the result of fires on vehicles being transported on the HGV shuttles.

The first of the fires was the most serious; although it was attempted to run the train through the tunnel, the intensity of the fire actually damaged the overhead catenary power line, and the train came to a halt in the tunnel. The revised policy is to stop the train within the tunnel, evacuate passengers as soon as possible, and then deal with the fire as soon as practicable.

Getlink (formerly Groupe Eurotunnel), the operator of the tunnel, has recently constructed four separate "SAFE stations" (SAFE is short for "station d'attaque du feu" in French) within the tunnel to deal with any fires on a train. These SAFE facilities comprise fire-fighting facilities installed within a designated 870 m long section of the tunnel. Each facility is equipped with a high-pressure water mist system that can reduce the heat from 1000 to 250 °C within 3 min. The location of these SAFE facilities is such that trains can reach a station from any part of the tunnel within 15 min.

The Channel Tunnel was built with four separate crossover facilities over its 50 km length—two located in the undersea section, and another toward each of the portals on the French and UK sides. These allow for flexibility of operation during periods of maintenance and following any incidents in the tunnel, and have proved invaluable to the viability of the tunnel during the time periods that followed the fires mentioned above.

Following the first fire, in November 1996, one section of the tunnel was closed for a total of six months. The inclusion of the crossover facilities allowed trains to bypass this section and maintain services, albeit with reduced frequency, throughout the period when the damaged section was being repaired. Other minor incidents have also occurred in the tunnel, such as damage to the overhead catenary by vehicles in the HGV shuttle; however, operations have been maintained because of the foresight of providing sufficient crossover facilities to compartmentalize the tunnel into a smaller number of sections.

As mentioned, the cause of all fires to date has been the vehicles on the HGV shuttles. This rolling stock, if not unique to the Channel Tunnel, is not a common method of transporting goods vehicles. However, due to the length of the tunnel and the volume of traffic that uses the tunnel, the HGV shuttle is a key component in the success of the scheme. Any future undersea tunnels would probably require similar rolling stock to be provided to transport HGVs through the tunnel, unless such vehicles are prohibited from the tunnel and remain on ferries. Some lessons may need to be learned regarding the design of the rolling stock; however, cognizance should be given to the provision of intermediate fire-fighting facilities and sufficient crossovers along the length of the tunnel in order to maintain services.

### *3.3. Summary*

It is clear that the compartmentalizing of the overall tunnel by the inclusion of crossovers is of major benefit to the operation of the railway, and that the provision of intermediate shafts along the length of the overall tunnel is of benefit to both the construction and operation of any form of transportation tunnel. The challenge remains, however, of how to form such intermediate facilities when a tunnel is located under a large expanse of sea. A solution may have been identified by looking at another industry that, by necessity, must sometimes be located in a deep-sea environment: the oil and gas industry.

## 4. Potential solutions

Gravity structures have been successfully used for over 30 years for oil and gas production, mainly in the Norwegian sector of the North Sea, with installation depths of over 300 m. A schematic of the Draugen platform in the Norwegian sector of the North Sea is illustrated in Fig. 4. This structure has a central shaft of 20 m

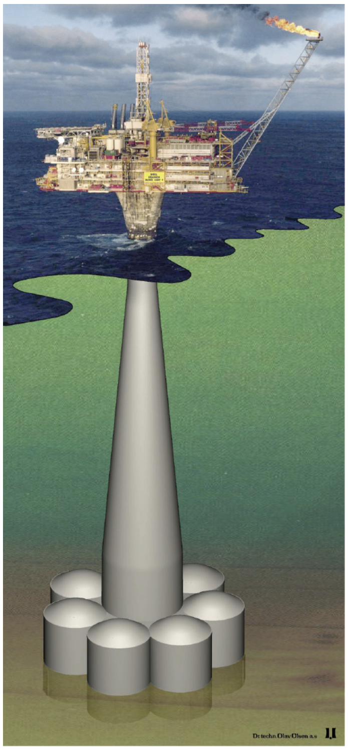


**Fig. 4.** Schematic of the Draugen platform.

diameter and is located in water 250 m deep [3]. The accommodation modules for the workforce are secured on the "topsides" superstructure. These structures could readily be used as construction sites for the proposed tunnel, with tunneling being carried out in two directions from each structure. In the oil and gas industry, the design of the operational support systems on the "topside" is far more complex than those required to support tunnel construction, with the presence of pressurized hydrocarbons and an associated process plant being required for the oil and gas industry.

The space available on the "topside" is more than adequate to accommodate the personnel required for manning the multiple TBMs that would undertake the tunneling works, and for the generators and workshops required to support the tunneling operations. Tunnel segments would be delivered by barges that could be moored alongside the platform.

For the permanent works, the structures would provide the means of ventilating the ultra-long tunnel and of discharging drainage water, and would also provide emergency access/egress points along the route. The novel use of this proven technology can provide the means of overcoming the logistical constraints of both constructing and operating an ultra-long undersea tunnel.

Other papers have been published on the means of safely installing and securing the gravity structures to the sea bed, so those methods will not be repeated here.

A number of routes have been identified for which fixed links are desired, particularly in the Asia-Pacific region. The shortest tunnel across the Taiwan Strait to link the mainland of China with the Taiwan region would be approximately 150 km in length. The depth of the sea is approximately 70 m, which is well within the range of the gravity structures described in this paper. The use of four gravity structures to form intermediate staging points along the route would allow the tunnel to be divided into five sections, each 30 km in length. The longest tunnel drive would then be 15 km, which is similar to the longest drive on the Gotthard Base Tunnel. It is acknowledged that any structures located in the Taiwan Strait would need to be designed to resist major seismic loadings and the adverse weather conditions encountered during typhoons. However, the fact that these types of structures have been built in the harsh environment of the North Sea, and are still operational after 30 years, demonstrates that these challenges can be met.

The Korean tunneling community is investigating a potential fixed link between the southern tip of the Korean Peninsula and the holiday island of Jeju. The direct route would require a tunnel of about 75 km in length; although use could be made of existing islands, the tunnel would then be approximately 15 km longer. Such a tunnel would be a considerable undertaking in its own right, so the direct route has many advantages.

A link between Japan and Korea has been the subject of a number of studies extending over many years. The shortest route for this link would require an undersea tunnel of 128 km in length, with a maximum water depth of 220 m for this particular route. Shallower water depths can be identified, but the associated tunnel lengths are greater.

More recently, a tunnel linking Korea and China has been discussed, the route of which would pass across the Yellow Sea from near Incheon in Korea to the Shandong Province in China; such a route would require a tunnel in excess of 300 km to be formed under the sea. It is noted that there are no islands in the Yellow Sea to simplify the construction logistics. However, the use of gravity structures could provide a solution.

## 5. Conclusions

All countries mentioned above—that is, China (mainland and Taiwan), Korea, and Japan—have high-speed rail systems. Thus, the use of gravity structures could provide a sustainable solution for providing fixed link connections between these countries. The platforms could provide staging points for energy generation for the transport system, through wind or solar means, and could provide accommodation for maintenance and safety crews along the route of the link.

One final consideration is the benefit in terms of construction time that may result from using intermediate construction points along the route of a tunnel. If the overall tunnel is subdivided into lengths of approximately 30 km by the use of gravity structures, then the actual construction time for the overall tunnel would be similar to each other—no matter the length of the overall tunnel.

## Compliance with ethics guidelines

Gareth Mainwaring and Tor Ole Olsen declare that they have no conflict of interest or financial conflicts to disclose.

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