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High Speed Rail in the Chilterns: Feasibility Study of Alternative Tunnelling Options

Final Report

Project Ref: 30067 | [Rev AA] | Date: April 2014

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Introduction

This report has been prepared in response to the government's proposal to build a high speed rail line partly in a tunnel and partly as a surface route across the widest part of the protected landscape of the Chilterns Area of Outstanding Natural Beauty (Chilterns AONB). The report provides a technical evaluation of alternative continuous tunnel alignments. The alternatives which have been considered are all along the Misbourne Valley and within 3km either side of the horizontal alignment of the government's Proposed Scheme.

The designation of the protected landscape of the Chilterns AONB rests on the unique characteristics of its landscape. The design of the government's Proposed Scheme takes no account of the designated landscape of the Chilterns AONB or the protective provisions of Part IV of Countryside and Rights of Way Act 2000.

Peter Brett Associates LLP (PBA) was commissioned by Chiltern District Council (CDC) to consider options for alternative solutions to that being promoted by HS2 Ltd. The CDC is working in association with Aylesbury Vale District Council, Buckinghamshire County Council and the Chilterns Conservation Board.

PBA worked together with OTB Engineering Ltd on tunnelling and Beazley Sharpe (Railwise) Ltd on rail alignment and systems to develop alternative tunnel alignments and prepare this report.

This report describes the methodology which has been used, and the alternative routes which have been examined. The implications of local geology and hydrogeology on these routes and other matters relating to topography and location of settlements have also been considered. The results have been compared to the government's Proposed Scheme and to the continuous tunnel and the extended tunnel proposals, on the same horizontal alignment, advocated by local action groups.

It concludes with a review of the costs of the proposed alternative route which has been selected and demonstrates that it has far less impact on the Misbourne Valley and the Chilterns AONB and will be a better route operationally.

The reasons for undertaking this study

Most infrastructure programmes or projects impact on the urban or rural landscape in which they are placed and on the people within them. Linear, dispersed or single location programmes or projects all have impacts but in different ways. Linear ones for example will always impact more because the perimeter length in proportion to the whole is greater than in the case of those in a single location.

CDC has not accepted the role of commissioning this study lightly. It has done so because government is considering the imposition of a major linear infrastructure project across the widest part of the Chilterns AONB. The basis of CDC's argument is that the current government proposals militate rather than mitigate the impact. It is not the purpose of this report to pass judgement on either of these approaches but to draw attention in an evidence-based and disinterested way to the consequences of the government's approach in this case and to provide what CDC considers to be a better proposal.

The report serves two purposes. They are to inform CDC of the possible alternative routes within the River Misbourne valley, the underlying geology and hydrogeology, and the manner of construction; and to encourage a much wider debate to support this alternative approach.

The methodology used

Four possible alternative tunnel alignments have been considered. These are compared to three published reference alignments, one of which was the government's Proposed Scheme, referred to here as the Reference Route. The other two were tunnel alignments of varying length on the same horizontal alignment as the government's Proposed Scheme. The relative lengths of tunnel and location of the northern portals for these published routes are:

Route	Start	Finish	Tunnel Length
Reference	M25	Little Missenden	13.2km
Reference Tunnel	M25	Wendover	23.7km
Intermediate Tunnel	M25	South Heath	15.8km

These are the three reference alignments. The Reference Tunnel, developed in response to earlier consultation processes and with limited resources, was based on the horizontal alignment originally designed as a surface route. Similarly the Intermediate Tunnel which adopts the same alignment was not driven by the principle of tunnelling the whole route. The Reference Tunnel, which is the government's Proposed Scheme, did establish the technical feasibility of a full tunnel.

This report is grounded in the design of a tunnel in the first instance rather than a tunnel the genesis of which was a surface route. The basis of this report is a balanced engineering based approach to evaluating a new alternative horizontal and hence vertical alignment for a full tunnel through the Chilterns AONB.

In developing the alternative horizontal alignments for a full tunnel solution, consideration has been given to the applicable railway alignment standards and system requirements in the context of:

- the topography;
- geology;
- hydrogeology;
- construction and logistics;
- suitability; and
- operation of the railway

Furthermore, the built environment has also been taken into account, recognising:

- the large and small urban and rural settlements distributed along the valley and at each end;
- the A413 highway; and
- the Chiltern Line railway

The other significant design characteristics which have been taken into account are:

- Geotechnical characterisation based on the likely nature and engineering behaviour of the ground to be tunnelled through based on desk study and field reconnaissance;

- Exploration of the groundwater regime on the basis of desk study using hydrogeological maps and other records, the likely ground water behaviour, and its possible influence on route selection; and
- The application of the European Technical Specification on Interoperability on the form and location of an intermediate means of escape for tunnels over 20km long

The geology of the Chiltern Hills dictates the fundamental nature of the Chilterns AONB. The Chalk escarpment and its dip slope as well as its nature and degree to which it has been weathered and eroded means there is a range of features which influence the development of the railway and how it will be delivered. Geology specifically influences the hydrology and hydrogeology of the Chilterns and the Misbourne Valley. The Chilterns forms a Major Aquifer, which is used for public water supply.

The alternative horizontal and vertical alignments shown comply with the HS2 design requirements although further refinement will be needed on the selected route to accommodate certain specific standards related to transition curves, interaction between curves, and lengths of gradient where the gradients approach the recommended maximum.

The requirement to provide a railway which allows train speeds of up to 320kph in the tunnel and 400kph on the surface imposes restrictions on vertical and horizontal alignment. The horizontal and vertical radii limits to achieve the necessary operational speed mean that the potential for avoiding every feature on any particular alignment constrains the options available. These constraints are more pronounced on the Reference Tunnel Route, where the constraints have been determined for a surface route and then the route suppressed to be in tunnel.

The EU Decision *Technical Specification for Interoperability on safety in railway tunnels on conventional and high speed rail systems* (TSI 2008/163/EC), requires some form of safety measure if the tunnel extends beyond 20km between portals. A twin bored tunnel extending the full width of the Chilterns through the Misbourne Valley will be in the order of 25km long and therefore this safety measure will be required. It could take the form of an underground emergency station as in the Gotthard Base Tunnel. Alternatively a stopping point within 20km of either portal with access to the surface from the full length of a train, called an ‘intervention gap,’ and is the solution adopted by HS2 Ltd and used in the current design of all the alternative tunnel alignments.

The preliminary assessment considered four alternative alignments. These are referred to as Blue, Orange, Black and Green.


ROUTE ALTERNATIVES
KEY
URBAN AREA
HS2 REFERENCE ROUTE
BLUE ALTERNATE TUNNEL ROUTE
ORANGE ALTERNATE TUNNEL ROUTE
BLACK ALTERNATE TUNNEL ROUTE
GREEN ALTERNATE TUNNEL ROUTE
INFORMATION TAKEN FROM DRAWING 30067/001/015

The results of the analysis

The Blue Route, northwards from the portal at the M25 takes a direct line towards the HS2 surface route immediately north of Wendover. The line takes a very oblique path under the River Misbourne. Apart from crossing under a part of Amersham at Station Road and Rectory Hill, the slight horizontal bends avoid other settlements to enable an intervention gap to be positioned between South Heath and Ballinger; not an ideal arrangement.

The Orange Route from the portal at the M25 takes a long curve around the 'Chalfonts' before crossing under the River Misbourne and then heading towards Little Kingshill. The route is designed to cross under the fewest number of dwellings located between Great Missenden and Prestwood. The intervention gap would be situated across Rignall Road and Kings Lane, north of Prestwood, often referred to as Hotley Bottom. Access for emergency services would be very difficult.

The Black Route follows the Reference Route under the River Misbourne at Chalfont St Giles as far as the A404. The route then diverges to follow a line west to run beneath Little Kingshill and curving northwards under Great Missenden. The route heads back towards the Chiltern Line and the A413; crossing under the floor of the Misbourne Valley upstream of the recognised source of the river in Great Missenden. The intervention gap is located at Wendover Dean in the vicinity of Bowood Lane. This brings the gap closer to existing transport infrastructure and access for emergency purposes is easily achieved from the A413.

The Green Route also follows the Reference Route under the River Misbourne at Chalfont St Giles as far as the A404. The route then diverges to follow a line east of Little Kingshill and west of Little Missenden to cross under the River Misbourne, Chiltern Line and A413. It then runs parallel to the A413 passing to the east of Great Missenden and the intervention gap is close to the A413 south of Bowood Lane. This is close to existing transport routes ameliorating the effect of this open section. Access to the gap for emergency purposes is also from the A413.

The route lengths between south and north portals of the four alternatives compared to the Reference Route (to equivalent portal locations) are shown in the table which follows.

Schedule of Route lengths

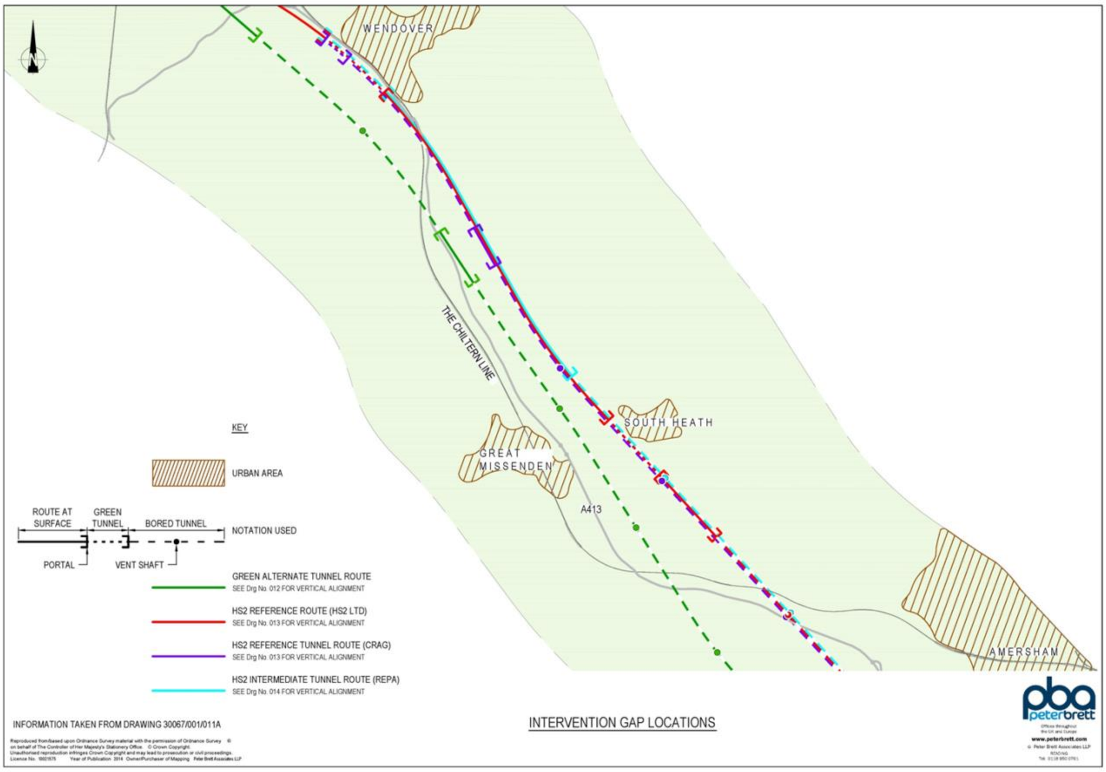
Route	Length
Reference	23.7 km
Blue	24.0km
Orange	25.6km
Black	25.1km
Green	24.7km

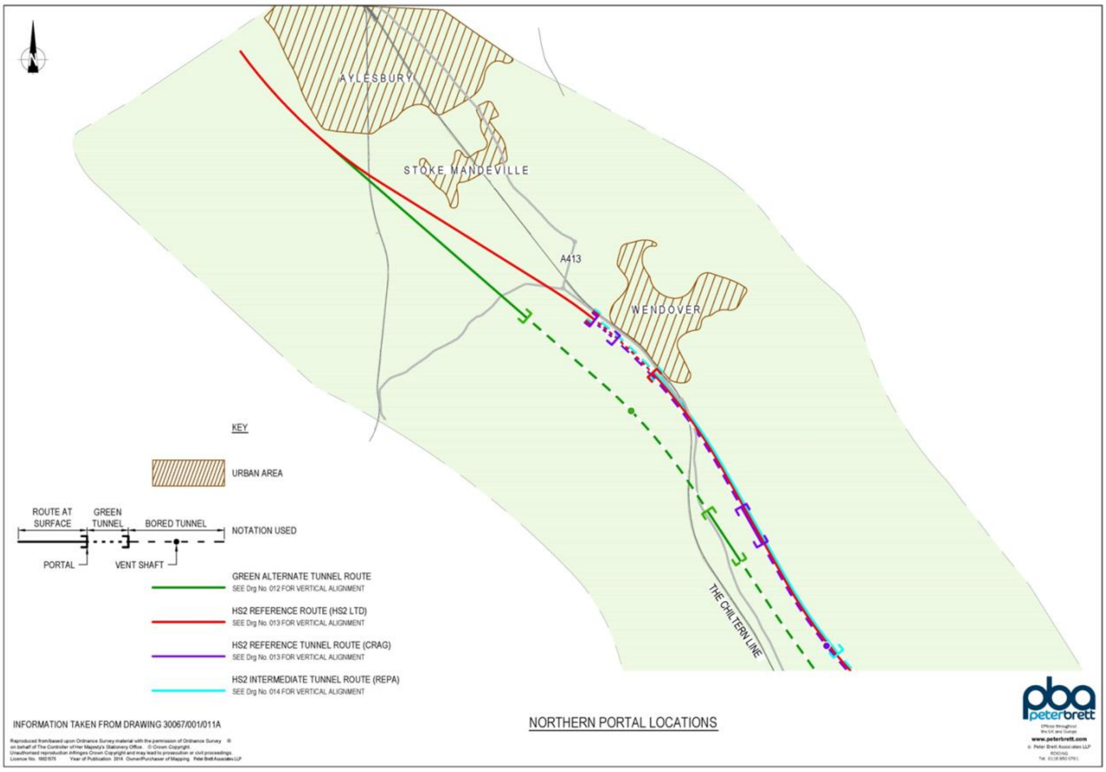
Summary of routes for comparison

Characteristic	Reference Route (HS2 Ltd)	Reference Tunnel Route	Blue	Orange	Black	Green
Tunnel length	13.4km	23.7km	24.0km	25.6km	25.1km	24.7km
Location of Intervention Gap	None	Durham Farm	South Heath	Hotley Bottom, Gt Missenden	Wendoverdean Farm and A413	Wendoverdean Farm and A413
Distance from Wendover Station	160m	160m	270m	1440m	880m	880m
Distance from Stoke Mandeville Church	600m	600m	600m	1000m	800m	800m
Gradients south to north Maximum gradient	3.0%	2.0%	2.0%	1.3%	0.9%	0.9%
Maximum gradient length	2.3km	3.7km	2.3km	4.8km	6.0km	5.5km
Gradients north to south Maximum gradient	2.1%	2.0%	0.9%	1.0%	0.7%	0.5%
Maximum gradient length	0.9km	1.2km	5.2km	4.0km	5.2km	5.9km
Summit location	Leather lane	Park Farm South heath	South Heath	Hotley Bottom Gt Missenden	Wendoverdean Farm A413	Wendoverdean Farm A413
Maximum height rise River Misbourne to Summit	149m	129m	113m	123m	110m	106m

The vertical alignment of the Green Route will be more beneficial in operation as the gradients are less than 1%, whereas the Reference Route has gradients up to 3%. The more gentle slopes reduce energy requirements and wear on the track. Where a specifically designed through-tunnel route can be provided, rather than the partial or whole suppression of a surface based route to become a tunnelled route, then both horizontal and vertical alignments can be optimized to provide smoother and more efficient alignments. Such is the case for the Green Route which, overall, has flatter curves and gentler gradients, with less undulation than the Reference Route and Reference Tunnel Routes.

In operational terms, the Green Route offers a much more attractive alignment, both vertically and horizontally. The vertical alignment in particular, will reduce the power requirements to achieve the summit, rather than the considerable power to achieve the summit of the Reference Alignments, which is slightly improved by the Reference Route. The actual speeds achieved on the Reference Route due to the gradients will make the lower design speed of the extended length of tunnel irrelevant in the context of overall journey time.


WENDOVER
THE CHILTERN LINE
SOUTH HEATH
GREAT MISSENDEN
A413
AMERSHAM
KEY
URBAN AREA
ROUTE AT SURFACE
GREEN TUNNEL
BORED TUNNEL
NOTATION USED
PORTAL
VENT SHAFT
GREEN ALTERNATE TUNNEL ROUTE
SEE Drg No. 012 FOR VERTICAL ALIGNMENT
HS2 REFERENCE ROUTE (HS2 LTD)
SEE Drg No. 013 FOR VERTICAL ALIGNMENT
HS2 REFERENCE TUNNEL ROUTE (CRAG)
SEE Drg No. 013 FOR VERTICAL ALIGNMENT
HS2 INTERMEDIATE TUNNEL ROUTE (REPA)
SEE Drg No. 014 FOR VERTICAL ALIGNMENT
INFORMATION TAKEN FROM DRAWING 30067/001/011A
INTERVENTION GAP LOCATIONS
pba peterbrett


AYLESBURY
STOKE MANDEVILLE
A413
WENDOVER
THE CHILTERN LINE
KEY
URBAN AREA
ROUTE AT SURFACE
GREEN TUNNEL
BORED TUNNEL
NOTATION USED
PORTAL
VENT SHAFT
GREEN ALTERNATE TUNNEL ROUTE
SEE Drg No. 012 FOR VERTICAL ALIGNMENT
HS2 REFERENCE ROUTE (HS2 LTD)
SEE Drg No. 013 FOR VERTICAL ALIGNMENT
HS2 REFERENCE TUNNEL ROUTE (CRAG)
SEE Drg No. 013 FOR VERTICAL ALIGNMENT
HS2 INTERMEDIATE TUNNEL ROUTE (REPA)
SEE Drg No. 014 FOR VERTICAL ALIGNMENT
INFORMATION TAKEN FROM DRAWING 30067/001/011A
NORTHERN PORTAL LOCATIONS
pba peterbrett

All options will encounter broadly the same solid chalk geology. However, the geology will vary considerably according to vertical alignment and to a lesser extent by horizontal alignment and the proportion of each geology type will therefore vary. The tunnels will encounter chalk of varying type and quality. Tunnel Boring Machines (TBM) working from the southern portals will commence their drives in Seaford Chalk, very pure white chalk with flints; those working from the northern portals will commence drives in the West Melbury Marly Chalk and Zig Zag Chalk, calcareous mudstone and limestone and with no flints. The type of chalk will therefore vary and will affect how the chalk is processed. The majority of the chalk in any of the tunnels will breakdown to silt due to the application of mechanical action since the majority of the drives are in low to medium density chalk.

