Le tunnel des Chiltern sur la LGV High Speed 2, éléments de conception fonctionnelle

The Chiltern tunnel on High-Speed 2, key design features for a 16-km long high-speed railway tunnel

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Résumé

High-speed 2 (HS2) est une nouvelle voie ferrée à grande vitesse actuellement en construction au Royaume-Uni. Elle améliorera la connectivité entre les grandes villes britanniques et contribuera à atteindre les objectifs de transport à faible émission de gaz à effet de serre du pays. Situé au nord-ouest de Londres, le tunnel de Chiltern est un tunnel bitube de 16 km passant sous les collines des Chiltern, une zone environnementale protégée, et qui sera le deuxième plus long tunnel ferroviaire du Royaume-Uni après le tunnel sous la manche.

L'ouvrage présente plusieurs caractéristiques de conception singulières, principalement dues à sa longueur ainsi qu'aux exigences opérationnelles spécifiques à HS2, en particulier une fréquence de trains inhabituellement élevé (jusqu'à 18 trains par heure). Cet article décrit les facteurs clés qui qui sont intervenus dans la conception du tunnel, notamment la sécurité, les performances aérodynamiques et la fonctionnalité ferroviaire.

L'article présente également la stratégie de ventilation mise en œuvre sur l'ouvrage, qui repose sur une série de puits situés le long du tunnel. La conception du système de ventilation et la conception structurelle des puits ont été réalisées conjointement entre l'équipe génie civil et l'équipe systèmes ferroviaires dès les phases amont du projet, afin d'allier au mieux fonctionnalité et constructibilité. L'article présente comment une intégration très en amont entre les concepteurs, les constructeurs, les ingénieurs des systèmes ferroviaires et le client permet de développer des solutions efficaces et innovantes pour satisfaire les exigences de sécurité tout en minimisant l'empreinte carbone et l'impact environnemental des ouvrages.

Abstract

High Speed 2 (HS2) is a new high-speed railway under construction in the United Kingdom. It will improve connectivity between Britain's major cities and help achieve the United Kingdom's low carbon transport targets. Construction is underway on the first phase which will connect London to Birmingham. The Chiltern tunnel passes beneath the Chiltern hills (an area of outstanding natural beauty) which are located northwest of London. The tunnel is a 16 km long twin-bore arrangement. It will be the longest on the HS2 route and, after the Eurotunnel, it will be the second longest rail tunnel in the UK.

The tunnel has a series of distinctive design features, largely due to its length (16 km), as well as HS2's specific operational requirements such as an unusually high train frequency for a high-speed railway (up to 18 trains per hour). This paper describes the key factors that affected the tunnel design, including safety, aerodynamic performance and railway functionality. The paper also presents the ventilation strategy which includes a series of shafts up to 65 m deep located along the tunnel alignment. The design of the ventilation system and the structural design of the shafts were done jointly to best combine functionality and constructability, whilst limiting the environmental impact and carbon footprint of the infrastructure.

The paper concludes by discussing how early collaboration between civil engineers and railway systems engineers is essential to the success of such complex projects. The paper also presents the key design lessons learnt during the project.

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1 Introduction

HS2 is a new high-speed railway which will enhance capacity and connectivity between Britain's major cities, including London, Birmingham, and Manchester. Two new underground stations are being built in the London area and two above ground stations in/near Birmingham. One of the most interesting features of this project is that it will provide entirely new infrastructure dedicated to HS2 and will not use any section of the existing rail network, including on the section which brings the line into central London. The new and dedicated high speed tracks will free up commuter and freight service capacity on the existing network. Works are underway on the first phase connecting central London and Birmingham.

Tunnelling is an important component of the project with 35 km of tunnels (mostly twin bore) currently being built to bring the railway out of the London area. In total about 45 km of tunnel will be constructed between London and Birmingham. In addition to the sheer scale of the project, HS2 has several distinctive technical features which make it unlike most European high-speed railway projects. To outline and understand the specific challenges linked to HS2, and how they influenced the design of the tunnels, this paper presents the case of the Chiltern tunnel.