Groundwater will vary according to the relative elevation of the groundwater table which does vary according to season and rainfall, as well as permeability and transmissivity of the fracture zones.

There is the greatest risk of ongoing slope instability could be associated with the hill slopes around Bacombe Hill near Wendover. The Reference Route and Intermediate Route both require a cutting into this hill as it is necessary to form a 1.3km long cut-and-cover tunnel, potentially creating slope instability. Whereas the Green Route portal is further to the north in gently sloping land and away from this potential area of instability.

Thus, the alternative proposed by this study (the Green Route) offers a better operational alignment and passes through better and more consistent ground conditions below the water table, characterized by relatively flint-free chalk, reduced permeability chalk, mostly below the deeply weathered zones underlying the dry valleys, zones containing solution features and chalk mines and, at the northern portal, avoids extensive unstable slopes.

In summary therefore, at the southern end of both the Reference Alignments and the Green Route the geological conditions for tunnelling are the same between the southern portal and the first crossing of the Misbourne Valley just beyond the Chalfonts. However northwards the routes depart in plan and level. It is generally the case that the Reference Alignments continue at a shallower level than for the Green Route. As a result of these departures the Green Route passes through better and more consistent ground conditions below the water table. This is characterized by relatively flint-free chalk, reduced permeability chalk, mostly below the deeply weathered zones underlying the dry valleys, zones containing solution features and chalk mines and, at the northern portal, avoids extensive unstable slopes. Its alignment also avoids impact upon Shardeloes Lake. Consequently taking account of the potential for geohazards, the linked impacts upon the surface and the engineering challenges posed, the Green Route offers many advantages over the Reference Route.

The geology and hydrogeology peer review has been undertaken by Rory Mortimore, Emeritus Professor of Engineering Geology at the University of Sussex, Visiting Professor of Geology at the University of Leeds and President of the Geologists Association; and Dr Haydon Bailey who specialises in Chalk micropaleontology and stratigraphy and is a Fellow of the Geological Society.

Design refinements

Introduction

Several design refinements have been proposed in this report. Amendments can be made to reduce the scope in some areas. It is unnecessary to have shafts at 2 to 3km centres for the full length of the route. Rather these can be placed at key points along the alignment. The number of cross-passages can also be reviewed to reduce a spacing to 500m which is being used in Germany. Relative costs for portals between the schemes are probably similar though the deletion of the Intervention Gap would remove the cost of two additional portal locations and the considerable environmental disbenefits it creates.

Shafts Intervals

The Alpine Base tunnels have far fewer vertical shafts because of the depth. Nevertheless, the application of current ventilation control systems and emergency evacuation procedures are sufficient to ensure adequate smoke control and safe evacuation. The relatively shallow HS2 tunnels do allow for additional emergency shafts, however, the strict adherence to a 2.5km to 3km separation is probably unnecessary as some shafts may be located away from the main roads and special access will be required. Consequently, their locations on either route could be re-examined to reduce their number and site them closer to easy surface access points.

Cross passages

The size and spacing of the cross passages are fairly conventional and are related to the train length and passenger capacity. However, on the Alpine Base Tunnels cross passages are provided at 325 to 333m intervals. They are 375m apart on the Channel Tunnel. The frequency of these passages warrants review to optimise it with the tunnel design and construction methods.

Emergency underground station

The intervention gap escape station could be readily and cost-effectively constructed entirely underground in bored tunnels, inclined adits and shafts. Since it would provide a full and equivalent provision for emergency evacuation it should satisfy the TSI requirements. This approach has been adopted for all of the Alpine Base tunnels and presents some substantial benefits over the planned surface intervention gap on the Reference Tunnel or Green Route.

The parallel ovoid profile station platform tunnels would be 500m long and about 13m wide to accommodate the required 5m wide platforms. An escape and emergency services tunnel would run between the tunnels at platform level and connected to the platform tunnels by short crosscuts at about 100m intervals.

Underground crossover

In order to provide operational flexibility a track crossover could be located in the intervention gap thereby extending its length by a further 500m. Alternatively the crossover can be readily constructed underground at any point along the tunnel alignment using Sprayed Concrete Lining techniques. Again this approach has been adopted for the Alpine Base tunnels and has also been employed on Channel Tunnel, Heathrow Express Rail Link, Jubilee Line Extension and Crossrail, all in similar circumstances.

Logistics

Tunnel boring machines

The logistics of the entire tunnel construction scheme will revolve around the selection, number required and procurement of the TBMs, together with their back-up facilities including spoil treatment and disposal and the manufacturing and supply of the precast concrete segmental lining.

For example, the procurement of four TBMs may potentially reduce the overall construction time as opposed to using 2 or 3 machines but would increase the rates of spoil disposal and materials supply, probably requiring larger facilities and certainly increasing surface activities, traffic movement and short-term environmental impact.

Shafts Construction

The shafts can be constructed using a number of methods; however the most cost effective is by first raise boring from the running tunnels to the surface then shaft sinking from the surface to the running tunnels. Although the feasibility of this method is highly dependent on the main tunnelling programme and logistics it would significantly reduce the cost of the large number of shafts required by HS2 Ltd.

Emergency underground station

The emergency underground station and crossover can be constructed by conventional Sprayed Concrete Lining (SCL) methods gaining access via a vertical shaft sunk from the surface or by inclined tunnels. Similarly to the Ventilation Shafts, this vertical shaft could then be installed with fans and dampers for forced ventilation and smoke extraction of the completed station whilst the inclined tunnels would provide the passenger escape route to the surface and access for the emergency services.

Underground crossover

The form of construction could be simply four SCL turnout caverns constructed from the running tunnels and linked by SCL crossover tunnels. Depending on programme requirements, the crossover could be constructed in advance of the TBM drive reaching it, in which case access for construction would be via a vertical shaft from the surface, which would later serve as a ventilation and emergency escape shaft. Alternatively, it could be constructed from the running tunnels once completed.

Spoil processing and disposal

An advantage of the chalk slurry from the TBM drives is that it can be transported for very long distances by pipeline before treatment, which reduces both the cost and impact of transportation. It would, therefore, be preferable to locate the slurry treatment plant close to the site of final disposal. Since 1965 Cemex (and its predecessors) have been operating a 92km (55 miles) chalk slurry pipeline from the Chilterns to its cement works at Rugby. Such a pipeline could be laid to Calvert, approx. 20km northwards along the trace of HS2, for disposal. Subject to suitable environmental assessment, particularly in relation to groundwater impacts, there could be opportunities also to feed the slurry to Pistone Quarry, approximately 11km north east, for cement materials use or to Chinnor Quarry, 11km south west for selective backfilling.

Chalk spoil arising from open excavations or SCL tunnelling should be generally suitable for use as construction fill material. Depending on its type and moisture content it could, however, be sensitive to excessive disturbance and handling resulting in a rapid degradation to what is often referred to a ‘putty chalk'. In this form it becomes difficult to handle, store, lay down and compact and can present an unsightly mess or even a hazard on site and nearby roads that is difficult to remove.

Phasing

In the Reference Alignments the main logistical problems would be phasing the construction of the ventilation shafts and crosscuts so as to minimise their programming impact on the main TBM drives. If a section of the running tunnel lengths were constructed in SCL this would be far less a problem and may even assist in programming the works by providing additional access to multiple advancing faces.

The additional works required for the emergency underground station and underground crossovers could be phased into the TBM drives by commencing them early in the programme. The time required procuring, manufacturing, supplying, assembling, launching and drive the TBMs to these locations should allow sufficient time to complete them to a degree sufficient not to interfere unduly with TBM progress. Furthermore the platform and turnout caverns would provide an opportunity to maintain and refurbish the TBMs, as was the case on the Channel Tunnel.

Worksites

Due to the length of the tunnels two main tunnelling worksites are required one located at the southern portal the other at the northern. The ability to economically deliver the works relatively unhindered by worksite size, access and environmental constraints is an important factor and may influence the particular location of the portal. The southern portal in all of the options is fixed and lies between the M25 and the River Colne/A412 corridor.

Construction options

It is possible to undertake the entire tunnelling with only two TBMs working from one end of the scheme and progressing to the other. At the intervention gap or emergency underground station the TBMs would be maintained and refurbished before continuing to the exit portals.

Alternatively, though less likely, each TBM could progress from one portal on opposite sides of the Chilterns to the intervention gap, turn around and continue to the second portal on the side it started from. This option would probably not be possible in the emergency underground station. Another option would be to launch the TBMs from the intervention gap and turn them around at the portals. On the face of it this may look attractive in that it confines the main worksite to the intervention gap but it would present major problems for materials and spoil movement and would likely be rejected.

A more feasible scenario that would accelerate the programme if the intervention gap were to be located closer to one side of the scheme than the other would be to use three TBMs. Two TBMs would progress from the portals on one side of the scheme towards the intervention gap, where they would be extracted. The third TBM would commence from one of the portals on the opposite side of the Chilterns and turn around at the intervention gap to return to the same side. This option would involve duplication of the worksites at either end of the scheme but one would be smaller than the other offering some flexibility. Again this option would not be possible if an emergency underground station is used instead of the intervention gap

However, if the emergency underground station was constructed, the shorter running tunnels could be constructed using Sprayed Concrete Lining (SCL) methods progressing simultaneously on four faces from the ends of the platform tunnels and from the portals. This would have the advantage that the same SCL set up could be used to construct the cross passages and underground cross over as well as the emergency underground station and shafts.

A modern slurry-TBM driving through soft rock should achieve an average advance rate of between 300 to 400m per week, working 24/7, 365 days per year, including down-time for routine maintenance. However, the back-up services together with tunnel lining segment supply and spoil treatment and disposal should be geared to a minimum advance rate of 400m per week, year-round. If more than one TBM is operating simultaneously then these should be increased accordingly.

This will require careful sizing and implementation of the segment manufacturing facility, together with storage at the factory and on site with adequate transportation arrangements from their delivery to site. It is an obvious advantage for major tunnelling projects such as this to locate the manufacturing facility as close as possible to or within the worksite thereby reducing transportation costs, storage areas and environmental impact. On Crossrail this has not been the case.

The cost implications

The table below summarises the costs of the Reference Alignments each between the portals and the equivalent chainage at Wendover.

The cost base used by HS2 Ltd has also been used in these calculations. It is therefore not surprising that the Green Route has been estimated to cost more. 85% of the estimated cost of the Green Route is accounted for by the cost of the tunneling and the total cost is therefore very sensitive to the unit rates which have been used. A 13% change in this cost results in a reduction of £0.20bn in the total cost. None of the alternative features referred to in this report have been taken into account in preparing the cost of the Green Route.

Summary of comparative costs

Summary table of comparative costs			
Reference Route	**Reference Tunnel**	**Intermediate Tunnel**	**Green Route**
23.7 km	**23.7 km**	**23.7 km**	**24.7 km**
£ 1.48bn	£1.79bn	£ 1.61bn	£ 1.85bn
Overall comparative rate £'000/km			
62.4	**75.5**	**67.9**	**74.9**

The difference in cost represented by either the Reference Tunnel or the Green Route represents 1.5 - 2% of the overall construction cost of the HS2 Phase One in a budget currently with a P50 contingency level. That is there is a 50% probability of the estimated cost being exceeded. However it will be a significant mitigation of the effects of the route through the Chilterns AONB and avoid extensive compensation costs which are not included in this budget.

The effectiveness and value of the proposed tunnel alternative can only truly be assessed by consideration of its whole life costs. A detailed quantitative examination of the cost basis is beyond the remit of this report. However, it is possible to assess comparatively and qualitatively the relative impact of the proposals on cost in terms of CAPEX and OPEX.

Qualitative CAPEX comparison

CAPEX cost	Comparison of Green Route against Reference Route
Land acquisition and permanent rights (incl. compensation)	Lower
Environmental mitigation measures	Lower
Permanent civil works	Higher
Rail systems	Similar (lower)

Qualitative OPEX comparison

OPEX cost	Comparison of Green Route against Reference Route
Traction power	Lower
Maintenance	Similar
Renewals	Lower
Operation	Lower

Against these figures must be placed the costs of 'loss of environment' in the Reference Route. It is for society to judge, perhaps through the Cabinet Office's Natural Capital Committee, whether indeed the costs of permanent and irretrievable 'loss of environment' outweighs the cost of the Reference Route. In the past, infrastructure promoters and planners have been all too ready to develop schemes to the detriment of the environment and the permanent and irretrievable 'loss of environment' even though engineering solutions could have been used that would have prevented the loss at a small additional cost against the whole life costs.

For the Reference Route, the cost of 'loss of environment' is very high. This is discussed in the Non-Market Effects Report prepared by Peter Brett Associates and Chilterns Conservation Board, submitted is response to the Environmental Statement.

The Treasury Green Book and the Supplementary Guidance on Accounting for Environmental Impacts led the way starting in 2003. Subsequently the Natural Environmental White Paper (2012) and the publication of the National Ecosystem Assessment (2011) provided a firm intellectual base from which to develop an approach to evaluating environmental impacts in general and non-market effects in particular.

Conclusion

Risks and impacts

In assessing the risks and impacts of the proposals a broad comparison has been undertaken of each route, considering relative effects on programme, cost and receptors. This is summarized in the table below.

It can be seen from this assessment that the Green Route has significantly better risk and impact on programme, cost and receptors than any of the other routes and represents a good solution to the provision of a full tunnel for HS2 through the Chilterns AONB.

		Assessed route			
Topic	**Indicator**	**Reference Route**	**Reference Tunnel**	**Intermediate Route**	**Green Route**
Rail alignment	Gradients	H	M	H	L
	Curvature	H	H	H	L
	Exposure	H	L	H	L
	Security	H	L	H	L
	Safety	M	M	M	L
Rail systems	Maintenance liability	H	L	H	L
	Journey time	L	M	L	M
	Operational flexibility	L	M	L	M
Geology	Stability	H	M	H	L
	Ground movement	M	M	M	L
	Ground water	M	L	M	L
Tunnelling	Construction sites	H	L	H	L
	Spoil handling	H	L	H	L
	Imported materials	M	H	M	H
Construction	Unforeseen ground	H	M	H	L
	Traffic	H	L	H	L
	Weather delays	H	L	H	L
	Complex foundations	H	L	H	L
	Programme	H	M	H	L
Environmental	AONB Land area lost	H	L	M	L
	Visual impact	H	L	H	L
	Ancient Woodland	H	L	M	L
	Listed Buildings	M	L	L	L
	Noise	H	L	M	L
	Water	H	L	H	L
TOTAL	**H**	**18**	**2**	**15**	**1**
	M	**5**	**8**	**7**	**2**
	L	**2**	**15**	**3**	**22**

Risks and Impacts	**In comparison to each whole route**
High	High risk or impact on programme, cost or receptor
Medium	Medium risk or impact on programme, cost or receptor
Low	Low risk or impact on programme, cost or receptor

The study concludes that there is a more advantageous alignment which will offer a more efficient operational alignment and therefore should be considered if the tunnel is adopted as a solution.

The tunnel avoids loss of Ancient Woodland and impacts on Listed Buildings and Scheduled Ancient Monuments. Noise effects are limited to the intervention gap and portal locations,

The tunnelling for the Green route will be simpler as it runs predominantly through the grey marl chalk. The depths will also avoid most solution features which will be affected by the shallower Reference routes, notably that currently proposed by government as its Proposed Scheme.

The tunnel routes will also provide protection to other railway systems infrastructure, such as the OLE wires and supports and is a protected site whenever maintenance is required. Rail thermal stress variations will be significantly less within the tunnel and the risks of buckling and rail breaks due to excessive tensile stress would be greatly reduced.

The cost differential for provision of either the Reference tunnel route or Green Route represents less than 2% of the overall cost of HS2 Phase One, including contingencies, while avoiding significant damage to the AONB.

In order to make a true cost comparison then the design refinements and logistics proposals must be considered, the whole life cost of the alternatives must be independently assessed, and the non-market effects evaluated.

1 Project Briefing

1.1 Introduction

1.1.1 Proposals for the construction of a High Speed Railway, known as HS2, between London and Birmingham and then to Manchester and Leeds have been developed by the government and its holding company established for the purpose, HS2 Ltd. These proposals have included route selection followed by further analysis of the preferred route. In 2013 Environmental Statement was published and the Hybrid Bill prepared for construction of Phase One of the line on this route, incorporating the construction, operation and mitigation measures considered necessary at this stage.

1.1.2 During this period, which has included ongoing consultation with affected parties, the route through the Chilterns Area of Outstanding Natural Beauty (Chilterns AONB) has been promoted as including extensive tunnelling in mitigation of the effects. The bored tunnelling proposed extends from the M25 for 13km into the AONB where it then becomes a mixture of cuttings, embankments, green tunnels and over a distance of over 11km viaducts through a landscape protected by statute. In the process its construction will result in the loss of extensive Ancient Woodland and a Scheduled Ancient Monument, severe impacts on the landscape and biodiversity, extensive landtake of about 400ha, not only for the railway but also for associated drainage infrastructure to drain the surface route, and a large tract of land for disposal of over 1 million cubic metres (about 1.5 million tonnes) of surplus soil. A number of dwellings are lost and many more will still be affected by the construction and operation of the railway with ongoing noise effects in an area otherwise unaffected by such a major transport artery.

1.1.3 The designation of the protected landscape of the Chilterns AONB rests on the unique characteristics of its landscape. The design of the government's Proposed Scheme takes no account of the designated landscape of the Chilterns AONB or the protective provisions of Part IV of Countryside and Rights of Way Act 2000.

1.1.4 Throughout the consultation it has been a concern of Chiltern District Council and its statutory partners in this study, Buckinghamshire County Council, the Chilterns Conservation Board and Aylesbury Vale District Council that the bored tunnelling be extended through the whole AONB so that the impacts are almost entirely avoided, whilst recognizing that such a tunnel is likely to require ventilation shafts at intervals through the landscape. The feasibility of constructing a full tunnel has been accepted by HS2 Ltd but rejected on cost grounds. The cost differential between the proposed scheme and a full tunnel is based on HS2 Ltd's own figures. However, the value placed on the land in these calculations is generally as low grade agricultural land, the very reason for the AONB classification, but this does not account for the impact on a landscape which, as one of only two AONB's with a Conservation Board, is close to National Park status.

1.1.5 In addition, the potential for selecting an alternative route more suited to tunnelling the whole length has not previously been examined. The proposals so far have all been on the published route which was originally designed to be on the surface. This study considers alternative routes should a tunnel solution be adopted to provide the most beneficial solution for construction and operation.

1.2 The reasons for undertaking this study

1.2.1 Most infrastructure programmes or projects impact on the urban or rural landscape in which they are placed and on the people within them. Linear, dispersed or single location programmes or projects all have impacts but in different ways. Linear ones for example will always impact more because the perimeter length in proportion to the whole is greater than in the case of those in a single location.