2 The Chiltern tunnel: an overview

2.1 Key features

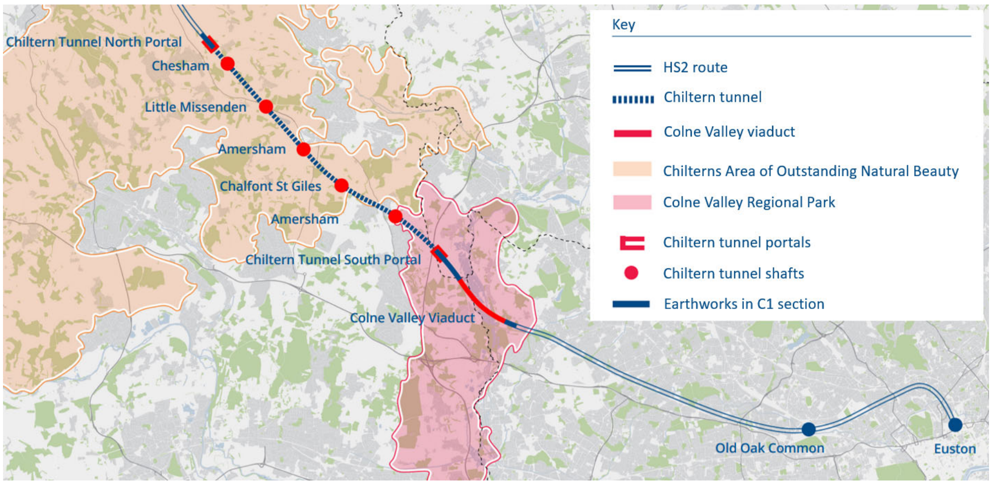

Figure 1 Location of the Chiltern tunnel

The Chiltern is the last tunnel as the line exits London. It is a twin bore 16 km long arrangement (one track per tube) and is the longest tunnel on HS2 (the next longest is 13.4 km). It goes under the Chiltern hills, a mostly rural setting designated as an area of outstanding natural beauty. An open-air infrastructure would have been both impractical and environmentally unacceptable. The tunnel (blue dashed line) and associated shafts and portals (red symbols) are shown in Figure 1. Key characteristics of the tunnel are listed in Table 1.

Table 1 Chiltern tunnel key figures and facts

Location	Buckinghamshire, UK	Tunnel internal diameter	9.1 m
Tunnel length	16 km	Track form	Ballast-less
Number of tubes	2	Tunnel spacing	25 m
Maximum radius in plan	5400 m	Maximum depth	90 m
Maximum applied cant	150 mm	Maximum gradient	2.5%

The tunnel starts near the M25, the major motorway encircling London, and finishes in the northern section of the Chiltern hills at which point the railway continues north in an open-air section of track. The north portal is located 120 m higher in altitude than the south portal giving the last section of the tunnel a steep gradient of up to 2.5%. The north portal of the tunnel also marks a change in line speed, transitioning from 320 km/h in tunnel to 360 km/h further north.

The tunnel has an internal diameter of 9.1 m and provides a free cross-sectional area of approximately 59 m^2 per bore. There are five shafts located along the tunnel, the details and purpose of which are presented in the following chapters. The main operational requirements of the tunnel are shown in Table 2.

Table 2 Main operational requirements

	Requirement	Impact on tunnel design	Comment
Line speed	320 km/h	Large diameter required to manage the drag force, traction power requirement and heat release in tunnel.	Traction requirements amplified by the maximum 2.5% gradient of the tunnel.
Peak train service frequency	18 trains/h	Increased heat release in tunnel, introduction of a congestion scenario where several trains can be stopped in the tunnel.	Unusually high requirement, specific to HS2, which has many consequences on the design.

The tunnel is in Chalk, a soft rock which is the main geological formation of the Chiltern hills (and most of southeast England). Two thirds of the tunnel is bored under the water table in a sensitive aquifer that provides drinking water to the region. The tunnel is constructed using two variable density tunnel boring machines (TBMs). The TBMs drive south to north.

The permanent tunnel lining is formed from precast segments. These are principally reinforced with steel fibres, with polypropylene fibres also added to provide the resistance to spalling under fire (the EUREKA temperature curve was adopted by HS2).

2.2 Project organisation

The Chiltern tunnel is included in the Section C1 of the project - a 22 km portion of line which is being delivered by ALIGN, a joint venture of Bouygues travaux publics (60%), VolkerFitzpatrick (20%) and Sir Robert McAlpine (20%), partnered with the designers Jacobs, Ingérop/Rendel and Gall Zeidler (see Table 3).

Table 3 Key entities on the Chiltern tunnel project

Client	High-Speed 2 Ltd.
Main works civil contractor	ALIGN, a joint Venture of Bouygues Travaux Publics, VolkerFitzpatrick and Sir Robert McAlpine
Design consortium	ALIGN (see above), Jacobs, Ingérop/Rendel, working with Gall Zeidler
HS2 Railway Systems Support Contract	WSP

The civil works were awarded in 2017 as a design and built contract with an Early Contractor Involvement (ECI) phase. Under the ECI contractors, consultants, and the client work collaboratively as an integrated team to develop a scheme which best integrates functionality, design requirements and constructability. Railway systems technical input was provided by WSP as part of the Railway Systems Support Contract (RSSC). This included analysis and design of tunnel ventilation, tunnel systems and shaft mechanical and electrical services. HS2 developed an internal management team for both civil and railway systems works.

3 The functional cross section

The general tunnel cross section applicable to the straight track section of the tunnel can be seen in Figure 2.

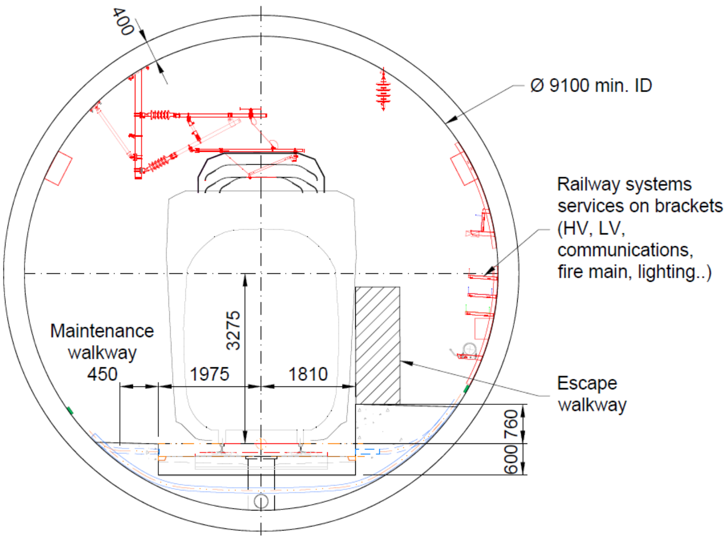

Figure 2 The Chiltern tunnel functional cross section

Unreinforced concrete walkways (formed by slip forming) are provided either side of the track. These provide a means for both escape and maintenance access. The escape walkway (on the right side of the cross section shown in Figure 2) is approximately 400 mm below the train floor level.

Most of the services are located above the escape walkway. These include the traction power cables and insulators, a 33 kV high voltage to feed the shaft and portal facilities, radiating cables for train communications, low-voltage cables for lighting and cross passage services and fibre optic communication cables. A 200 mm pre-charged tunnel fire main with dual hydrant outlets at up to 60 m centres is also provided. On the left-hand side of the tunnel there are further radiating cables at high level. Below these there is space allocation for signalling marking boards and cabinets, which are in practice discrete and hence the left-hand side is comparatively free of services. Most of the tunnel systems are mounted on steel brackets post-fixed onto the tunnel segment lining. The fixings use stainless steel threaded inserts which have been pre-cast into the tunnel segments. The escape walkway also provides containment to protect the services from a derailed train.

A slab track system is used due to avoid the maintenance associated with tamping ballasted track. A mass concrete invert is cast against the tunnel lining to provide a flat surface for the track slabs to be mounted onto. A perforated pipe is cast within the concrete invert to act as the tunnel's main carrier drain. It also provides a relief path for any water pressurised by a passing train that might otherwise be trapped between the segmental lining and the underside of the invert. There carrier drain has catch pits at regular centres to allow track level seepage water to be captured.

To improve tunnel construction logistics the invert is cast concurrently with the TBM excavation using a bespoke self-propelled "bridge" structure located a few hundred metres behind the TBM (Figure 3). This widens the highway used by the tunnel construction traffic meaning vehicles can cross each other at any point in the tunnel. This arrangement also frees up more space at the cross-passage locations to provide a safe dedicated work area whilst leaving one lane open to the construction traffic going to other areas of the tunnel. The invert is cast in 15 m long sections under the bridge, allowing vehicles to pass over it with enough space below to permit concurrent safe working and pouring of the invert.