1.2.2 CDC has not accepted the role of commissioning this study lightly. It has done so because government is considering the imposition of a major linear infrastructure project across the widest part of the Chilterns AONB. The basis of CDC's argument is that the current government proposals militate rather than mitigate the impact. It is not the purpose of this report to pass judgement on either of these approaches but to draw attention in an evidence-based and disinterested way to the consequences of the government's approach in this case and to provide what CDC considers being a better proposal.

1.2.3 The report serves two purposes. They are to inform CDC of the possible alternative routes within the River Misbourne valley, the underlying geology and hydrogeology, and the manner of construction; and to encourage a much wider debate to support this alternative approach.

1.3 Scope

1.3.1 This is the full report on a feasibility study to establish the engineering and economic case for a continuous tunnel through the Chilterns AONB to carry the proposed high speed railway. Peter Brett Associates LLP (PBA) were commissioned by Chiltern District Council to consider options for proposing alternative solutions to that being promoted by HS2 Ltd. PBA worked together with OTB Engineering Ltd on tunnelling and Beazley Sharpe (Railwise) Ltd on rail alignment and systems to develop alternative tunnel alignments and prepare the assessment. Two alternative horizontal alignments, out of four considered, to that currently proposed by Government of the route of High Speed 2 across the Chilterns AONB were initially presented for comparison to the three reference alignments based on the government's proposed Scheme. This was done in terms of railway functionality/operability, environmental impact, and constructability. One of the alternative alignments has been considered in more detail as it was determined part way through the study that the second alternative did not offer sufficient clear benefits.

1.4 Reference alignments

1.4.1 In this study the government's Proposed Scheme, which is part tunnel and part surface route, is referred to as the Reference Route. An alternative engineering solution had been previously developed, which takes the form of a continuous tunnel on the same horizontal alignment as the Reference Route and is referred to in this report as the Reference Tunnel Route. An additional proposal, also based on the same horizontal alignment, has also been proposed by local action groups and is referred to in this report as the Intermediate Tunnel Route. The relative lengths of tunnel and location of the portals for these routes are set out in Table 1.1.

Table 1.1 The Comparative Proposals

Route	Start	Finish	Tunnel Length
Reference	M25	Little Missenden	13.2km
Reference Tunnel	M25	Wendover	23.7km
Intermediate Tunnel	M25	South Heath	15.8km

1.4.2 These are the three Reference Alignments. The Reference Tunnel, developed in response to earlier consultation processes and with limited resources, was based on the horizontal alignment originally designed as a surface route with no consideration of options presented by constraints such as the geology or hydrology of the Misbourne Valley and surrounding area did establish the technical feasibility of a full tunnel. The Intermediate Tunnel Route, which adopts the same alignment, was not driven by the principle of tunnelling the whole route.

1.4.3 The term Reference Alignments is used in this report for all these proposals unless the context requires a specific route to be mentioned.

1.4.4 This feasibility study adopts a balanced engineering based approach to evaluating new alternative horizontal and, hence, vertical alignments for a full tunnel through the Chilterns AONB within 3km of each side of the Reference Route, with a portal at the location of the southern end (London Portal) and one near the location of the northern end (Wendover Portal) of the Reference Route. The need for considering an alternative has been the result of concerns about the appropriateness of the route proposed, should a full tunnel be adopted and whether a better alignment could be developed.

2 Study Programme

This study was commissioned on 17th February 2014 by Chiltern District Council, supported by Aylesbury Vale District Council, Buckinghamshire County Council and the Chilterns Conservation Board, and a programme was agreed with the Employer's Agent (EmA) on 21st March 2014.

This is the Final Report on the Feasibility Study and sets out the results of the work undertaken, describing the alternative routes examined and evaluation of the reference schemes against the possible alternative.

Progress of the Study

Meetings have been held with the Employer's Agent at regular intervals and other feedback from the Council Team during the study period has assisted in determining the preferred solution.

The drawings included in this report reflect this feedback and other design developments as the scheme assessment progressed.

3 Route Selection

3.1 Introduction

3.1.1 In developing the alternative horizontal alignments for a full tunnel solution, consideration has been given to the applicable railway alignment standards and system requirements in the context of:

- topography;
- geology;
- hydrogeology;
- construction;
- suitability; and
- operation of the railway.

3.1.2 Furthermore, the built environment has also been taken into account, recognising:

- the large and small urban and rural settlements distributed along the valley and at each end;
- the A413 highway; and
- the Chiltern Line railway.

3.1.3 In considering some of the details of the route design, the location of Ancient Woodland and Listed Buildings that could be affected by the selected route were determined and these have influenced some of the refinements to the route as it has been developed.

3.1.4 The preliminary assessment considered four different routes to the Reference Alignments. Particular elements in the design of the routes are the intervention gap required to satisfy safety requirements and the location of the north portal near Wendover. In addition to these the tunnel requires ventilation shafts to the surface at nominally 3km intervals. The position of these shafts is influenced by topography and surface features. The chainage used on the Reference Alignments, are based on the Hybrid Bill sections commencing with 0km in Work No 2/1. In this definition the south (London) portal is located at approximately Ch5.5km.

3.1.5 The broad environmental impacts, in particular noise and vibration during construction and operation, have been taken in to account in selecting a preferred route.

3.1.6 The need for an ‘intervention gap’ is described in Section 4 - Railway Alignment and Systems.

3.2 Route Descriptions

3.2.1 The Alternative Routes developed to elements the key elements and considered in the study are set out in Appendix A. Key features on the routes considered are shown on PBA Drawing 30067/001/015. In summary, they can be described as follows:

1. Blue Route – following a straight alignment, which results in lengthy crossing under the River Misbourne the route heads for an intervention gap between South Heath and Ballinger in the interfluve between the Rivers Misbourne and Chess. Apart from crossing under a part of Amersham at Station Road and Rectory Hill, the slight horizontal bends

avoid other settlements to enable an intervention gap to be positioned between South Heath and Ballinger, not an ideal arrangement, before then reaching the Reference Alignments at the portal north of Wendover. This crosses under more residential dwellings, has a risky long crossing of the Misbourne and the intervention gap is intrusive.

2. Orange Route – taking a more curved alignment to cross under the River Misbourne over a shorter length south of Amersham, near Finch Lane, the route heads westwards to curve around and under Little Kings Hill, Prestwood and Great Missenden heading for an intervention gap situated across Rignall Road and Kings Lane, north of Prestwood, often referred to as Hotley Bottom. Access for emergency services would be very difficult. The tunnel would end in the northern portal about 1km west of the Wendover Portal on the Reference Route. The route continues on the surface east of Terrick to rejoin the HS2 route to the south of Aylesbury. This is a very twisting alignment and the intervention gap is also in an intrusive location.

3. Black Route – following the Reference Route under the Misbourne through Chalfont St Giles but continuing straighter then curving around under Great Missenden to an intervention gap adjacent to the A413 in the vicinity of Bowood Lane (Wendover Dean Farm) before continuing to a northern portal about 700m west of the Wendover Portal on the Reference Alignments and continues on the surface across Nash Lee Road and Risborough Road to rejoin the HS2 route to the south of Aylesbury. This avoids a second crossing under the visible River Misbourne and locates the intervention gap in an accessible and least intrusive location, but crosses under more residential dwellings, currently unaffected by the scheme.

4. Green Route - also following the Reference Route under the River Misbourne through Chalfont St Giles it curve around Little Missenden to cross under the Misbourne again, heading to the intervention gap also adjacent to the A413 near Bowood Lane and the northern portal about 700m west of the Wendover Portal on the Reference Route. It continues on the surface across Nash Lee Road and Risborough Road to rejoin the HS2 route to the south of Aylesbury. This avoids crossing under many residential dwellings, has a straighter alignment and locates the intervention gap in an accessible and least intrusive location.

3.2.2 The preliminary evaluation undertaken during the study process as briefly described above has reduced the options for further consideration and comparison to one alternative route, the Green Route. This route has been the subject of the more detailed evaluation against the Reference Alignments.

4 Railway alignment and systems

4.1 Design standards

4.1.1 The horizontal and vertical alignments of the Alternative Routes comply with the design requirements of HS2 Ltd, although further refinement will be needed on the selected route to accommodate certain specific standards related to transition curves, interaction between curves and lengths of gradient, where the gradients approach the recommended maximum. These refinements will not change the fundamental locations of the indicated routes significantly and for the proposed Green Route there will be few, if any, necessary changes to the outline vertical alignments.

4.1.2 The requirement to provide a railway that allows train speeds of up to 320kph in tunnels and 400kph on the surface imposes restrictions on both the vertical and horizontal alignments. The horizontal and vertical radii limits to achieve the necessary operational speed mean that the potential for avoiding every feature on any particular alignment constrains the options available. These constraints are more pronounced on the Reference Alignments, where the constraints have been determined for a surface route and then suppressed to be in tunnel.

4.1.3 The EU Decision: *Technical Specification for Interoperability on safety in railway tunnels on conventional and high speed rail systems* (TSI 2008/163/EC), requires some form of safety measure if the tunnel extends beyond 20km between portals. A twin bored tunnel extending the full width of the Chilterns through the Misbourne Valley will be in the order of 25km long and, therefore, this safety measure will be required. This could take the form of a third bore for escape, as is provided in the Channel Tunnel for example, with complex fire control measures and dedicated safety and rescue infrastructure. It could take the form of an underground emergency station as in the Gotthard Base Tunnel. Alternatively, a stopping point within 20km of either portal with access to the surface from the full length of a train and accessibility for emergency vehicles is deemed to be an acceptable form of safety measure. This is called an ‘intervention gap’ and is the solution adopted in the current design of all the alternative tunnel alignments.

4.1.4 The TSI, which sets out these requirements, is currently under review and they may change. There is a question over whether the 20km limit is absolute or whether 25km is considered to increase the safety risk. This study does not address this point and seeks to use solutions that are compliant with the standards. Whilst the TSI provides minimum standards/guidance it is for individual countries and their railway authorities to determine the precise criteria and standards for the ‘safety measure’.

4.1.5 The ‘ideal’ vertical alignment of one peak in the middle (at the intervention gap) and falling to both ends is not possible due to the approach level of the Reference Alignments (up to ch 5.500), and having to pass under the River Misbourne at Chalfont St Giles.

4.1.6 The Green Route offers the best access to the proposed surface intervention gap from the existing road and rail network,

4.1.7 The northern portal still falls in the AONB. This is due to the need to tie into the Reference Alignment northwards, but there would be no green tunnels on the approach.

4.1.8 Provision of appropriate crossovers, at least in the intervention gap, would isolate each of the four bores (twin bores, north and south of the intervention gap) and permit multiple combinations of single line maintenance and, moreover, access to greater lengths of protected track within the tunnel than is possible with only 5m twin-track separation. Appropriate adjustments to the horizontal alignments to produce a 'wineglass' effect will bring the track centres closer in the intervention gap than would be possible if the parallel alignments between the twin tunnels was simply carried through the gap. For this reason, the proposed gap is currently approximately 1km long, rather than the absolute minimum of 500m.This also provides the opportunity to incorporate emergency cross-over within this gap. The total excavated volume and foot-print of the gap cutting can be minimized by such alignments and by using the central space in the portal vicinity for any vehicular access adjacent to both tracks, whilst limiting outside access to foot access only.

4.1.9 Tunnel tracks are no less safe than open tracks. Indeed, if slab track (where the track is cast into or fixed onto a concrete base rather than ballast) is used with any derailment protection and in a single bore, the removal of potential train-train impacts would remove some risks. The tunnel is designed for a slightly lower train speed with possible reduced risks and reasonably constant environment with no exposure to extreme weather or errant vehicles. Safety and security in a tunnel is thus well controlled.

4.1.10 Regular provision of cross passages and shafts in the tunnel clearly mitigates the evacuation risks. The intervention gap is as effective as a portal and therefore there is no increased risk due to intrusion onto the line.

4.1.11 Recent weather events have demonstrated that overhead line equipment in open, high ground is vulnerable to extreme winds. It would be protected in the tunnel. Prevailing winds are generally from the west, so the either Green Route or Reference Tunnel would be on the windward side of the Chilterns and replace some exposed areas of embankment and viaduct. The tunnel routes will also provide protection to other railway systems infrastructure and provide a protected site whenever maintenance is required. Semi-automated video-based inspection methods are well suited to standardized ballastless track systems, such as those that could be expected within the tunnels. These inspections can be carried out at higher speed than traditional inspections and would not be subjected to weather-related problems. Rail thermal stress variations will be significantly less within the tunnel and the risks of buckling and rail breaks due to excessive tensile stress would be greatly reduced.

4.1.12 A critical path analysis of the programme for the extended tunnel would provide for as much parallel working as possible and should be compared with the time taken for the embankment/viaduct and track fit-out. The overall time to complete the tunnel construction is discussed in Section 6.

4.1.13 Good slab track construction progress in tunnels will not be any more significant in programme terms than the formation, drainage, sub-ballast and ballasted track construction along an end-fed section of ballasted track. All this work would take place through the tunnel rather than travelling on the surface roads in the Chilterns AONB, which will minimise impacts.

4.1.14 The Reference Route and Intermediate Tunnel would revert to ballasted track outside of the tunnels and viaducts. This would result in isolated sections of ballasted track and the need to convey ballast maintenance plant and material through tunnels to reach these isolated sections and result in regular noise from overnight maintenance activities to maintain the necessary track line and level for the design speeds. The proposed longer tunnels would remove this requirement and it is proposed that the suggested ballastless track-form be provided through the intervention gap, to ensure inspection and maintenance consistency and minimization throughout the Chilterns AONB.

4.2 Track and tunnel alignment comparison

4.2.1 Referring to drawing 30067/001/011 at Appendix B, comparison is made here between the Reference Route, shown red, the Reference Tunnel Route, shown light blue, and the Intermediate Tunnel Route, shown purple and the alternative alignment of the proposed 'Green Route'. Drawings 012 to 014 at Appendix B have the corresponding vertical alignment for each route.

4.2.2 For the Intermediate Tunnel Route, the variation from the Reference (Red) Route is to slightly extend the southern tunnel to a portal beyond South Heath and then regain the HS2 Reference Route including the viaducts and section of green tunnel at Wendover.

4.2.3 Further detail describing the alternative alignments is discussed in Appendix A.

4.2.4 In operational terms, the Green Route offers a much more attractive alignment, both vertically and horizontally. The vertical alignment in particular, will reduce the power requirements to achieve the summit and allow more coasting as trains pass through the Chilterns, rather than the considerable power to achieve the summit of the Reference Alignments, which is slightly improved by the Reference Tunnel. The actual speeds achieved on the Reference Route due to the gradients will make the lower design speed of the extended length of tunnel irrelevant in the context of overall journey time.

4.2.5 Immediately to the north of the study area, the Reference Alignments include the provision of a maintenance loop, where maintenance trains will be held in readiness for accessing the section of the Reference Alignments south into London. This enables deployment of maintenance teams as soon as possible once the last train of the day has passed through. The loop is located on a relatively level stretch of line about 1.2km in length and comprises a pair of lines adjacent to the through lines to allow maintenance trains to stand. It can also be used to hold passenger trains for operational reasons such as a breakdown.

4.2.6 The alignment of the Green Route will allow such a facility to be created between the Risborough Road crossing and the Chiltern Line crossing. This is slightly further north than the Reference Alignments, The vertical alignment can be adjusted in further design development to provide the required gradient, indicated on the Reference Route as being 0.25%.

4.2.7 It can be seen from this that not only does the proposed Green Route offer a more balanced vertical alignment and avoid impacts upon Great Missenden, South Heath and Wendover but also provides a smoother and less convoluted horizontal alignment, taking advantage of being a specific tunnel route alignment, rather than a suppressed surface alignment,

5 Geology and Hydrogeology

5.1 General

5.1.1 The Chiltern Hills (‘the Chilterns’) is a south-west to north-east trending chalk escarpment up to 267m high that forms the northern edge of the London Basin, a broad synclinal structure bounded to the south by the North Downs escarpment. As a consequence, the Chalk and overlying Lambeth Group dip gently south eastwards; normally <5 degrees.

5.1.2 The geology of the Chilterns influences the fundamental nature of the Chilterns AONB; the halk escarpment and its dip slope and the nature and degree to which it has been weathered and eroded means there is a range of features that also influence the development of the railway and how it will be delivered. Geology specifically influences the hydrology and hydrogeology of the Chilterns and the Misbourne Valley. The Chilterns also forms a Major Aquifer, which is used for public water supply.

5.1.1 The geological sequence along the tunnel route corridor is shown in Appendix C Tables C.1 and C.2 and summarised in Table 5.1 below.

Table 5.1 Summary of geological sequence along route corridor.

	Stratum	Lithology	Thickness
Superficial (Drift) geology	Alluvium	Silt, sand and gravel	<3m
	Head	Gravel, silt and clay	<6m
	Clay with Flints	Clay with flint gravel	<6m
	River Terrace Deposits	Sands and gravel	<10m
Solid geology	Lambeth Group	Clays with gravel and sand	<10m
	Seaford Chalk	White chalk with flints	<40m
	Lewes Nodular Chalk	Nodular chalk with flints, marls and limestone	<35m
	New Pit Chalk	White chalk with marls	<45m
	Holywell Nodular Chalk	Nodular chalk with marls and limestone	<15m
	Zig Zag Chalk	Grey chalk	<70m
	West Melbury Marly Chalk	Mudstone and limestone	

5.1.2 The geology is characterised by the Chalk that underlies the entire route through the Chilterns from the River Colne to south of Aylesbury. This is overlain by the clays and sands of the Lambeth Group, though these are only present over the southern part of the Chilterns. Over much of the Chilterns the Lambeth Group has been deeply weathered to leave a residual soil called ‘Clay with flints’ that caps much of the hills.

5.1.3 River Terrace Deposits (sands and gravels) are present over the southern part of the route and valleys are also characterised by superficial deposits formed by mass movement (variously termed 'Head') and by Alluvium deposited by recent watercourses. In places the River Terrace Deposits directly overly the Chalk where it has been eroded away.

5.1.4 The river terrace deposits are present as a staircase of terraces that step down progressively showing that the former proto-Thames river cut down gradually into the geological sequence through geological time. Prior to the onset of the Anglian glaciation the proto-Thames river flowed north-eastwards. Extension of the ice sheet southwards into the Vale of St Albans blocked the river's flow and produced a pro-glacial lake that caused the river to back up and find a new route to the south and east, eventually forming the route of the modern River Thames that extends south past Maidenhead.

5.2 Route Geology of the Reference Alignments and the Green Route

5.2.1 The following describes the broad geology presented in the cross sections shown on Drawings 30067/001/021 and 022 at Appendix B.

5.2.2 At the southeast end of the Reference Alignments and the Green Route the portal is located just south of the junction between Chalfont Lane and the M25 Motorway. At the portal the tunnel lies within the Seaford Chalk. Northwards the tunnel alignment curves eastwards around Chalfont St Peter passing close to Robert's Wood near to Hornhill. The tunnel route then swings westwards and passes below the eastern edge of Chalfont St Giles and crosses the River Misbourne close to the position of Chalfont Mill. Between the southern portal and Chalfont St Peter the tunnel passes through southwards dipping Seaford Chalk. However, as it approaches the River Misbourne valley the tunnel passes into the underlying Lewes Nodular Chalk. The tunnel level continues within the Lewes Chalk as it passes below the River Misbourne.

5.2.3 As the Reference Alignments continue northwards beyond Chalfont St Giles it penetrates down through the dipping chalk sequence eventually encountering the Chalk Rock at the base of the Lewes Nodular Chalk. The alternative Green tunnel route is located at a deeper level than the Reference Alignments hence they meet the Chalk Rock layer at differing depths and locations beneath the River Misbourne valley and northwards beyond. In plan, the two tunnel routes continue northwards to pass closely below Hobbs Hole along Bottom House Farm Lane that runs along the floor of a dry valley. Just beyond this point the tunnel alignments divide to take different routes going north. At this point the geological sequence comprises a deeply cut dry valley feature which cuts down through the Lambeth Group capped Seaford Chalk hilltops either side of the valley to reveal Lewes Chalk in the valley floor. The feature forms a northeast trending tributary valley to the Misbourne valley.

5.2.4 Continuing northwards below the west side of the Misbourne valley, both alignments pass to the southwest side of Amersham and Amersham Old Town. The routes take the tunnels below an area of high ground in the vicinity of Gore Hill and the north east side of Coleshill, crossing below Amersham Road, where Lambeth Group deposits cap the Seaford Chalk locally. A little further north is a large chalk dry valley feature with Whielden Lane extending along its floor, southwest of Amersham Old Town. Along this section the tunnels pass through the New Pit and Holywell chalks and approaching the level of the Melbourn Rock.

5.2.5 Northwards again the Green Route alignment crosses below another chalk dry valley feature south of Shardeloes and passes under Mop End Lane. Then the route veers back towards the River Misbourne valley crossing below it again between Little Missenden and Little

Kingshill. Along this section the tunnel passes through the Melbourn Rock and down into the underlying Grey Chalk Subgroup (Zig Zag Chalk and West Melbury Marly Chalk).

5.2.6 By contrast the Reference Alignments turn back under the River Misbourne valley floor beyond Amersham Old Town running at an angle that is more closely aligned with the valley floor axis of the Misbourne. The tunnel line passes below Shardeloes Lake within the valley floor. The Reference Alignments run at a constant grade and begins to rise after passing beyond the River Misbourne. South of the river the topographical highs comprise Seaford Chalk capped by Clay-with-Flints above the Lewes Chalk. Within the Misbourne valley floor river alluvium overlies New Pit Chalk exposed at the sides of the river. The tunnel passes through the New Pit and Holywell chalks just before the river valley floor position and then passes below the Melbourn Rock into the Grey Chalk Subgroup strata below the valley floor.

5.2.7 The next Reference Alignments and Green Route sections run north west through higher ground to the east side of the Misbourne valley where mostly Lewes Chalk is present overlain by variable thicknesses of Clay-with-Flints. Within some of the minor tributary valleys trending southwest towards the Misbourne valley the underlying New Pit Chalk is exposed. These ground conditions continue north towards Wendover where the route crossed back below the upper reaches of the Misbourne valley again. It is likely that the chalk exposed here in the valley floor is the Holywell Nodular Chalk Formation overlain by Head deposits in the valley floor axis. Beyond Wendover the head of the valley breaches the north-west facing chalk scarp face of the Chilterns. This results in a subdued topography where the Melbourn Rock and the Grey Chalk Subgroup strata outcrop and land levels fall away north-west towards the Lower Cretaceous strata (Gault Formation and Lower Greensand) beyond the Stoke Mandeville area.

5.2.8 This surface geology will typically be encountered by the Reference Tunnel Route to its north portal position. In contrast the Reference Route and Intermediate Tunnel Route passes through the shallower chalk strata in a series of deep cuttings and green cut-and-cover tunnels with some parts emerging to the surface upon embankments and viaducts. Just one short section through the edge of Balcombe Hill may either be tunnelled or constructed as cut-and-cover tunnel through the Grey Chalk Subgroup strata present before the railway emerges finally to the surface.

5.2.9 By contrast the Green Route remains at depth within the Grey Chalk Subgroup, potentially only rising above this level within the intervention gap site close to the A413 within the upper reaches of the Misbourne valley south of Wendover. This situation continues until its emergence at the northern portal location.

5.3 Hydrogeology

5.3.1 Information on groundwater levels has been derived from the published hydrogeological map and these levels are shown on the geological sections. It should be noted that the levels represent those measured before 1984 and that they will also vary with time, season and prolonged spells of rainfall as well as abstraction for water supply.

5.3.2 The volume of ground occupied by a twin bored tunnel is very small when compared with the overall volume of the Chalk aquifer and therefore its construction will not have any long term impact upon storage and water flow. It may affect local water supply boreholes where the tunnels are located in close proximity.

5.3.3 Ineson (1962) recognised the enhanced permeability of the Chalk below valley floors, increasing water flow largely as a result of periglacial weathering and dissolution widening of sub-vertical joints and bedding planes.

5.3.4 Significant portions of the tunnel route alignments pass below valley floors. The Reference Alignments contains longer sections in tunnel below valley floors (mostly the Misbourne valley) than the Green route. This is because the Reference Alignments crosse the valley floor axis at a more oblique angle and at a wider section than the Green Route making the crossing longer.

5.3.5 The Reference Alignments cross below Shardeloes Lake which is an important feature in the Misbourne valley. There is considerable uncertainty as regards the origin and form of construction of this feature and concern as regards the potential to impact of the tunnel upon its integrity and water levels. Consequently, a route alignment that avoids passing beneath it that removes this risk is preferred, particularly as the lake may be underlain by chalk solution features.

5.3.6 The Green Route passes under the Misbourne north of Little Missenden adjacent to the road junction with the A413. This is downstream of the accepted spring source of the river in Great Missenden, and does not risk disturbance to a protected landscape feature such as Shardloes Lake.

5.3.7 Overall, whilst the Chalk is a major aquifer it is a poor one; water flow and storage is essentially confined to the network of fractures within it and consequently the permeability of intact Chalk is very low and greatest within fault and fracture zones. The distribution of permeability is therefore highly variable and will change according to stratigraphical level, geological structure and weathering.

5.3.8 The impact on tunnel construction is that it may impede or limit the location of interventions made from a tunnel boring machine (TBM). It may also require that sections of tunnel, cross-passages and shafts may require dewatering. It is noted that HS2 have already identified the potential for intense fracture zone near to the south portal. This will need to be mitigated and will apply whichever route is selected. The Seaford Chalk in particular has high porosity and extends the duration of extreme groundwater flood events. This will need to be accommodated in the southern section of the tunnel on either selected route.

5.4 Geological hazards

Solution features

5.4.1 Chalk is a soluble carbonate rock in which solution features are present. The interface between the Chalk surface and overlying cover deposits often form a karstic horizon where solution features can be found and the Palaeogene/Chalk interface contains solution features that penetrate more than 50m from the upper surface of the Chalk. Solution features can also be present at depth as a result of the flow of groundwater including solution widened joints and bedding planes, phreatic tubes, cavities and tubular karst.

5.4.2 There are a large number of recorded solution features in the Chalk (Edmonds 2008) and more than 10,000 records are held within the UK's Natural Cavities Database managed by PBA, although not all of these are in the Chilterns. Those that are relevant to this study are indicated on the Drawings 021 & 022. Note that only those features that have been reported are shown. The records are indicative of the susceptibility of the Chalk of the Chilterns to solution and the prevalence of solution features.

5.4.3 Solution features may be columnar, planar or irregular shaped and may be present as an empty cavity or may be infilled with overlying cover deposits. Karst is a recognised hazard for tunnelling as it may result in the loss of slurry and face instability where infilled with soil. Where karst is of sufficient size it may lead to difficulties steering a TBM. However, very many tunnels have been constructed in karst in other parts of that is far more severe than the solution features associated with the Chalk in the UK world (e.g. Balkans, China, Singapore, Malaysia). Consequently, the risks associated with it are very well understood.

5.4.4 Instability within an infilled solution feature could result in localised higher ground movement, cavitation and potential collapse leading to the development of a sinkhole at the surface, particularly so where the tunnel is shallow. Where these features are known to exist (e.g. M25) or where the tunnel is shallow and in close proximity to sensitive structures and utilities it may be necessary to pre-treat these in advance of tunnel construction.

5.4.5 In this part of the route the chalk is overlain initially by the Gerrards Cross Gravel then mostly by the Beaconsfield Gravel. In this area the PBA Natural Cavities Database (as shown on Drawings 021 and 022) records that many solution features are present. A significant number of the recorded solution features have been identified as a result of carrying out ground investigations following the appearance of sinkholes causing subsidence and structural damage to property. The investigation results reveal that solution pipes commonly penetrate down into the chalk to depths of 30m or more and in some cases in excess of 50m. Based on the recorded field evidence the schematic cross sections (Drawings 021 and 022) indicate that dissolution weathering of chalk may feasibly extend to around 50m depth or more. About half of the tunnel length south and east of Chalfont St Peter passes through this zone. If metastable solution pipe infills were to be triggered to collapse as a result of the tunnelling activity then this could cause considerable subsidence damage if sinkholes appeared at the surface, particularly below buildings and utility services. Consideration will need to be given to advance stabilisation of the ground ahead of the TBM or from ground level.

5.4.6 Beyond the northeast side of Chalfont St Peter and Hornhill area the tunnel level passes below the water table and the main zone containing solution features (i.e. within 50m below the superficial geology and chalk surface interface). It should not be interpreted that solution features below the water table will be absent, simply that their number, size and impact should be reduced. However further along below the Misbourne valley floor the tunnel route may encounter more zones of disturbed ground – described later below.

5.4.7 It will be essential to investigate the distribution and nature of solution features along the proposed tunnel corridor and to develop process-response models to allow their distribution, form and number to be predicted with confidence. It will also be necessary to ensure that the tunnelling methods adopted can manage the potential presence of soft/weak material in an otherwise competent face of chalk.

Periglaciation

5.4.8 The manner in which Chalk weathers reflects its particular characteristics in respect of porosity and solubility that make it especially prone to certain forms of weathering. The porosity of Chalk and its ability to hold high moisture contents make it susceptible to the action of frost and ice producing fracturing, crushing, breakdown, cryoturbation (erosion due to repeated cycles of freezing and thawing), the development of involutions and even diapiric structures (movement of less dense material through overlying denser layers).

5.4.9 In the tunnel route corridors the Chalk has not been glaciated but has been affected by the processes that occurred immediately around the glaciers (i.e. periglaciation). Locally the severity and depth of weathering effects can vary from a few metres to tens of metres and in some cases 100m or more (Catt 2010). Faults within the Chalk may have been the foci for weathering and disturbance. Drawings 021 and 022 showing schematic cross sections for the Reference Alignments and Green Route have been annotated to show where such faulted, disturbed zones could exist.

Faulting

5.4.10 The Chalk comprises a series of blocks of relatively intact chalk rock mass divided by relatively narrow recti-linear zones of faulting. The effect of faulting is to change the material in the tunnel face and introduce a zone of higher permeability. They may also be associated with a higher incidence of solution features. Fault zones are associated with valleys and consequently also with sources of local water supply.

Flints

5.4.11 Certain levels of Chalk contain nodules, bands and infilled planes of flint. Flint is hard, incredibly tough and resilient. It is very abrasive and consequently tunnelling equipment has to be designed and planned to withstand the action of flint. This includes hardening certain parts prone to wear and planning for wear and replacement.

Chalk Mines

5.4.12 Historically the Chalk has been mined for a wide variety of reasons e.g. to make lime for mortar and spreading over fields to improve clay soil textures, also for brick and tile making.

5.4.13 The UK Mining Cavities Database held by PBA shows that old chalk mines are widespread throughout the Chilterns. Recorded chalk mines are shown on Drawings 021 and 022 (Appendix C). Abandoned mines leave remnant voids beneath otherwise undisturbed ground and, in time, are susceptible to collapse, making their presence known as a result since formal mine records usually do not exist.

5.4.14 A tunnel passing in close vicinity to an existing chalk mine poses a possible risk of triggering ground instability within the mine and immediately surrounding area. It may also result in the loss of slurry and create difficulties for steering the TBM.

5.4.15 There is a risk that unrecorded mines may be discovered as a result of constructing a tunnel. Analysis of recorded mines suggests that chalk mines are particularly associated with Lambeth Group and Clay-with-Flints cover deposits.

Slope Instability

5.4.16 The land surface is characteristically shaped into a series of valleys cut down into the Chalk and intervening hills. Some of valleys are relatively steep sided and may have originated while the chalk was frozen during the Pleistocene. While chalk can stand for long periods at steep angles, over time the valley sides relax and weather (e.g. frost action and stress relief) causing varying degrees of side slope instability.

5.4.17 This study has concluded that the greatest risk of ongoing slope instability could be associated with the hill slopes around Bacombe Hill near Wendover. The Reference Route and Intermediate Route both require a cutting into this hill as it is necessary to form a 1.3km long cut-and-cover tunnel, potentially creating for instability. Whereas the Green Route portal is further to the north in gently sloping land and away from this potential area of instability.

5.5 Chalk lithostratigraphy and intact geotechnical properties

5.5.1 The Chalk displays a wide variety of lithologies varying according to proportion of carbonate content and grain size. These lithologies and geotechnical properties vary with stratigraphical level and dictate how the Chalk will perform in engineering terms. These details are set out in Appendix C, Table C3 and summarised below.

Table 5,2 Summary of Chalk Lithostratigraphy

	Density	Flint content	Average calcimetry
Seaford Chalk	Low to medium	5 to 25%	95%
Lewes Chalk	Medium	<10%	95%
New Pit Chalk	Medium	<5%	90%
Holywell Nodular Chalk	Medium to High	<2%	87%
Zig Zag Chalk	High to very high	0%	77%
West Melbury Marly Chalk	High to very high	0%	70%

5.6 Anticipated tunnelling conditions

5.6.1 All options will encounter broadly the same solid chalk geology. However, the geology will vary considerably according to vertical alignment and to a lesser extent by horizontal alignment and the proportion of each geology type will therefore vary.

5.6.2 The type of Chalk varies with stratigraphy, the broad geotechnical properties of which are described in Appendix C. The tunnels will encounter chalk of varying type and quality. TBMs working from the southern portals will commence their drives in Seaford Chalk and cut down sequence, whereas those working from the northern portals will commence their drives in the West Melbury Marly Chalk and Zig Zag Chalk and cut up sequence.

5.6.3 Those commencing at the southern portal will be in very pure white chalk with flints whereas those commencing at the northern portal will be in calcareous mudstone and limestone and with no flints.

5.6.4 The quality of the chalk (C574 - Engineering in Chalk: CIRIA 2002) will vary according to the depth of weathering (the presence of Palaeogene cover) and the proximity to fault/fracture zones and solution features. The geological sections in Drawings 021 & 022 indicate the likely variation. A wide variety of chalk quality for each chalk type is to be anticipated and this should be planned for.

5.6.5 Groundwater will vary according to the relative elevation of the groundwater table which does vary according to season and rainfall, as well as permeability and transmissivity of the fracture zones.

5.6.6 The type of chalk will vary and will affect how the chalk is processed. The majority of the chalk in any of the tunnels will breakdown to silt due to the application of mechanical action since the majority of the drives are in low to medium density chalk. However, high density chalks will not always be broken down and these will form chips and lumps that will require separation using screens.

5.6.7 In summary therefore, at the southern end of both the Reference Alignments and the Green Route the geological conditions for tunnelling are the same between the southern portal and the first crossing of the Misbourne Valley just beyond the Chalfonts. However northwards the routes depart in plan and level. It is generally the case that the Reference Alignments continue at a shallower level than for the Green Route. As a result of these departures the Green Route passes through better and more consistent ground conditions below the water table. This is characterized by relatively flint-free chalk, reduced permeability chalk, mostly below the deeply weathered zones underlying the dry valleys, zones containing solution features and chalk mines and, at the northern portal, avoids extensive unstable slopes. Its alignment also avoids impact upon Shardeloes Lake. Consequently taking account of the potential for geohazards, the linked impacts upon the surface and the engineering challenges posed, the Green Route offers many advantages over the Reference Route.

5.6.8 The geology and hydrogeology peer review has been undertaken by Rory Mortimore, Emeritus Professor of Engineering Geology at the University of Sussex, Visiting Professor of Geology at the University of Leeds and President of the Geologists Association; and Dr Haydon Bailey who specialises in Chalk micropaleontology and stratigraphy and Fellow of the Geological Society.

6 Tunnel Design and Construction

6.1 Introduction

6.1.1 This section initially sets out the options available for tunnelling on any of the routes as well as the construction methods for some of the design elements. It describes ground movement issues and methods of handling spoil, particularly at the northern portal for the Reference Tunnel or Green Route. It is expected that issues associated with the southern portal site are accepted and understood by HS2 Ltd.

6.1.2 The section continues with consideration of some of the issues which should be taken into account when evaluating the constructability and durability of the Reference Route and Intermediate Route.

6.2 Tunnelling methods

6.2.1 The Chalk, since it is weak rock, is a very good material within which to build tunnels having sufficient strength to stand-up unsupported and soft enough to be easily dug. Bored tunnels have subsequently been constructed with a very wide variety of methods in the UK since the Industrial Revolution. Today, two methods dominate for this type of project and these are discussed below.

Tunnel Boring Machine (TBM)

6.2.2 Construction of a long tunnel in the Chalk lends itself admirably to the use of a tunnel boring machine. The selection of the type of tunnelling machine depends on the permeability of the chalk, the likely groundwater pressures at the level of the tunnel and the strength/density/ behaviour of the Chalk. For the large diameter running tunnels (ca. 8 to 9m diameter) it would be appropriate to construct these using closed face slurry tunnel boring machines (slurry-TBM). The feature of these machines is that machine itself is isolated from the ground enabling the tunnel lining to be erected within it and that the chalk is excavated and transported using a pumped slurry via a pipeline. It is particularly suited to use in chalk because the rock will tend to break down very easily upon the application of mechanical action as a result of the excavation process (cutting action of the cutterhead, rotation of the cutterhead and slurry transportation). The advantages of such a system are the reduced mechanical wear on the machine (due to use of a fluid) and parts and the simple transportation system via pipeline, both highly important for a long tunnel. Being isolated from the ground means that any groundwater present in fractured zones is controlled by and contained within the slurry system.

6.2.3 This form of tunnel construction requires the installation of a circular precast concrete segmental lining that is erected within the skin of the TBM shield and extruded behind as the TBM moves forward. The annulus left between the cut profile and the extrados of the lining is fully grouted and the installed lining acts as a resistance against which the TBM is jacked forwards to penetrate the ground ahead.