Figure 3 Tunnel invert construction details - bridge (left), casting under the bridge (right)

3.1 Aerodynamics as a key driver of the cross section

The tunnel has an internal diameter of 9.1 m providing a free-air cross sectional area of approximately 59 m^2. The diameter of high-speed tunnels is influenced by the need to manage pressure safety such that if a train window seal fails the rapid pressure change inside the train is lower than 10 kPa. The diameter is also influenced by the need to manage pressure comfort (rather than pressure safety alone) inside the train. The diameter needed for pressure comfort is in-turn affected by the stiffness of the train car body. HS2 specified train car body stiffness commensurate with a high-quality modern train which allowed for slightly smaller tunnels than might otherwise have been adopted for similar tunnels in Europe.

Most of the power used by a high-speed train is spent in overcoming aerodynamic drag (which varies with the square of the speed) and can be around 150-300% higher in tunnels than in open route. For the Chiltern tunnel, with a train speed of 320 km/h and a steep gradient, the peak traction power requirement is expected to be high at around 18 MW. This power is eventually converted to heat which is mostly rejected into the tunnel. Given the high train frequency (see Table 2) there is usually at least one train in the tunnel at any time which means there is likely to be high heat rejection at most of the day. The heat increases the air temperature in the tunnel. Even accounting for the cooling effect of the surrounding ground and water table, as well as the cooling due to the air flow resulting from the piston effect, calculations showed that the air temperature could exceed 40 degrees centigrade for much of the summer. This would have affected the ability to evacuate passengers into the tunnel in an incident; decreased the life and reliability of the services in the tunnel; and, potentially, made it difficult to keep the train cooling system working if the train needed to stop in the tunnel for congestion.

At the initial planning stages, it was envisaged that the tunnel would have a free area of 56 m^2 and a nominal internal diameter of 8.8 m. During design development the required area increased to 59 m^2 with a nominal internal diameter of 9.1 m to reduce the traction power required to overcome drag (and the associated heat release from friction) and result in tunnel air temperatures lower than 40 degrees.

4 Safety, ventilation, and shaft designs

There are five shafts along the Chiltern tunnel. These shafts serve two important safety purposes. All five shafts provide fire and rescue services access from surface in case of an incident in the tunnels. The first four also provide mechanical tunnel ventilation used in case of a fire, train congestion or tunnel maintenance.

In addition to these two main functions, the shafts provide: firefighting lifts and stairs, fan rooms and electrical rooms for the tunnel ventilation system; railway and mobile network operators communications rooms to serve the tunnels; HV transformer and switchgear rooms; low voltage rooms for tunnel services and the shaft's own Mechanical, Electrical, and Plumbing (MEP) services and water supplies and muster areas for the fire and rescue services.

Figure 4 Plan view of the tunnel showing the five intermediate shafts (London is to the right)

The designs of the shafts were developed jointly between the client, rail systems engineers, civil designers, and contractors, all with the feedback from the fire and rescue services. This involved balancing the multiple (and sometimes conflicting) design requirements. Chiefly, these were: functional requirements, such as access space, ventilation capacity and services provisions, as well as structural, geotechnical and constructability requirements.

The following chapters detail the design development process and illustrates how successful collaboration between all parties lead to an optimised solution with significant environmental benefits, such as fewer lorries on the road and a significantly reduced carbon footprint.

4.1 Fire and rescue access

Emergency access into the tunnel from the portals using rubber tyred or road/rail compatible fire appliances is common in Europe. To allow for this the track form needs to be designed to accommodate the vehicles and the fire and rescue services need to be trained and comfortable in the procedure. The UK fire and rescue services do not adopt this practice. As an alternative, special trains are used for some countries, but they need to be deployed quite quickly and for HS2, with several long tunnels in succession, there are questions as to where to store such a train to be confident it would arrive quickly. In the UK, intervention shafts with a spacing of up to 3.3 km has become the accepted norm and so this was implemented on HS2.

4.2 Ventilation strategy in case of a fire

Whilst all shafts provide tunnel access for the emergency services, only the first four provide mechanical ventilation. The ventilation cools the tunnels during train congestion, provides airflows for tunnel maintenance works and controls smoke in a fire emergency. Unlike some European countries, where no mechanical ventilation would be provided to manage a fire event, the approach taken in the UK is to actively manage the risk with a combination of a mechanical ventilation system and train control system limiting the number of trains potentially exposed to smoke.