Sprayed Concrete Lining (SCL) method

6.2.4 Originally developed in Austria, where it is known as the New Austrian Tunnelling Method (NATM) and in Norway where it is referred to as the Norwegian Method of Tunnelling (NMT) these methods have been adapted to forms of contract and construction practice in the UK where it is referred to as the Sprayed Concrete Lining (SCL) method. As implied by the title the form of construction places the tunnel support in the form of sprayed concrete in a controlled sequential excavation using purpose-built and conventional mechanical excavators and loaders. The sprayed concrete is installed using semi-robotic concrete spraying equipment fed by specially formulated concrete that can be either batched on site or supplied as readimix. The initial sprayed concrete support may be followed by a further, sprayed concrete or cast-in-situ concrete permanent lining.

6.2.5 Compared to a TBM the rate of progress is relatively slow and more labour intensive but the method has a number of key advantages. It involves a relatively low capital and operating cost and is much quicker to set up. In addition, it requires far less operational and logistical back-up during construction, consequently a number of tunnelling faces can progress simultaneously and cost-effectively. However, its most attractive feature is its flexibility, which allows the construction of variable size and shapes of tunnel and complex interconnections.

6.2.6 For tunnel lengths of only several kilometres in length SCL can be more cost effective than TBM tunnelling. Recent examples include the 3.2km long, 12m diameter HS1 North Downs Tunnel and the twin bore 1.8km long, 11m diameter A3 Hindhead tunnels. The use of SCL does depend on the degree of fissure groundwater flow in the locality and the extensive use of this technique would need to take the conditions into account.

6.2.7 SCL is, therefore, often used as a supporting method to the main TBM tunnel construction where it can cost-effectively form a number of key features such as TBM launch and reception chambers, cross passages, turnouts, sumps and caverns. The method is also widely used for shaftsinking. SCL was used extensively on the Heathrow Rail Link, Jubilee Line Extension and Crossrail and is planned for future major projects in the UK.

6.3 Tunnel layout and dimensions

Running tunnels

6.3.1 As currently planned the circular running tunnels will be twin, uni-directional, 8.9m internal finished diameter TBM bores. This is similar to recently planned and constructed high-speed long railway tunnels in Europe such as the Alpine Base Tunnels. The tunnel size is dictated by the clearances required by the trains, overhead electrification, track bed and walkways together with the aerodynamic (transient pressure) criteria required by the high speed rail traffic. The tunnel lining thickness is indicated as being 400mm.

6.3.2 On the Channel Tunnel 2m diameter pressure relief ducts connect the running tunnels at 250m intervals enabling a reduction in tunnel size to 7.6m internal diameter. This approach could also be considered for HS2 although the planned train running speed is higher and therefore suitability would need to be checked along with a number of other parameters which influence tunnel diameter.

6.3.3 It is advantageous not only from a railway operational point of view but in construction to align the running tunnels as straight and at as constant a gradient as possible. Vertical and horizontal curves require the use of tapered precast lining segmental rings that can be offset rotated as they are erected inside the TBM to enable the installed lining to negotiate the curve. Straight tunnels or tunnels with only very gentle curves can utilise non-tapered rings, the slight offset being taken up by the compression of the gaskets between adjacent rings. However, as this degree of straightness is uncommon, the use of tapered rings has become the norm, with variable orientation of the taper used to produce the necessary vertical or horizontal curvature.

6.3.4 Modern TBMs have little difficulty in maintaining exact alignment; utilising state-of-the art laser guided steering systems. However, in order to steer the TBM around a curve it must exert greater thrust force on one side of the ring than the other, which if not carefully controlled can damage the concrete segment.

6.3.5 The Green Route offers a more direct and straighter alignment both horizontally and vertically and will therefore make tunnel lining manufacture and TBM operation easier, potentially offering programme and cost benefits.

Intervention gap

6.3.6 So as to classify the tunnel as two tunnels and remove the requirement under the TSI for special safety investigation it is necessary to provide an intervention gap in a suitable valley or open cut. Consequently a 1,000m long emergency intervention gap is planned on the Green Route at Wendoverdeane Farm south of Wendover. The intervention gap will be provided with station platforms, passenger egress and emergency service access facilities. In addition, about half of its length may be taken up by a track crossover. The incorporation of this feature, though it may be considered beneficial for operational and emergency use, will add cost and risk implications which would need to be evaluated.

6.3.7 An alternative arrangement is discussed in paragraph 6.3 40.

6.3.8 The intervention gap will require the construction of four acoustic portals and will be open to the weather resulting in slope erosion, drainage issues, snow and leaves accumulation and frost trapping. It would also present a very large security problem both during construction and long-term requiring a fenced, floodlit and monitored perimeter over 2km in length. Furthermore, the excavation and spoil removal volumes could be substantial (up to 0.5M cubic metres on the Green Route).

6.3.9 If this feature were to be constructed as a covered box to avoid the above problems and permanently scarring of the landscape, much of the excavated material would need to be temporarily stored on site for backfilling and compaction after the reinforced concrete structures, which would themselves be expensive, are constructed. Both the removal of spoil from the site and the transportation of construction materials to the site would also be substantial, the works for which requiring a major site set-up in itself.

6.3.10 An alternative arrangement is discussed in paragraph 6.3.33.

Tunnel lining

6.3.11 The running tunnels will be lined with pre-cast concrete segments that are assembled to form a ring attached to the previous constructed rings forming the tunnel within the TBM. The tunnel segment rings are likely to be about 2m wide and assuming that 7 segments are required for each ring, then, very simply 3,500 rings are required for 1km of one tunnel. For 25km of twin bored tunnel then the number of segments required is approximately 175,000. Crossrail, currently under-construction, involves the excavation and lining of 21km of running tunnels using pre-cast concrete segments and the casting of some 173,000 segments each 1.7m wide. On Crossrail, segment manufacture is being undertaken from 4 factories; two located in the Medway, one located in west London and one located in central Ireland. The choice of location for manufacture is highly dependent on the proximity to the location of use, the availability of land to create a temporary (site) factory and transportation costs. For HS2 it would be preferable to create a temporary (site) factory at or close to the point of use i.e. at the tunnel portal, particularly given the very large size of the segments. Another option would be to establish a manufacturing site located along the Chiltern Line and a rail loop and handling facility near the portal. Although this could duplicate some infrastructure it could be shared with spoil handling arrangements if this was also transported by rail for which see paragraph 6.5.

6.3.12 The segmental lining design is usually bespoke to the particular project and takes into account the geological and hydrogeological environment, spatial and operational requirements of the railway, internal structures and fixings. In addition, it should take account of stresses applied during manufacturing, handling, storage, transportation and installation as well as the forces exerted by the forward thrust of the TBM. Consequently the product must be of the highest quality and manufactured to exacting tolerances. It will likely incorporate one or more gaskets to prevent water ingress and a system for post-grouting behind the lining. Once installed it is extremely difficult and costly to repair a damaged segment therefore quality control is essential at all stages leading to the completed lining installation.

6.3.13 The 400mm thick lining indicated in the HS2 information implies that the segmental lining will be steel fibre reinforced rather than using steel rebar cages. At 8.9m internal diameter it is probably within, though at the upper end of the economical range for this type of lining. The use of rebar cages has certain disadvantages in terms of material cost and manufacture but has a significant advantage in terms of its structural performance, which can significantly reduce its thickness by as much as 100mm. This in turn reduces tunnel diameter by 200mm thereby reducing the size and power consumption of the TBM and the volume of spoil to be removed as well as a number of lesser economic benefits such as reduced transportation cost, grout volumes etc. Over the tunnel lengths being proposed this option should be considered carefully.

6.3.14 If the Intervention Gap or alternatively, an Emergency Station, is located closer to one end of the alignment, then it may be more economical to construct the shorter portion of the tunnel using Sprayed Concrete Lining (SCL). Excavation in this case would be performed with a roadheader in top heading and a road planer to remove much of the remaining material to the tunnel invert. This has the added advantage of producing engineering fill at source for use locally. In this case the primary tunnel lining would comprise sprayed concrete whilst the secondary or permanent lining may comprise either sprayed concrete or cast-in-situ concrete.

6.3.15 Very effective fire resistance can be provided for all forms of concrete tunnel linings by the inclusion of a small amount of fine plastic fibres in the mix. This adds little to the cost and does not affect the concrete performance. It will, however, enable the tunnel linings withstand fire loads of up to 1,300^{O}C and should be considered.

Tunnel separation

6.3.16 In low-stress rock environments there are no technical criteria for tunnel separation despite the generally accepted 'rule of thumb' that this should be not less than one tunnel diameter. This is traditionally based on the concept of tunnels potentially interfering with or destabilising each other during construction but this is only true in high rock stress environments such as through the high Alps. The tunnel separations shown in the HS2 proposals are at least 19.4m centre to centre and appear to follow this rule.

6.3.17 It is true, however, that if the tunnels are too close together an intervening rock pillar in weak rock can become overstressed but since the tunnels will be driven by TBM and structurally lined immediately, this has little consequence. For example, many large segmental (cast iron and concrete) and SCL lined London Underground tunnels in clay are extremely close together and, in some cases, actually touching.

Tunnel cover at the Portal

6.3.18 In a similar approach to tunnel separation, a commonly used 'rule of thumb' to define the minimum cover to the tunnel at the portals is that this should be not less than one tunnel diameter. Again, unless there are specific geotechnical, environmental of constructional reasons for this there are no general requirements relating to the portal depth, indeed the cover to the crown of the tunnel at the portal can be virtually zero. Whilst it may be convenient to cut or bench back unstable superficial deposits or weathered rock to expose rockhead there is usually no need to further excavate the face to establish the tunnel portal.

6.3.19 It is, however, sometimes useful to excavate the initial portion of the tunnel in Sprayed Concrete Lining as a launch cavern for the TBM. This enables the shield section of the TBM to be initially advanced without thrusting off the lining rings, which can then be erected in the launch chamber behind the shield. Here the SCL launch chamber can be constructed almost entirely in the superficial deposits and weathered rock without need to excavate them back to expose the rockhead.

6.3.20 In addition, it is becoming current practice to drive the TBM directly out of the exit portal, which is then completed after removal of the shield rather than fully pre-preparing it for the TBM arrival. This could be done, for example, at the intervention gap if it suited the programme.

Portal arrangements

6.3.21 It is assumed that the southern portal has been fully assessed by HS2 Ltd as it forms part of the Reference Route and the relevant mitigation measures would apply, whichever route is selected.

6.3.22 The north portals will be constructed either as a retaining cutting (Reference Route at Mantles Wood, Intermediate Route at South Heath and Reference Tunnel at Wendover) or as a landscaped engineered cutting (Green Route at Wendover) depending on the location and vertical alignment, though the final portal may probably contain a combination of the two solutions. At the commencement of the tunnel drive the portal would temporarily be in cut, with the permanent engineered arrangements following, to suit the programme.

6.3.23 The portals can be designed to facilitate TBM construction and consequently the cover above the tunnel to the ground can be much reduced on the Reference Tunnel route, removing this constraint on vertical alignment and removing the need for the green tunnel at its northern end.

6.3.24 As discussed with the tunnel separation there is no reason why the portals cannot be located close together, unless there are other overriding operational or acoustic criteria.

Shafts

6.3.25 Vertical shafts connect the running tunnels to the surface at nominal 2.5 to 3km intervals. These are provided for emergency intervention access and escape and for emergency mechanical ventilation to control smoke and hot gasses. The shafts vary in depth along the route but little detail is available on the dimensions or internal structures and equipment required except to note that it is known that a minimum depth of 25m is required to accommodate the plant and equipment. It is assumed that the same principles would be applied to any of the tunnel routes.

6.3.26 As an example, the Alpine Base tunnels have far fewer vertical shafts because of the depth. Nevertheless, the use of current ventilation control systems and emergency evacuation procedures are sufficient to ensure adequate smoke control and safe evacuation. The relatively shallow HS2 tunnels do allow for additional emergency shafts, however, the strict adherence to a 2.5km to 3km separation is probably unnecessary as some shafts may be located away from the main roads and special access will be required. Consequently, their locations on either route could be re-examined to reduce their number and site them closer to easy surface access points.

6.3.27 The shafts can be constructed using a number of methods; however the most cost effective is by first raise boring from the running tunnels to the surface then shaft sinking from the surface to the running tunnels. Although the feasibility of this method is highly dependent on the main tunnelling programme and logistics it would significantly reduce the cost of the large number of shafts required by HS2 Ltd.

Cross Passages

6.3.28 A means of access from one running tunnel to the adjacent tunnel is required for evacuation should an incident occur. This is usually accommodated by means of regular equi-spaced cross-passages so that a central service tunnel is not required.

6.3.29 The tunnel walkways connects to these 3.5m internal diameter cross passages located at 250m centres between the twin bores. The cross passage dimensions are set mainly by the requirements for passenger evacuation and emergency services access. In the event of a train emergency passengers can transfer along the walkways and through the cross passages to the adjacent tunnel bore from where they can be evacuated via shafts or train. The cross passages would be provided with doors to maintain the independent air flow along the running tunnels and prevent smoke from moving between them. Other than their basic dimensions, little information is provided as to their construction or internal finishes.

6.3.30 The size and spacing of the cross passages are fairly conventional and is related to the train length and passenger capacity. However, on the Alpine Base Tunnels cross passages are provided at 325 to 333m intervals, whilst they are 375m apart on the Channel Tunnel. The frequency of these passages warrants review to optimise it with the tunnel design and construction methods. The will not affect the critical path of tunnelling and mechanical fitout.

6.3.31 The criterion used for the selection of the cross passage interval should therefore be closely re-examined.

Alternative to surface intervention gap - Emergency Underground Station

6.3.32 The intervention gap escape station and crossover could be readily and cost-effectively constructed entirely underground in bored tunnels, inclined adits and shafts. Since it would provide a full and equivalent provision for emergency evacuation it should satisfy the TSI requirements. This approach has been adopted for all of the Alpine Base tunnels and presents some substantial benefits over the planned surface intervention gap on the Reference Tunnel or Green Route.

6.3.33 The emergency underground station and crossover can be constructed by conventional Sprayed Concrete Lining (SCL) methods gaining access via a vertical shaft sunk from the surface or by inclined tunnels. Similarly to the Ventilation Shafts, this vertical shaft could then be installed with fans and dampers for forced ventilation and smoke extraction of the completed station whilst the inclined tunnels would provide the passenger escape route to the surface and access for the emergency services.

6.3.34 The parallel ovoid profile station platform tunnels would be 500m long and about 13m wide to accommodate the required 5m wide platforms. An escape and emergency services tunnel would run between the tunnels at platform level and connected to the platform tunnels by short crosscuts at about 100m intervals. The crosscuts would be provided with double ventilation doors that would prevent smoke entering the escape and emergency services tunnel and the adjacent platform tunnel. In addition, the escape and emergency services tunnel would be pressurised by the ventilation system to maintain a clean airflow during an emergency evacuation. Passengers would be directed by electronic signage and public address announcements to either move along the escape and emergency services tunnel to the inclined escape tunnel leading to the surface or onto the adjacent platform. Lifts would be provided in the ventilation shaft to convey mobility impaired persons to the surface; alternatively electric vehicles could be stationed at the bottom of the inclined escape tunnel.

6.3.35 Smoke and heat extraction would be through a tunnel located above the escape and emergency services tunnel, which is connected by horizontal crosscuts at about 100m intervals to the crown of the platform tunnels via vertical ducts. The crosscuts would be provided with dampers to prevent smoke and heat from entering the adjacent platform tunnel. The smoke and heat extraction tunnel is connected to the ventilation shaft where fans maintain a negative air pressure in the tunnel and crosscuts.

6.3.36 Sprinkler systems could be installed to control the spread of fires and reduce heat allowing the emergency services to gain access.

6.3.37 The main advantages of the emergency underground station are that:

- It can be sited at the most advantageous location along the tunnel route for emergency access.
- The running tunnels vertical alignment would be unaffected by the location of the station and could therefore be the most economical in terms of train operations.
- The surface environmental impact of the facility would be minimal.
- Security would be much simpler.
- The facility would be unaffected by weather.
- A fire would be better contained and controlled whilst the emergency services arrive.
- Passengers can be rapidly evacuated to safe and secure areas to await the arrival of the emergency services.

6.3.38 Taking into account the above benefits an emergency underground station would provide a much more cost-effective and sustainable long-term solution than the proposed intervention gap facility, the deemed TSI compliant solution for the Reference Tunnel and Green Routes. An example layout of an emergency underground station is provided in Appendix D.

Alternative Underground Crossover

6.3.39 In order to provide operational flexibility a track crossover is located in the intervention gap thereby extending its length by a further 500m. Alternatively the crossover can be readily constructed underground at any point along the tunnel alignment using SCL techniques. Again this approach has been adopted for the Alpine Base tunnels and has also been employed on Channel Tunnel, Heathrow Express Rail Link, Jubilee Line Extension and Crossrail.

6.3.40 The form of construction is simply four SCL turnout caverns constructed from the running tunnels and linked by SCL crossover tunnels. Depending on programme requirements, the crossover could be constructed in advance of the TBM drive reaching it, in which case access for construction would be via a vertical shaft from the surface, which would later serve as a ventilation and emergency escape shaft. Alternatively, it could be constructed from the running tunnels once completed.

6.3.41 The main advantages of the underground crossover are:

- The running tunnels vertical alignment would be unaffected by the location of the crossover and could therefore be the most economical in terms of train operations.
- The surface environmental impact of the facility would be minimal, particularly noise.
- Security would be much simpler.
- The facility would be unaffected by weather.

6.3.42 Taking into account the above benefits an underground crossover would provide a much more cost-effective and sustainable long-term solution than the proposed intervention gap facility.

6.4 Ground movement

6.4.1 Once the tunnels have reached a depth below the superficial materials and weathered rock (around 1 or 2 tunnel diameters) surface settlement will be negligible or too small to measure. In low stress rock environments ground movement resulting in tunnel convergence (also referred to as volume loss) is also generally very small, although in very weak rock or faulted ground localised squeezing conditions can occur but these can be predicted in advance by adequate ground investigation and geotechnical analysis. The greatest risk of significant ground movement would occur if karstic features or buried valleys were encountered. Again this risk can be quantified and taken account of in the tunnel design.

6.4.2 Ground movement can also occur in Marl seams and Marly chalk through long term creep. Where this could cause a risk at the surface stress distribution modelling will be needed but it is anticipated to be a low risk to buildings and private properties along the Green Route where the tunnel depth is over 70m.

6.5 Spoil behaviour, processing and disposal

6.5.1 Chalk slurry arising from the slurry-TBM will usually require processing to convert it into a material suitable for other purposes, such as engineering fill. This involves passing the slurry first through screens (to separate flints) and then into filter presses, with the addition of a small amount of slaked lime to make a suitably dry cake. Given the size of the slurry-TBMs, their likely rate of advance and the length of the tunnel a very large quantity of slurry will require treatment.

6.5.2 An advantage of the slurry system is that it can be transported for very long distances by pipeline before treatment, which reduces both the cost and impact of transportation. It would, therefore, be preferable to locate the slurry treatment plant (STP) close to the site of final disposal, otherwise it would be necessary to haul the filter cake on public roads or rail to its disposal site. For example, since 1965 Cemex (and its predecessors) have been operating a 92km (55 miles) chalk slurry pipeline from the Chilterns to its cement works at Rugby. Such a pipeline could be laid to Calvert, approx. 20km northwards along the trace of HS2, for disposal. Subject to suitable environmental assessment, particularly in relation to groundwater impacts, there could be opportunities also to feed the slurry to Pistone Quarry, approximately 11km north east, for cement materials use or to Chinnor Quarry, 11km south west for selective backfilling. This gives considerable scope to the final locations of the spoil and the STPs and will reduce the impact of potentially transporting the material by road through adjacent communities such as Stoke Mandeville and Aylesbury. Transport by rail along the Chiltern Line to Calvert or elsewhere is also a possibility.

6.5.3 In contrast, the Reference Route and Intermediate Tunnel will incur considerable road transport movements of materials into the AONB and in the surrounding area, particularly for the placement of over 1,000,000 cu.m of surplus material in Hunts Green, much of which has been stated in the Environmental Statement to be unsuitable material from elsewhere in the works

6.5.4 Chalk spoil arising from open excavations or SCL tunnelling should be generally suitable for use as construction fill material. Depending on its type and moisture content it could, however, be sensitive to excessive disturbance and handling resulting in a rapid degradation to what is often referred to a ‘putty chalk’. In this form it becomes difficult to handle, store, lay down and compact and can present an unsightly mess or even a hazard on site and nearby roads that is difficult to remove.

6.6 Logistics

6.6.1 The logistics of the entire tunnel construction scheme will revolve around the selection, number required and procurement of the TBMs, together with their back-up facilities including spoil treatment and disposal and the manufacturing and supply of the precast concrete segmental lining.

6.6.2 For example, the procurement of four TBMs may potentially reduce the overall construction time as opposed to using 2 or 3 machines but would increase the rates of spoil disposal and materials supply, probably requiring larger facilities and certainly increasing surface activities, traffic movement and short-term environmental impact.

6.6.3 The main ancillary tunnelling activities to the running tunnel drives will comprise:

- Portal construction;
- Cross passage construction; and
- Shaftsinking.

6.6.4 If the emergency underground station and underground crossovers were adopted this would also include:

- Inclined SCL escape and emergency services access tunnel (ca.1000m long).

- Horizontal SCL escape and emergency services access tunnel (500m long).
- SCL platform tunnels (2 x 500m long).
- SCL escape and emergency services access crosscuts (10 no. 2m long).
- Smoke extraction tunnel (500m long).
- Smoke extraction cross passages (10 no. 12m long).
- Vertical smoke extraction ducts (10 no. 2m long).
- SCL turnout caverns (4 no. ca 100m long)
- SCL crossover tunnels (2no. ca 200m long)

6.6.5 However the formation of four portals in the intervention gap together with the open excavation would be eliminated.

6.6.6 In the Reference Alignments the main logistical problems would be phasing the construction of the ventilation shafts and crosscuts so as to minimise their programming impact on the main TBM drives. If a section of the running tunnel lengths were constructed in SCL this would be far less a problem and may even assist in programming the works by providing additional access to multiple advancing faces.

6.6.7 The additional works required for the emergency underground station and underground crossovers could be phased into the TBM drives by commencing them early in the programme. The time required procuring, manufacturing, supplying, assembling, launching and drive the TBMs to these locations should allow sufficient time to complete them to a degree sufficient not to interfere unduly with TBM progress. Furthermore the platform and turnout caverns would provide an opportunity to maintain and refurbish the TBMs, as was the case on the Channel tunnel.

6.7 Tunnel impacts

Construction noise, dust, light pollution and vibration

6.7.1 Construction noise dust and light pollution arising from the tunnelling operations would be confined to the worksites located adjacent to the portals and shaft headworks. Modern tunnelling sites impose strict controls on these areas, particularly at sensitive locations such as near hospitals, schools and residential properties. The local environmental impact can be restricted by the erection of hoardings or even acoustic sheds around the worst affected areas. Further restrictions on floodlighting and night-time traffic movement can also be imposed.

6.7.2 The main noise pollution emanates from the ventilation fans, mobile generators and compressors, assuming that they are required and other plant operating in these areas. Virtually no noise would emanate from the underground tunnelling operations themselves.

6.7.3 Ground vibration arising from the tunnelling and shaftsinking excavation activities may be a problem in certain sensitive areas, particularly at night. However, these would likely be confined to areas where the tunnels and shafts are at shallow depth. Since most, if not all of these activities will comprise mechanical excavation in weak rock ground-borne vibrations are likely to be small. Ground vibration problems tend to arise from the use of hydraulic breakers and blasting, neither of which are anticipated on this project.

Operational noise and vibration

6.7.4 Operational noise will be confined to the portal areas where trains enter and emerge from the tunnels at high speed causing a pressure wave to emanate from the portal mouth. To counter this effect the portals will be provided with specially designed structures that will attenuate this effect to an acceptable level. Once a train has fully entered the tunnel there would be no discernable noise transmitted to the surface.

6.7.5 As second significant source of operational noise will be the ventilation fans located in the shafts. Each shaft would be provided with a surface structure housing the attenuators that would restrict the noise to acceptable levels. However, during an emergency or routine maintenance testing, the fans may be boosted and the normal noise levels exceeded for the duration of the incident.

Worksite locations

6.7.6 Due to the length of the tunnels two main tunnelling worksites are required one located at the southern portal the other at the northern. Main tunnelling worksite locations (from which the tunnels are constructed) are largely dictated by where the tunnels break the surface, at the tunnel portals. The ability to be able to economically deliver the works relatively unhindered by worksite size, access and environmental constraints is an important factor and may influence the particular location of the portal. The southern portal in all of the options appears fixed and lies between the M25 and the River Colne/A412 corridor. In this study it is considered that the northern portal location may vary and so may the location of the tunnelling worksite. Its final location may be due to the ability to provide a suitable worksite as much as meet the requirement of the railway or meet environmental requirements.

6.7.7 The main tunnelling worksites for this project will need to provide the following:-

- Access to the tunnel, probably via an open cut or retained cutting (an anchored retained cut would occupy a smaller plan area than an open cut);
- Space to construct the portal structure;
- Space along the alignment to allow for construction of the tunnel boring machines;
- Space for materials storage, welfare facilities, offices, workshops, car parking etc;
- Space for slurry processing, water treatment and spoil stockpiling (if the slurry is not pumped direct to the disposal site);
- Space for segment manufacture including batching plant and storage.
- Space for temporary worker accommodation.

6.7.8 To incorporate all the above features, a main tunnelling worksite will cover a total area of about 200,000m^2. A segment factory would cover an area of about 30,000m^2 assuming that the SCL method discussed in paragraph 6.2.4 is not used.

6.7.9 There are two potential worksite locations for the northern portal. One adjacent to the A413 and Chilterns Railway Line north of Wendover (Reference Route), the other northwest of Wellwick Farm (Green Route).

6.7.10 Worksites will also be required at other locations to receive the TBMs. These will be located wherever the drives are concluded; this may be an intervention gap or an underground station. Ideally, it would be preferable not to have to construct a further worksite and access point specifically to retrieve the TBMs, rather they should be combined with a permanent structure. A slightly enlarged vent shaft could be used, such as one located near a main road

6.7.11 Options for the location of the intervention gap appear to be limited, on the Reference Tunnel Route at Durham Farm and on the Green Route adjacent to the A413 at Wendoverdean Farm.

6.7.12 An underground emergency station referred to in paragraph 6.3.33 gives significantly greater options for its location, though for programming the works and optimising the work from any one worksite this would make a location close to mid-point along the alignment preferable. The location of the main surface worksite may not necessarily coincide with the plan position of the emergency underground station as its location may be gained via inclined adits (direct surface access above the station will probably be required for ventilation shafts). The location of the emergency underground station may be dictated by the proximity to the major roads and conurbations with supporting established emergency services and hospitals. This could be adjacent to the A413 just outside Amersham. The TBM could actually be used to form the inclined adits and be retrieved at the surface.

6.7.13 Smaller worksites will be required for shafts. These are ideally located adjacent to existing roads where these cross the alignment. If additional facilities are required for pressure relief then these should be managed within the tunnel system without breaking the surface, such as was done on the Channel Tunnel and reducing the number of shafts.

6.8 Construction programme for Reference Tunnel and Green Route

6.8.1 The discussion below only relates to the Reference Tunnel and Green Routes as it has been reported that adopting a fully tunnelled solution will add about 8 months to the programme for the whole of HS2 Phase One.

Construction options/arrangements

6.8.2 There are a number of options available for sequencing the tunnelling and shaftsinking activities and will be largely dictated by the overall programme requirements and the decision on how many TBMs will be used. This means there are flexible solutions but there are risks which have to be managed.

6.8.3 As discussed, the ancillary works such as the portal construction, shaftsinking, possible emergency underground station and underground crossover could be undertaken as advance works, which could be separate from the main TBM tunnelling, though there would be risks associated with interfaces and delays if they were procured as a separate contract or contracts.

6.8.4 It is possible to undertake the entire tunnelling with only two TBMs working from one end of the scheme and progressing to the other. At the intervention gap or emergency underground station the TBMs would be maintained and refurbished before continuing to the exit portals.

6.8.5 Alternatively, though less likely, each TBM could progress from one portal on opposite sides of the Chilterns to the intervention gap, turn around and continue to the second portal on the side it started from. This option would not be possible in the emergency underground station. Another option would be to launch the TBMs from the intervention gap and turn them around at the portals. On the face of it this may look attractive in that it confines the main worksite to the intervention gap but it would present major problems for materials and spoil movement and would likely be rejected.

6.8.6 A more feasible scenario that would accelerate the programme if the intervention gap were to be located closer to one side of the scheme than the other would be to use three TBMs. Two TBMs would progress from the portals on one side of the scheme towards the intervention gap, where they would be extracted. The third TBM would commence from one of the portals on the opposite side of the Chilterns and turn around at the intervention gap to return to the same side. This option would involve duplication of the worksites at either end of the scheme but one would be smaller than the other offering some flexibility. Again this option would not be possible if an emergency underground station is used instead of the intervention gap.

6.8.7 However, if the emergency underground station was constructed, the shorter running tunnels could be constructed using SCL methods progressing simultaneously on four faces from the ends of the platform tunnels and from the portals. This would have the advantage that the same SCL set up could be used to construct the cross passages and underground cross over as well as the emergency underground station and shafts.

6.8.8 Railway systems fit out rates will not be the determinants of overall programme progress, as long as appropriate hand-over of accessible linear sections can be provided. Modern ballastless track laying on this scale will be achieved by purpose built contractor-owned track-laying trains, which achieve progress rates of around 300m per day. There are unlikely to be any demands for complex resilient track such as floating track systems, which do have a much more significant cost and programme impact. Fit-out of control, communication and electrification systems will generally follow close behind the track laying train. Testing and commissioning can be achieved in stages and again, this will not have any significant impact upon the overall programme.

Rates of progress

6.8.9 It is important to bear in mind the long lead-in time for each TBM. The works programme should allow for:

- Design.
- Procurement.
- Manufacture.
- Factory commissioning.
- Transportation to site.
- Assembly.
- Site commissioning.
- Launching.

6.8.10 The entire process can take 1 to 2 years and may be affected by the demand for TBMs worldwide at the time since there are only a limited number of manufacturers, particularly in Europe that would be capable of producing machines to the specifications required.

6.8.11 Once underway a modern slurry-TBM driving through soft rock should achieve an average advance rate of between 300 to 400m per week, working 24/7, 365 days per year, including down-time for routine maintenance. However, the back-up services together with tunnel lining segment supply and spoil treatment and disposal should be geared to a minimum advance rate of 400m per week, year-round. If more than one TBM is operating simultaneously then these should be increased accordingly.

6.8.12 This will require careful sizing and implementation of the segment manufacturing facility, together with storage at the factory and on site with adequate transportation arrangements fro their delivery to site. It is an obvious advantage for major tunnelling projects such as this to locate the manufacturing facility as close as possible to or within the worksite thereby reducing transportation costs, storage areas and environmental impact. On Crossrail this has not been the case as discussed in paragraph 6.3.12.

6.8.13 Similarly the spoil treatment facility would normally be located close to or within the worksite, although it may be possible using modern slurry pumping technology to transfer this to a more remote location to reduce the local environmental impact.

6.8.14 Rates of progress for SCL tunnelling and shaftsinking would be far less than the TBM drives amounting to only several metres per day. However simultaneous multiple drives can significantly increase the overall rates of progress and the materials delivery and muck away logistics can become significant.

6.8.15 For large SCL projects sprayed concrete and cast-in-situ concrete batching is normally undertaken on site. This provides better control and consistency of the concrete mix but the process will impact on the worksite environment. Smaller SCL projects often rely on readimix but this would be unlikely for the HS2 tunnels and shafts except to supplement the site batching if necessary.

6.8.16 It should be noted that major tunnelling projects such as this where large volumes of concrete are consumed there can be an impact on local supply of cement and aggregates that can affect concrete quality and production and consequently affect the programme. This risk should be taken into account.

Activity durations

6.8.17 The entire tunnelling works (not including TBM procurement) should be completed in about 3.5 years.

6.8.18 This shows that adopting the Green Route or the Reference Tunnel offers a number of flexible methods of working, which would be tailored to suit the timetable and not result in delay to the whole project.

6.9 Constructability of Reference and Intermediate Routes

6.9.1 In order to compare the Reference Alignments with the alternative Green Route, the issue of constructability of the Reference and Intermediate Routes are considered below.

6.9.2 As well as the portal structures in Mantles Wood (Reference Route) or South Heath (Intermediate Route) there are a number of significant structures proposed as part of these Routes, namely:-

- Wendover Green Tunnel

- Small Dean Viaduct
- Wendover Dean Viaduct
- South Heath Green Tunnel (not required with the Intermediate Tunnel Route)

6.9.3 As discussed in Section 5 of this report, it is considered certain that sink hole features will be encountered on any of the proposed routes as they cross the Chilterns. The effect these have will vary dependent on the chosen solution. The effect on the tunnel is evidently significant but as noted it is something that can be dealt with through the use of a specialist TBM. However, if these are encountered in the vicinity of the proposed viaducts on the Reference Route and Intermediate Tunnel, then this could have consequences for the foundations to the viaducts. The infilling of the sink holes will have a programme and cost impact.

6.9.4 If the sink holes, deep fissure and groundwater flows are encountered near the locations of the green tunnels, they will also have a cost and programme impact. In addition the stability of the slope across which the Wendover Green Tunnel passes, as discussed in Section 5, could make this construction solution very challenging.

6.9.5 As the costs included in the current figures for the Reference Route are very generic it is difficult to estimate what has actually been included for the construction of the viaducts alone. A figure of £790 million is included in HS2 Ltd.'s Cost and Risk Model (Jan 2012) Table 4 for bridges and viaducts. The cost of infilling sink holes could be relatively small compared to this figure, although still run into millions of pounds. However, the effect on the programme could be several months of delay and the costs associated with this delay would potentially be more significant.

6.9.6 The issue of risk was considered in the appendices of HS2 Ltd.'s Cost and Risk Model. The issue of geology and potential impact does not appear to have been considered to any significant extent. This will affect both tunnel and surface route; however, the means by which it can be dealt with can be mitigated more effectively with the TBM. For the viaducts and surface route permanent way encountering a sink hole will result in a halt to construction work while the issue is overcome. In the long term, instability below the surface track due to undiscovered solution features below the formation, potentially destabilised due to the change in surface loading, drainage regime or more direct exposure to weathering could cause ongoing maintenance problems with the permanent way.

6.9.7 The Cost and Risk Model at Appendix C includes a risk to the programme of 'uncertain ground conditions' but this does not appear to adequately address this issue, and neither does the table in Appendix D of the same document. It is therefore concluded that this significant risk has not been adequately dealt with in these estimates.

6.9.8 Other issues that the proposed structures cause that a tunnel alternative does not:-

- Maintenance liability – of the structures and track, the tunnel provides a more stable and reliable environment in which the train can operate.

- Construction programme uncertainty. Given the geology that will be encountered through the Chilterns, programme delay due to this issue is likely. The mitigation of this risk is more effective in a tunnel solution as the capabilities of the TBM are known. The size of sink holes and the time it will take to infill them is difficult to quantify, but something should be added to the costings of the surface route to take this into account.

- As noted in Section 4 the track will be more durable in the tunnel and whole life track costs, currently not included in the HS2 CRM will be reduced if the track is 'protected' within the tunnel. As the alignment of the tunnel is straighter than the surface route, wear and tear on the track will also be reduced.

6.10 Comparative Cost Model

6.10.1 The effectiveness and value of the proposed tunnel alternative can only truly be assessed by consideration of its whole life costs. A detailed quantitative examination of the cost basis is beyond the remit of this report. However, it is possible to assess comparatively and qualitatively the relative impact of the proposals on cost in terms of CAPEX and OPEX.

Table 6.1 Qualitative CAPEX comparison

CAPEX cost	Comparison of Green Route against Reference Route
Land acquisition and permanent rights (incl. compensation)	Lower
Environmental mitigation measures	Lower
Permanent civil works	Higher
Rail systems	Similar (lower)

Table 6.2 Qualitative OPEX comparison

OPEX cost	Comparison of Green Route against Reference Route
Traction power	Lower
Maintenance	Similar
Renewals	Lower
Operation	Lower

6.10.2 Against these figures must be placed the costs of 'loss of environment' in the Reference Route. It is for society to judge, perhaps through the Cabinet Office's Natural Capital Committee, whether indeed the costs of permanent and irretrievable 'loss of environment' outweighs the cost of the Reference Route. In the past, infrastructure promoters and planners have been all too ready to develop schemes to the detriment of the environment and the permanent and irretrievable 'loss of environment' even though engineering solutions could have been used that would have prevented the loss at a small additional cost against the whole life costs. Schemes such as the M40 cutting at Stokenchurch, M27 Brighton Bypass and the M3 at Winchester have all demonstrated the incredible permanent damage infrastructure schemes have on the environment and the chalk landscape in particular, when greater mitigation measures could have been employed to limit the damage had the cost of 'loss of environment' been considered. Conversely, the A3 at Hindhead has demonstrated the tremendous value of delivering major infrastructure with negative 'loss of environment' costs. For the Reference Route, the cost of 'loss of environment' is very high. This is discussed in the Non-Market Effects Report prepared by Peter Brett Associates and Chilterns Conservation Board, submitted in response to the Environmental Statement.