In case of a fire, the mechanical ventilation system operates using two shafts on a push/pull basis in the incident tunnel bore, with a third shaft providing air to pressurise the non-incident bore such that smoke does not flow through any opened cross passages. Each shaft is provided with duty/standby 200 m^3/s reversible axial fans and associated dampers, sound attenuators, drives and control system and a series of jet fans provide air flow control at the tunnel portals.

The train signalling system is designed so that there can never be more than one train between two ventilation shafts or between a shaft and a portal (a so-called ventilation zone) such that smoke can be exhausted without affecting a second train. In a fire emergency, if the train cannot leave the tunnel it would attempt to stop at a signal marker just before the ventilation shaft where a series of cross passages would allow the passengers to evacuate to the non-incident bore. The tunnel ventilation system would typically operate to direct the smoke forward in the direction of any existing piston effect airflow (which can be significant in long tunnels and take several minutes to decay). A revenue train would be emptied in an adjacent station and sent into the non-incident bore to act as a rescue train. The fire and rescue services intervene directly from the shaft closest to the designated stopping location.

4.3 Development of the shaft design

One important lesson learnt from the development of the Chiltern tunnel is the importance and value of concurrent and collaborative engineering when designing complex systems such as the tunnel ventilation system. The spirit of collaboration encouraged by HS2 was key to developing an efficient design, and it could not have been developed successfully without close collaboration between civil engineers, railway systems engineers, contractors, designers, and the client. To illustrate this and share the lessons learnt, this chapter recounts the development process of the shaft designs.

The ventilation requirements were initially based on a configuration with three fans per shaft, with airway connection to the tunnels of approximately 50 m^2, which would provide an air flow of 400 m^3/s from the shaft to any tunnel bore.

ALIGN JV introduced for consideration a shaft design inspired from a concept used successfully on the Cairo metro (see Figure 5), where the TBMs cut through the sides of the shaft. This concept removes the need for extensive mined tunnel works to create the connection and keeps the impact on tunnel construction minimal since the TBMs do not have to break-out in the shaft: the design includes a backfilled area so that they simply bore through the sides of the shaft, with the cutterhead partly against ground and partly against a mass concrete backfill, before continuing their journey.

The first stages of the ECI stage were dedicated to reviewing both this structural concept and the ventilation design to arrive at the best overall solution. Working from the quantified ventilation requirements listed above, it proved very complicated to design a 50 m^2 connection into a 9.1 m tunnel only by having the TBM intersect the edges of the shaft.

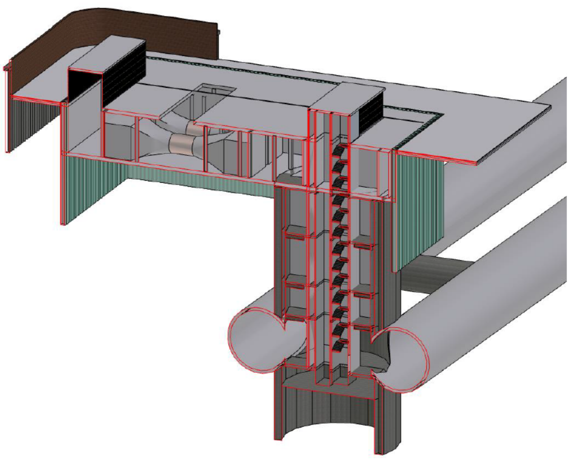

Figure 5 Shaft concept inspired by the Cairo metro design

To appreciate the difficulty, it is important to understand further the geotechnical context of the Chiltern tunnel shafts. The shafts are constructed in Chalk, a highly permeable soft rock which is also one of the main aquifers of the London area, protected by England's Environmental Agency. Due to tunnel alignment constraints, the deepest shaft is 65 m below ground with a hydrostatic head of 40 m at shaft formation. This water pressure introduces significant loads into the structures. The environmental context of this sensitive aquifer also pushes to limit the amount of ground treatment works (grouting), and therefore limit the amount of mined works to be done, which also brings the benefit of reduced risks during construction.

Two initial design concepts (see Figure 6) were developed to deliver the larger 50 m^2 tunnel to shaft connections. These designs consisted of a large diameter shaft option (on the left), which would cover both tunnels, and a smaller shaft option (on the right) where the ventilation was provided to the crown of the tunnels via significant mined works. Although it would have been technically possible to implement these designs, the downsides would have been significant: increase in quantities of material handled and transported on the roads, and increase in the carbon footprint of the project, both of which are subject to limits imposed by HS2. Therefore, as part of the collaboration, the integrated team undertook a significant amount of additional ventilation and structural modelling as well as construction methods studies to investigate alternative shaft and ventilation configurations.