6.10.3 There are some very important considerations that have to be taken into account in estimating the costs associated with long distance tunnels and the provision of the railway in tunnel. There are considerable economies to be achieved in long distance tunnelling and the cost per m reduces the longer the tunnel. It would be interesting to compare whole life route cost per m for a long tunnel versus the whole life route cost per m for surface railway. Long distance tunnelling would be constructed from essentially only two sites, whereas the Reference Route and Intermediate Route involves the costs associated with multiple and long linear sites throughout much of the length of the route through the Chilterns. The Reference and Intermediate Routes also require diversion of major overhead powerlines.

6.10.4 Arguably the scheme can be amended to reduce the scope in some areas, for example, it is unnecessary to have shafts at 2 to 3km centres for the full length of the route. Rather these can be placed at key points along the alignment best for ventilation (emergency) and for access. The number of cross-passages can also be reviewed with a view to reducing scope (a spacing of 500m is being used in Germany). Relative costs for portals between the schemes are probably similar though the deletion of the Intervention Gap would remove the cost of two additional portal locations and the considerable environmental disbenefits it creates. An Emergency Underground Station can be provided at a modest additional cost, probably about £60million. Given the benefits that an Emergency Underground Station has on the vertical alignment, reduced environmental impact and its flexibility of location, this cost is not significant. The equivalent facilities built as a cut-and-cover structure would probably be more than double that for the mined solution. Furthermore, there are significant environmental disbenefits in the construction of a cut-and-cover structure.

6.10.5 Rail systems whole life costs are probably cheaper for the tunnel than for the surface, as the systems are protected from the weather which extends their life. Certain structures are much smaller and simpler to install and maintain for the fact that the tunnel itself provides the structure upon which to fix equipment.

6.10.6 Whilst the initial capital cost for ballastless track is generally higher than that for ballasted track, the cost per metre within tunnels is closer, due to the similar requirement to move and handle material within a confined, linear site and the relative ease with which concrete can be placed (pumping) whereas ballast handling is more difficult in open sites.

6.10.7 Well-constructed ballastless track (which, by the time these tunnels are fitted out, will be better defined due to the pending Euronorm EN-16432-1 Railway Systems – Ballastless Track Systems) will require significantly less maintenance than ballasted track and is well suited to semi-automatic inspection and fault detection, such that the whole life cost of the tunnel track system can be expected to be increasingly lower than that for ballasted track.

6.10.8 A cost basis which has been used is the Estimate of Expense dated 15th November 2013. This document provides costs for elements of work associated with HS2 and is a document presented before Parliament. It identifies CAPEX costs only and suggests a total of £19.39bn for Phase One, including contingencies at a P50 level of confidence.

6.10.9 A comparison of costs has been undertaken using this document, which is set out in the Cost Model in Appendix E along with a pro-rata calculation of the options adjusted to examine the relative cost difference between the Reference Routes and the Green Route.

6.10.10 Clearly, it is not practical to challenge the cost basis for the Reference Route as this is being used to set fiscal budgets for the project with Government, though it would be possible to do so and to demonstrate that it would be possible to deliver the scheme at a reduced cost. In particular the extension of the tunnelling work will result in significant economies of scale. However, the Estimate of Expense cost can be considered to include everything associated with the delivery of that element of works.

6.10.11 Table 6.3 summarises the costs of each between the portals and equivalent chainage at Wendover. They include anticipated land, road and services diversion costs The Green Route is measured as being 1km longer. This is partly due to rounding but mainly due to the northern portal being further down the scarp slope than the Reference Routes. Hence a comparative overall average rate has been calculated. This indicates that over an equivalent length of 23.7 km the Green Route would cost £1.78bn.

6.10.12 The cost base used by HS2 Ltd has also been used in these calculations. It is therefore not surprising that the Green Route has been estimated to cost more. 85% of the estimated cost of the Green Route is accounted for by the cost of the tunneling and the total cost is therefore very sensitive to the unit rates which have been used. A 13% change in this cost results in a reduction of £0.20bn in the total cost. None of the alternative features referred to in this report, for example in sections 6.3, 6.5 and 6.6, have been taken into account in preparing this cost estimate of the Green Route. The matter of relative risk is discussed in paragraph 7.3.2.

Table 7.3 Summary of comparative costs

Summary table of comparative costs			
Reference Route	**Reference Tunnel**	**Intermediate Tunnel**	**Green Route**
23.7 km	**23.7 km**	**23.7 km**	**24.7 km**
£ 1.48bn	£1.79bn	£ 1.61bn	£ 1.85bn
Overall comparative rate £'000/km			
62.4	**75.5**	**67.9**	**74.9**

6.10.13 The difference in cost represented by either the Reference Tunnel or the Green Route represents 1.5 - 2% of the overall construction cost of the HS2 Phase One in a budget currently with a P50 contingency level, that is it is assumed that there is a 50% probability of the estimate being exceeded. However it will be a significant mitigation of the effects of the route through the Chilterns AONB, as described in Section 7 below, and avoid extensive compensation costs which are not included in this budget.

6.10.14 In order to make a true cost comparison then the design refinements and logistics proposals must be considered, the whole life cost of the alternatives must be independently assessed, and the non-market effects evaluated.

7 Environmental

7.1 Environmental evaluation

7.1.1 In the scope of this study, the engineering solution developed through the Green Route has taken account of the potential environmental impacts of the comparative routes and avoiding key elements of particular concern. These include long term damage to the protected landscape and its tranquility, tourist benefits, Ancient Woodland and Listed Buildings/Scheduled Ancient Monuments as well as aiming to minimize impacts on residential property. The study does not include a full environmental assessment.

7.1.2 The overall principle of developing a tunnel solution is to provide overall protection of impact on the Chilterns AONB which is not the case for the Reference Route and the Intermediate Tunnel Route. The Reference Tunnel Route offers similar protection to the Green Route although the Intervention Gap is in a more intrusive location.

7.1.3 In considering the tunnel solution, the disposal of spoil from the TBM at the northern portal has also been considered and potential options to avoid the use of road transport, which would have to travel through Stoke Mandeville and Aylesbury are feasible.

7.1.4 The Green Route has been aligned to avoid going directly under Great Missenden Church and Listed Buildings near Leather Lane and the intervention gap is located close to existing transport infrastructure to simplify construction and operational access.

7.2 Aspects

Area of Chilterns AONB affected

7.2.1 Previous studies and the HS2 Environmental Statement has identified that the Reference Route will affect 400ha of land in the Chilterns AONB. Whilst this is considered to be insignificant in the context of the whole Chilterns AONB it is an important impact in a single entity which is the Misbourne valley.

7.2.2 The Reference Tunnel route will only affect 50ha and this is mainly due to the need to construct a section of green tunnel at the northern end to meet the HS2 vertical alignment.

7.2.3 It is estimated the Intermediate Route will affect over 300 ha as the reduction in surface route and avoiding construction of South Heath Green Tunnel represents a small part of the whole length.

7.2.4 The Green route will affect the least, possibly as little as 40ha, as the northern portal will lead directly into an open section and not require construction of green tunnel section. The construction compound for the TBM at the northern portal is estimated to require about 23ha on the edge of the AONB. The intervention gap will require about 5ha, adjacent to the A413.

Visual Impact

7.2.5 The visibility of the Reference Route is significant across the valley and, in the Environmental Statement, is expected to be significant for 60 years despite the additional planting. This time period is effectively admitting that it will continue to be an impact on the Chilterns AONB for a very long time. The infrastructure itself has to be considered as a permanent impact.

7.2.6 The same will apply to the Intermediate Tunnel Route as it is still largely on the surface.

7.2.7 The Reference Tunnel Route and Green Route will both have insignificant effects on the visual impact with only ventilation shafts and the intervention gap visible on the surface.

Ancient Woodland

7.2.8 The area of Ancient Woodland affected by the Reference Route is stated as being 10.2 ha but this could increase if ground conditions at the north portal in Mantles Wood require additional stabilization, which, from our geological assessment, is likely to be the case.

7.2.9 The Reference Tunnel does not affect Ancient Woodland and neither does the Green Route. The Intermediate Tunnel will impact on a small area near the Wendover Dean viaduct.

Listed Buildings and Scheduled Ancient Monuments

7.2.10 As well as requiring the demolition of a number of properties, the Reference Route will run on the surface close to listed buildings resulting in degradation and will destroy a section of Grim's Ditch, as will the Intermediate Tunnel.

7.2.11 The other Reference Tunnel Route and the Green Route will not impact either listed buildings or Grim's Ditch.

Noise

7.2.12 The noise impacts of the Reference Route are set out in the Environmental Statement (ES). These will be substantial and not fully mitigated by the proposed attenuation bunding or fences, particularly on the viaducts. A particular aspect of the Reference Route lies in relation to the noise levels as the northbound trains leave the tunnel at the Mantles Wood portal on a 2.2km stretch at maximum gradient of 3% and are still climbing to the summit for a further 2.7km at 0.76%. This noise will, in every case with each train, result in noise levels higher than the averages predicted in the ES. The operational variations in noise resulting from this steep climb are not reflected by the studies undertaken and underestimate the noise impacts in this part of the AONB,

7.2.13 The Intermediate Tunnel will improve the situation for some properties around Hyde Heath and Hyde End Lane, as well as replacing the South Heath Green Tunnel.

7.2.14 The Reference Tunnel and Green Route will offer the most noise mitigation. The location of the north portal for the Green Route in particular will considerably improve the noise impacts on Wendover and Stoke Mandeville, although some properties in Nash Lee and North Lee might experience a significant change for which additional mitigation measures will have to be considered. The flatter gradients will however reduce the need for full power to be applied to achieve the summit at Wendover Dean Farm, thus reducing the noise levels at source.

Water

7.2.15 The impact of the Reference Route and Intermediate Tunnel on the water regime is substantial and significant. The open sections require major drainage infrastructure away from the line to drain the cuttings and embankments, with large storage and infiltration areas. These could induce movement in filled solution features across a wide area as the routes for infiltration are uncertain.

7.2.16 The Reference Tunnel and Green Route will both have a negligible effect on the water regime as no major drainage systems are needed. There is the potential for interaction with ground water aquifers but these interfaces will be localised within the otherwise broad body of the chalk aquifer.

7.3 Summary of Risks and Impacts

7.3.1 In assessing the risks and impacts of the proposals a broad comparison has been undertaken of each route, considering relative effects on programme, cost and receptors. This is summarized in table 7.1 below.

7.3.2 It can be seen from this assessment that the Green Route has significantly better risk and impact on programme, cost and receptors than any of the other routes and represents a good solution to the provision of a full tunnel for HS2 through the Chilterns AONB.

Table 7.1 Risk and Impacts comparison

		Assessed route			
Topic	**Indicator**	**Reference Route**	**Reference Tunnel**	**Intermediate Route**	**Green Route**
Rail alignment	Gradients	H	M	H	L
	Curvature	H	H	H	L
	Exposure	H	L	H	L
	Security	H	L	H	L
	Safety	M	M	M	L
Rail systems	Maintenance liability	H	L	H	L
	Journey time	L	M	L	M
	Operational flexibility	L	M	L	M
Geology	Stability	H	M	H	L
	Ground movement	M	M	M	L
	Ground water	M	L	M	L
Tunnelling	Construction sites	H	L	H	L
	Spoil handling	H	L	H	L
	Imported materials	M	H	M	H
Construction	Unforeseen ground	H	M	H	L
	Traffic	H	L	H	L
	Weather delays	H	L	H	L
	Complex foundations	H	L	H	L
	Programme	H	M	H	L
Environmental	AONB Land area lost	H	L	M	L
	Visual impact	H	L	H	L
	Ancient Woodland	H	L	M	L
	Listed Buildings	M	L	L	L
	Noise	H	L	M	L
	Water	H	L	H	L
TOTAL	**H**	**18**	**2**	**15**	**1**
	M	**5**	**8**	**7**	**2**
	L	**2**	**15**	**3**	**22**

Risks and Impacts	**In comparison to each whole route**
High	High risk or impact on programme, cost or receptor
Medium	Medium risk or impact on programme, cost or receptor
Low	Low risk or impact on programme, cost or receptor

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Appendix A Alternative Routes considered

A.1 Introduction

A.1.1 The descriptions set out below outline the primary features of the alternative routes considered in comparison to the Reference Route. The alignments of the routes considered are shown on Drawing 30067/001/015.

A.1.2 The main principle adopted in developing these alternatives was to commence at the southern (London) portal in the same location as the Reference Route and end at an appropriate location to allow alignment with the Reference Route to the north of Wendover where it passes Stoke Mandeville, but not further north than Aylesbury. The need for a surface Intervention Gap to limit a single length of tunnel bore to 20km to comply with safety criteria constrained some of the alignment. Consideration was also given to the length passing under residential properties.

A.1.3 The gradients quoted are along any section of the route different from the Reference Route and the maximum rise is from the lowest point where it passes under the River Misbourne at Chalfont St Giles to the summit, which in each case is the Intervention Gap.

A.1.4 The Reference Route has a maximum up gradient of 3% south to north and 2.1% north to south, and a total rise of 149m from the River Misbourne to the summit. By their nature the Reference Tunnel and Intermediate Routes have slacker gradients and lower summits.

A.1.5 On review of these routes it was determined to proceed with the Green Route and further refinement to this route was made to meet certain environmental requirements, notably the location of Listed Buildings and Ancient Woodland. The Green Route forming the basis of the study is the refined version of this initial Green Route.

A.2 Blue Route

A.2.1 Northwards from the portal at the M25, the route takes a direct line towards the HS2 surface route immediately north of Wendover. The line takes a very oblique line across the Misbourne. Apart from crossing under a part of Amersham at Station Road and Rectory Hill, the slight horizontal bends avoid other settlements to enable an intervention gap to be positioned between South Heath and Ballinger.

A.2.2 This alignment both horizontally and vertically would offer good operational conditions for the railway as it avoids too many horizontal or vertical curves. However, the traverse beneath Amersham will increase the number of dwellings which could be affected by ground borne noise and vibration during construction and operation. In addition the location of the intervention gap would not be ideal for access, and would introduce noise into an otherwise tranquil part of the AONB.

A.2.3 The tunnel ends in a North Portal slightly west of the Reference Route.

A.2.4 The route has a maximum up gradient of 2% south to north and 0.9% north to south, and a maximum total rise of 113m which is 36m lower than the Reference Route.

A.3 Orange Route

A.3.1 Northwards from the portal at the M25, the route takes a long curve around the 'Chalfonts' before crossing the Misbourne and then heading towards Little Kingshill. The route seeks to cross under the fewest number of dwellings located between Great Missenden and Prestwood.

A.3.2 The intervention gap would be situated across Rignall Road and Kings Lane, north of Prestwood. This is a convenient depression in the surface which would make an open section feasible but it would affect these two minor roads and introduce a source of noise into an otherwise tranquil area. Access for emergency services would be difficult.

A.3.3 The line then runs north to a portal in a field in the vicinity of Chalkshire, about 1km west of the Proposed Route. The route would run on the surface from here to rejoin the Reference Route on the edge of Aylesbury that lies approximately 1.5 km to the north of Stoke Mandeville.

A.3.4 The route has a maximum up gradient of 1.3% south to north and 1.0% north to south, and a maximum total rise of 123m which is 26m lower than the Reference Route.

A.4 Black Route

A.4.1 Northwards from the portal at the M25 this follows the Reference Route across the River Misbourne at Chalfont St Giles as far as the A404. The route then diverges to follow a line west to run beneath Little Kingshill and curving northwards under Great Missenden.

A.4.2 The route heads back towards the Chiltern Line and the A413, crossing the floor of the Misbourne Valley upstream of the recognised source of the river in Great Missenden. The intervention gap is located at Wendover Dean in the vicinity of Bowood Lane. This brings the gap and associated source of noise closer to existing transport infrastructure which will ameliorate the effects of this section of open track. It is located here to avoid the valley floor which could introduce unacceptable impacts on the existing hydrology. Access to the gap for emergency purposes is easily achieved from the A413.

A.4.3 The route continues to a portal in the same locality as Orange Route but approximately 0.6km west of the Reference Route and nearly 1km further north enabling the portal to be located closer to the AONB boundary. The route would run on the surface from here to rejoin the Reference Route on the edge of Aylesbury approximately 1.5 km north of Stoke Mandeville.

A.4.4 The route has a maximum up gradient of 0.9% south to north and 1.0% north to south, and a maximum total rise of 110m which is 39m lower than the Reference Route.

A.5 Green Route

A.5.1 Northwards from the portal at the M25, this follows the Reference Route across the River Misbourne at Chalfont St Giles as far as the A404. The route then diverges to follow a line east of Little Kingshill and west of Little Missenden to cross under the River Misbourne, Chiltern Line and A413.

A.5.2 It then runs parallel to the A413 passing to the east of Great Missenden and the intervention gap is close to the A413 south of Bowood Lane. This again means the source of noise is close to the existing transport sources, ameliorating the effect of this open section. Access to the gap for emergency purposes is achieved from the A413.

A.5.3 The route then continues to a portal at the about same location as the Black Route, as noted approximately 0.6km west and nearly 1km north of the Reference Route, enabling the portal to be located closer to the AONB boundary. The route would run on the surface from here to rejoin the Reference Route on the edge of Aylesbury approximately 1.5 km north of Stoke Mandeville.

A.5.4 The route has a maximum up gradient of 1.1% south to north and 1.0% north to south, and a maximum total rise of 106m which is 43m lower than the Reference Route.

A.6 Route Overview

A.6.1 The gradients and summits of the Alternatives considered are all less severe than the Reference Route. This would lead to more efficient operation and less energy consumption for all rail traffic transiting the Chilterns for the life of the scheme a significant element of the operational costs, which have not been assessed.

A.6.2 The route lengths between south and north portals of the four alternatives compared to the Reference Route (to equivalent portal locations) are as below:

Table A.1 Schedule of Route lengths

Route	Length
Reference	23.7 km
Blue	24.0km
Orange	25.6km
Black	25.1km
Green	24.7km

A.7 Description of Study Routes

Green Route

A.7.1 The Green Route shares the HS2 Reference horizontal and vertical alignments from the southern portal at Ch.5.524 to approximately Ch.7.000 and continues to share the horizontal alignment until approximately Ch.11.250. The reduced gradients associated with the proposed Green Route result in Ventilation Shaft 2 being deeper and the tunnel some 15m further below the surface at this shaft.

A.7.2 The Green Route diverges from the Reference Route by continuing along the straight bearing, where the Reference Route enters a RH 5400m radius curve, in which there is a vertical sagging curve between the rising 0.5% grade entry at approx Ch.12.050 and following a 1% rising grade from Ch.12.690.

A.7.3 The Green Route however, is on a flatter rising gradient of 0.3% grade from Ch.8.500 to a short sagging curve (the length of which will be increased during subsequent design development) at approximately Ch.14.000 with a following rising grade of 0.5% to Ch.19.500. There is a much flatter horizontal curve in the Green route than in the Reference Route, with a 6631m radius RH curve between approximately Ch.15.300 and Ch.18.500. This divergence takes the Green Route further away from Amersham and unlike the Reference Route, the Green Route remains in bored tunnels for approximately 6km longer to a point in open country, north of both Great Missenden and South Heath, avoiding the open cutting and green tunnel construction adjacent to South Heath.