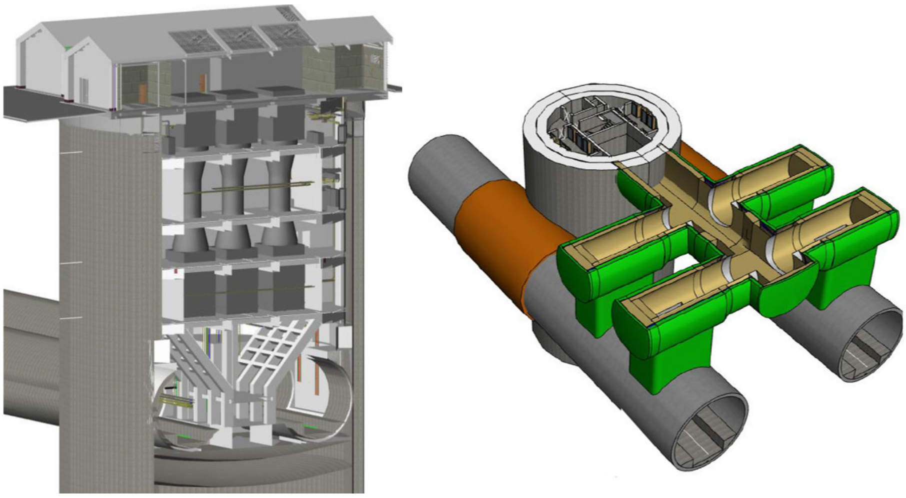

Figure 6 designs which would have complied, but at excessive cost and environmental impact

Further work was needed to provide an efficient shaft design which would comply with the commitment HS2 made to the community in terms of lorry movements and carbon footprint, and which would also reduce the overall quantities. The concept shown on Figure 5 was revisited and the structural design carried out concurrently with further detailed ventilation modelling. This ensured that the concept was developed holistically, providing the ventilation required to ensure the safety of the railway, whilst staying within the structural and environmental boundaries imposed by the geotechnical context.

A first step to reconfigure the ventilation design was to introduce the jet fans at the tunnel portals. These would be used manage the significant air pressure variations (up to 160 Pa) between the North and South tunnel portals (partly arising due to the difference in altitude of 120 m). Active control of the ventilation is used to adjust the jet fan configuration depending on the direction of the barometric pressure differences. These reduced the ventilation capacity at all the shafts. It was found that the optimal design overall was to provide a ventilation flow rate of 200 m^3/s per shaft using two fans per shaft (rather than three fans previously). These would operate as duty/standby, and the detailed geometry of the airway was refined to ensure the air speed at tunnel level remained less than 15.5 m/s.

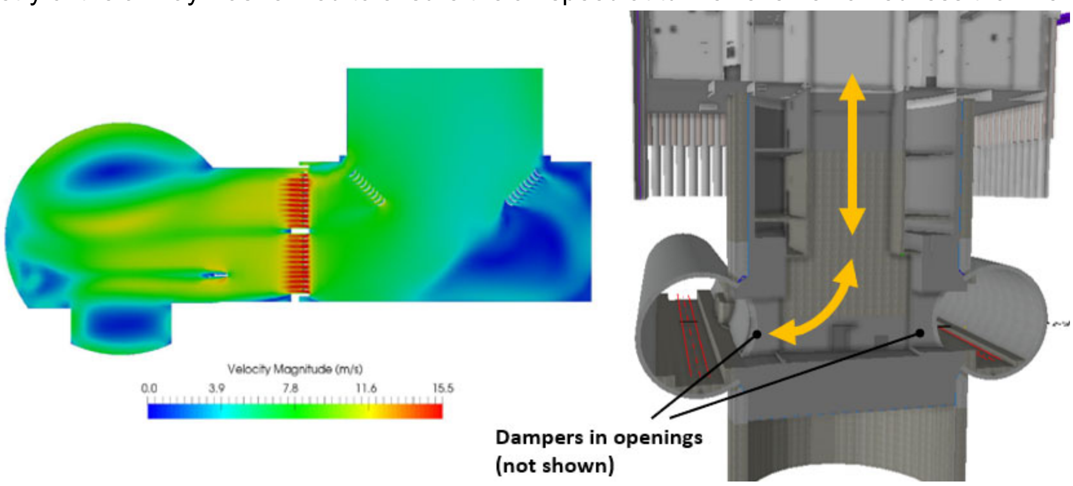

Figure 7 Air flow through the airway (in yellow on the right), predicted ventilation air speed (left)

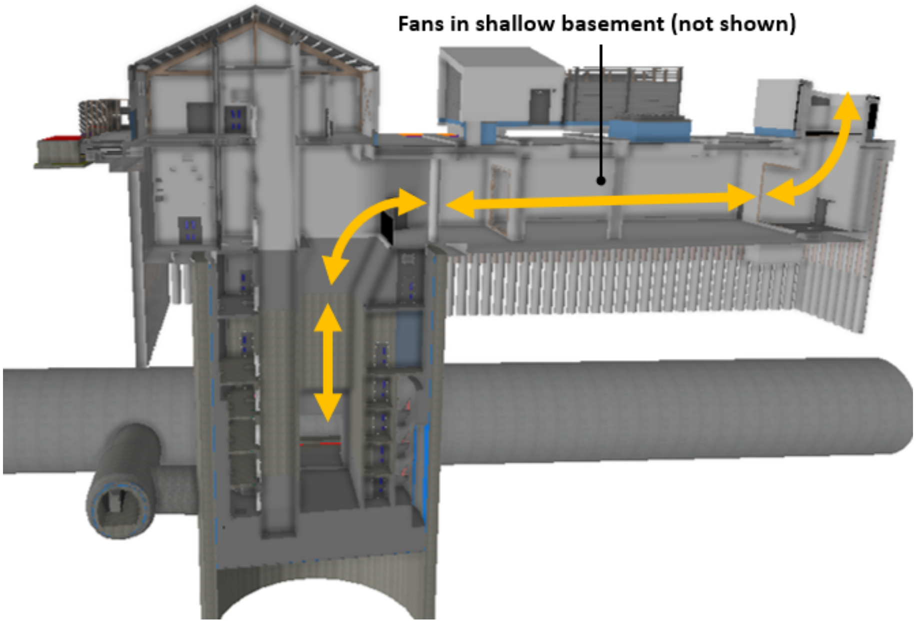

Figure 8 The final design, longitudinal section through the airway (airflow in yellow).

The final shaft design, currently under construction, is a 17.0 m internal diameter shaft which provides a 21.5 m^2 airway connection into each tunnel, providing the required functionality with a greatly reduced excavation compared to what would have been required with the initial ventilation concept. This demonstrates the benefit of a concurrent design development process, where the quantified ventilation requirements are not set as a hard input for the design of the structure, but rather where structural design and ventilation design are developed hand in hand with the contractor to make sure the final design is truly the optimal solution.

5 Conclusion

High speed railway tunnels are by essence functional assets, and the civil works are only a means to reach the required functionality.

The example of the Chiltern tunnel illustrates the benefit of early collaboration between contractor, civils designer and rail systems specialist to meet its functional objectives without compromising the civil cost or constructability. Chiefly, this can be considered a feedback loop between systems designers, civil designers and contractors, to ensure that neither's concept becomes a penalising constraint on the other. These included a change in the tunnel diameter to manage heat, the inclusion of cast-in sockets to the tunnel walls to avoid a significant amount of drilling for tunnel services and a change in the ventilation concept to reduce the risks, embodied carbon and costs associated with the shaft construction.

These benefits were achieved by the close collaboration between the civil contractor and railway systems team, enabled by interface process and relationships that were introduced by HS2 to allow for such outcomes.

6 References

Gilbert, P. et al. 2022. Collaboration & Innovation in the Design, Delivery & Construction of the tunnel shafts on HS2 Contract C1. British Geotechnical Association, Fleming award submission.

Perez, A. et al. 2022. The Chiltern Tunnel Shafts being delivered by Align JV as part of HS2 phase One in the UK. Proceedings of the Australasian Structural Engineering conference.

Lamand, R et al. 2020 Design of Chiltern Tunnel and ventilation shaft interfaces, HS2 learning legacy technical papers

Sivakumar, R et al. 2020 Design optimisation and challenges with the deepest shaft on HS2, HS2 learning legacy technical papers