A.7.4 The divergence from the Reference Route takes the bored tunnels and the ventilation shafts approximately through the centre of this countryside gap, with only the vent shafts intruding into the AONB. The gradients to achieve this are relatively gentle and climb steadily towards the proposed intervention gap. Beyond the intervention gap (north of Ch.25.950) the proposed Green Route falls steadily towards the north through a long section, approximately 6km of 0.5% grade and then a shorter section, approximateCh.1800 of 1.0% grade through the north portal, located in the scarp face and into open country where a sagging curve between Ch.33.550 and approximately Ch.34.000 brings it into the vertical alignment of the Reference Route. The northern portal is situated in the order of 1km further north and west of Wendover. This optimizes both smoother railway alignments and the additional cover provided by the scarp face to minimize the portal zone and avoid the need for green tunnel cutting and the significant disruption that this will cause.

Reference Route

A.7.5 By comparison, whilst the Reference Route follows a long straight alignment between approximately Ch.13.000 and Ch.22.000, it has an undulating vertical alignment, falling and then rising at 0.5% to a nadir and then a further sagging curve between approximately Ch.16.400 and Ch.17.400 before a steeply rising grade of 3%, which is approaching the permitted maximum grade through the north portal at Mantles Wood and a cutting at. The alignment flattens within the cutting and into the southern portal of a green tunnel at Ch. 20.367. The gradient of 0.76% continues in cutting beyond the northern portal of the green tunnel at Ch.21.567 and over a summit hogging curve between approximately Ch.22.400 and Ch.22.870, then falls at 0.4% out of the cutting and onto an elevated alignment steepening to as much as 2.1% within a long LH curve that takes the alignment just to the western edge of Wendover. Immediately to the west of Wendover, the Reference Route is hidden within a green tunnel, approximately 1300m long. Within this green tunnel, there is a sagging curve that reduces the gradient to 1.3% and, at approximately the foot of the northern scarp of the Chilterns, there is a further sagging curve which reduces the gradient to 0.25% into the open country.

Reference Tunnel Route

A.7.6 The Reference Tunnel Route differs insofar as it remains in tunnel for much more of the route, by reducing the steep rising grade to 2% after the second crossing under the River Misbourne to a hogging curve between approximately Ch.20.800 and Ch.21.400, where it flattens to 0.5% and keeps the tunnel between 38.5m and 25m below the general surface; over a buried summit between approximately Ch.22.750 and Ch.23.150; then falling at 0.5% into an open Intervention gap between Ch.24.995 and Ch.25.365. As the alignment enters the northern section of tunnel it is in a hogging curve that steepens the gradient to fall at 2.0% northwards, flattening to 0.5% and then through a section of cut and cover green tunnel between Ch.28.795 and Ch.29.270. The northern portal of the green tunnel is located at the same point as that on the Reference Route, immediately west of Wendover. The 0.25% falling grade rejoins the Reference Route vertical alignment at approximately Ch.32.000.

Summary

A.7.7 The tables that follow provide a brief set of data for comparison of all the routes considered to the Reference Route and Reference Tunnel route. They provide a quick assessment of the merits and demerits of each, in particular indicating why the Green Route was selected as the comparison for the study.

Summary of routes for comparison

A.7.8

Characteristic: Location	Reference Route	Reference Tunnel Route	Blue	Orange	Black	Green
Tunnel length	13.4km	23.7km	24.0km	25.6km	25.1km	24.7km
Length compared with reference route			+0.3km	+1.9km	1.4km	1.0km
Difference with Reference Route		0%	+1.3%	+8.0%	+5.9%	+4.2%
Transit length through weathered Upper Chalk deposits under River Misbourne (downstream)	2.0km	2.0km	3.5km	2.0km	2.0km	2.0km
Minimum depth to rail level under River Misbourne (downstream)	29m	29m	32m	38m	30m	30m
Minimum depth under River Misbourne (Upstream at Shardeloes lake)	30m	30m				
Location of Intervention Gap	None	Durham Farm	South Heath	Hotley Bottom, Gt Missenden	Wendoverdean Farm and A413	Wendoverdean Farm and A413
Distance from Wendover Station	160m	160m	270m	1440m	880m	880m
Distance from Stoke Mandeville Church	600m	600m	600m	1000m	800m	800m

Characteristic: Energy Requirement	**Reference Route**	**Reference Tunnel Route**	**Blue**	**Orange**	**Black**	**Green**
South to north						
Maximum gradient	3.0%	2.0%	2.0%	1.3%	0.9%	0.9%
Maximum gradient length	2.3km	3.7km	2.3km	4.8km	6.0km	5.5km
North to south						
Maximum gradient	2.1%	2.0%	0.9%	1.0%	0.7%	0.5%
Maximum gradient length	0.9km	1.2km	5.2km	4.0km	5.2km	5.9km
Summit location	Leather lane	Park Farm South heath	South Heath	Hotley Bottom Gt Missenden	Wendoverdean Farm A413	Wendoverdean Farm A413
Maximum height rise River Misbourne to Summit	149m	129m	113m	123m	110m	106m
Proportion of Reference Route height rise	100%	86%	76%	83%	74%	71%

Characteristic: Depths	Reference Route	Reference Tunnel Route	Blue	Orange	Black	Green
Depth under Chalfont St Giles	29m (93ft)	44m (141ft)	29m (93ft)	68m (223ft)	29m (93ft)	30m (96ft)
Depth under Coleshill					114m (366ft)	
Depth under Old Amersham	61m (196ft)		45m (147ft)			
Depth under adjacent to Old Amersham	32m (105ft)			72m (231ft)		
Depth under Little Kingshill				61m (196ft)	56m (183ft)	
Depth under South Heath	5m (16ft) (cutting)	20m (65ft)	Intervention gap			
Depth under Gt Missenden					33m (106ft)	69m (221ft)
Depth under Prestwood				46m (151ft)		
Depth under Coombe Hill				111m (364ft)	61m (200ft)	81m (260ft)

Further Commentary

A.7.9 It can be seen from this that not only does the proposed Green Route offer a more balanced vertical alignment and avoid impacts upon Great Missenden, South Heath and Wendover but also provides a smoother and less convoluted horizontal alignment, taking advantage of being a specific tunnel route alignment, rather than a suppressed surface alignment, which is far more determined by surface features, habitation and interfaces with other infrastructure.

A.7.10 Between the divergence point and the re-convergence north of the Chiltern scarp, the proposed Green Route may be marginally longer than the Reference Route but the smoother alignment, requiring less cant to sustain the operational speeds, will provide a more economical operational and maintenance railway. There are some features of the Reference Route and Reference Tunnel Route that push vertical curves and horizontal transitions close together, with the risk that these will actually overlap during detail design or cause speed constraints in order to maintain separation or require the use of maxima design criteria to reduce optimal transition lengths. The more gentle alignments of the proposed Green Route reduce this risk and it is not envisaged that maxima design criteria or non-compliant overlapping design elements would be necessary to support this route.

A.7.11 There is further capacity to improve and modify this proposed Green Route, during design development to Approval in Principle, at which stage detailed transitions will be confirmed and minor alignment adjustments inserted to address any environmental noise and vibration impacts upon potentially sensitive receptors. This will ensure that the least impact and optimized route is identified and developed. Particular benefits can be gained by introducing slight variations to the two tunnel alignments, such that they provide convergence into the Intervention gap and significantly reduce the overall width of that gap. A similar ‘wineglass’ effect was used to manipulate CrossRail tunnel alignments to avoid conflicts with other infrastructure around the Royal Oak Portal and although the rate of convergence and re-divergence will be much flatter than was applied to CrossRail, the benefits of closing the tunnel centres in this way are that there is very limited length over which the bores have less than one diameter separation.

A.7.12 The length of the Intervention Gap, at approximately 1km, may also support the provision of sufficient length of parallel straight to offer a location for emergency cross-overs; such that maintenance or perturbation management would facilitate limited single-line working in any one of the four bored sections, and would mean that the impact of planned or emergency maintenance could be reduced from that incorporating full track occupation between access cross-over south of the M25 and cross-over provision in the Stoke Mandeville area.

A.7.13 The Reference Route also includes a Maintenance Loop to the north of the AONB boundary. This is required to provide for operational maintenance trains, normally based at the proposed Calvert Infrastructure Maintenance Depot to be deployed in preceding closed periods to await access to the section southwards to London once the last train of the day has passed, or to return to before the first train comes through. The loop can also be used to hold passenger trains in case of operational needs.

A.7.14 The general requirements include a relatively level section of track (nominally 0.25% gradient) and an overall length of about 1.2km. The loop lines are shown each side of the main track and it is located such that there are no other structures affected by this widened section of the corridor. This limits the positions available.

A.7.15 Further design development will be needed to determine the exact location and format of the Intervention gap and the facilities provided there. This may include further investigation of alignment improvements to optimize the location of the gap or even the opportunity to introduce a mined intervention chamber, which would allow still flatter gradients and a reduced buried summit level, thus reducing even further the impact within the Chilterns AONB.

A.7.16 In railway design and operational terms, whilst new to the UK, such underground intervention facilities, with road tunnel adit access, are provided in other countries, where long tunnels are a necessary feature to penetrate natural mountainous barriers. Examples of such facilities can be found in new and under-construction Alpine tunnels and in the new railway tunnel providing a fast by-pass route into Oslo.

A.7.17 Design development will also be needed in determining the basic arrangement for the Maintenance Loop north of the tunnel from the Green Route. Initially, based on the parameters available and refinement of the vertical alignment, it could be located slightly further north between the Old Risborough Road and the Chiltern Line crossing. Other considerations could be given to the functionality and other opportunities presented by the longer tunnel and the associated operational and maintenance requirements.

Appendix B Route Alignment Drawings

B.1 Alternative Routes

B.1.1 Drawing 30067/001/012: Sections – Orange and Green Alternate Tunnel Routes

B.1.2 Drawing 30067/001/013: Sections – Reference, Reference Tunnel Routes

B.1.3 Drawing 30067/001/014: Sections – Intermediate Tunnel Route

B.1.4 Drawing 30067/001/015: Route Selection

B.2 Assessed Routes

B.2.1 Drawing 30067/001/011A: Route Plan

B.2.2 Drawing 30067/001/012A Section – Green Tunnel Route

B.3 Geological Plans and Sections

B.3.1 Drawings 30067/001/021 – Schematic Geological Cross Section and Plan for Reference Route

B.3.2 Drawings 30067/001/022 – Schematic Geological Cross Section and Plan for Green Route

Appendix C Geology and Lithology

C.1 Superficial deposits

*Based on Morigi et al (2005)

PERIOD	EPOCH	NAME	*LITHOLOGY & TYPICAL THICKNESS (M)
Quaternary	Holocene	Alluvium	Silt, sand & gravel 2-3
	Pleistocene	Head	Gravelly silt & clay Variable
		Clay-with-Flints	Clay with flint gravel Up to 6
		River Terrace Deposits	Sands & gravels Up to 10
Details of River Terrace Deposits			
Period	Stage	Development stage of the proto-Thames river	Terrace Name
Pleistocene	Pre-Anglian to Anglian	Pre-diversionary	Winter Hill Gravel
			Gerrards Cross Gravel
			Beaconsfield Gravel
			Westland Green Gravel

C.2 Solid Geology

*Based on Morigi et al (2005)

AGE	GROUP NAME	FORMATION NAME	*LITHOLOGY & TYPICAL THICKNESS (M)
Palaeogene	Thames	London Clay Harwich	Hard clay to mudstone over sand Locally <10
	Lambeth	Reading Upnor	Clay & sand Locally up to 20+ Clay, sand & gravel Locally 2-5
Upper Cretaceous	Chalk – *White Chalk Subgroup*	Seaford Chalk	Chalk with flints Up to 40
		Lewes Nodular Chalk	Nodular chalk with flints, marl seams and hardgrounds (notably Chalk Rock Member) Up to 35
		New Pit Chalk	Chalk with fewer flints and marl seams

			Up to 45
		Holywell Nodular Chalk	Nodular chalk with a hardground (Melbourn Rock Member) over marl at base (Plenus Marls) Up to 15
	Chalk – *Grey Chalk Subgroup*	Zig Zag Chalk	Grey chalk over alternating bands of chalk and marl Up to 70
		West Melbury Marly Chalk	

C.3 Lithology

Seaford Chalk ('Upper Chalk')	
Typical characteristics	Soft blocky smooth white chalk with abundant seams of large nodular and semi-tabular flint, with thin beds of harder nodular chalk near the base.
Thickness	up to 40m
Density	Low to Medium dense
Unconfined compressive strength	1 to 15MPa
Calcimetry	Average 95%
Flint content	5 to 25%
Brash	The volume of flint and the frequency of large flint nodules is generally much greater than on the Newhaven Chalk. Some of the large flint bands are characteristic enough to be locally recognised in brash. Individual fragments of typical Seaford Chalk are smaller and more equant than those of the Lewes Chalk; flints are generally larger and more abundant
Topography	Forms extensive dip slopes between primary and secondary escarpment. Base at a very slight negative feature in front of, or at, or behind the crest of that escarpment.
Lewes Chalk ('Upper Chalk')	
Typical characteristics	Hard to very hard, white to creamy or yellowish white nodular chalks and chalkstones, with interbedded soft to hard gritty white chalks and common seams of clay-rich chalk (marl seams). Regular bands of nodular flint, some large, occur more commonly than in the underlying beds The Chalk Rock (a variable sequence of mineralised hardgrounds, chalkstone and

	nodular chalk) occurs at or near base of formation
Thickness	up to 35m
Density	Medium dense
Unconfined compressive strength	1 to 15MPa
Calcimetry	Average 95%
Flint content	<10%
Brash	Rubbly, hard nodular chalk fragments and large nodular flints. Rough-textured and rather flaggy in appearance. It tends to be more voluminous and rather dirtier than that derived from the New Pit Chalk.
Topography	Forms a convex slope at the top of the primary escarpment, commonly including the crest. Base at a positive break of slope.
New Pit Chalk (‘Middle Chalk – upper’)	
Typical characteristics	Smooth-textured, rather blocky, massively bedded, firm white chalks, with regular thin beds of clay-rich chalk (‘marl seams’) and sparse smallish flints.
Thickness	up to 45m
Density	Medium dense
Unconfined compressive strength	1 to 15MPa
Calcimetry	Average 90%
Flint content	<5%
Brash	Fragments tend to be of very uniform, smooth, brittle white chalk of medium hardness, with little fossil debris. These break readily under the plough and so the brash commonly shows numerous clean broken surfaces.
Topography	Forms the steepest ground in the face of the primary escarpment, typically with a uniform gradient. Base at a negative break of slope.
Holywell Nodular Chalk (‘Middle Chalk – lower’)	
Typical	Medium hard to very hard, nodular, white to creamy white chalk

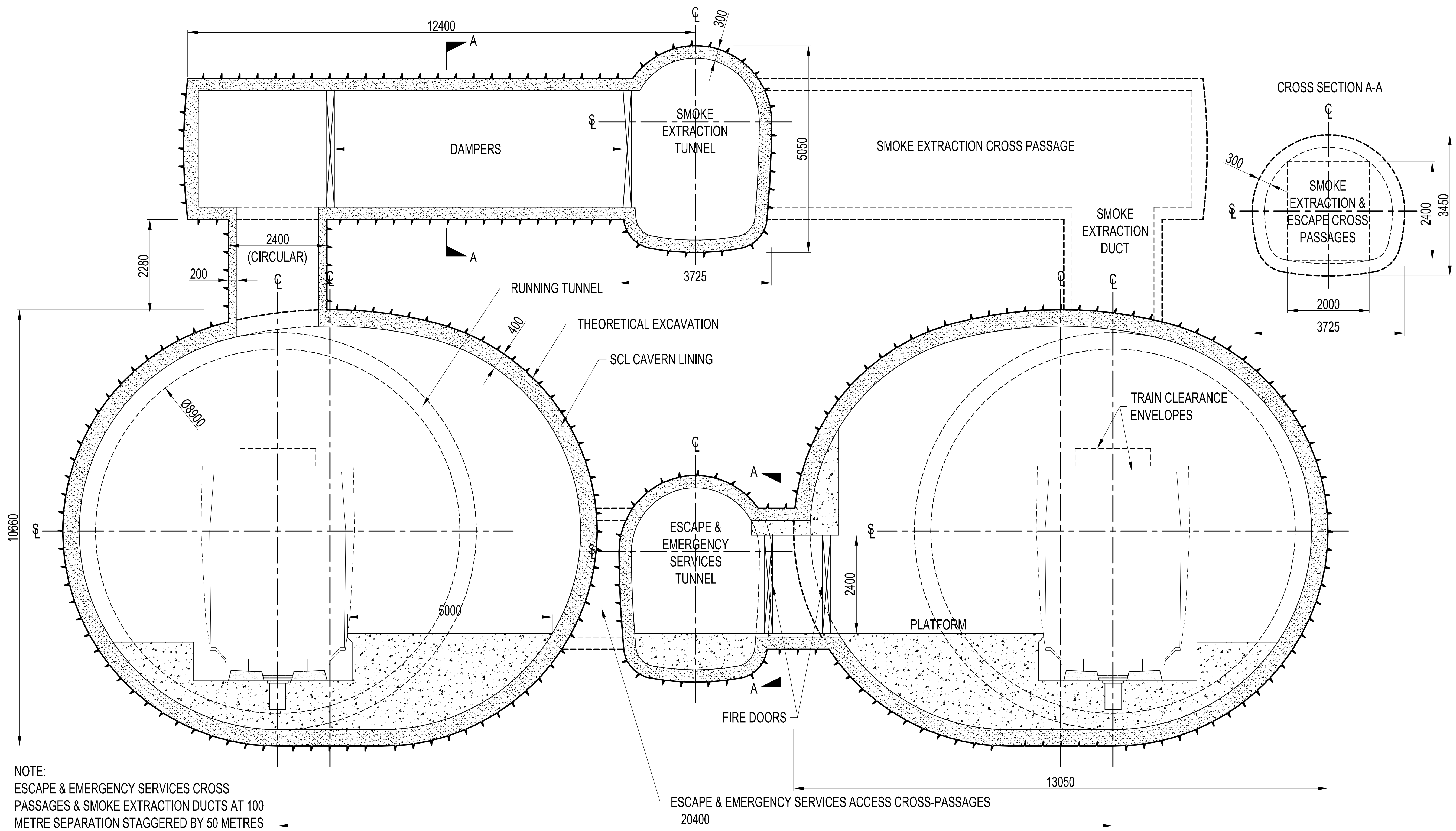
characteristics	with beds and laminae of clay-rich chalk (marl), including flaser-laminated marls. A thin alternating sequence of clay-rich chalks and clayey limestones (Plenus Marls) overlain by very hard, creamy white limestone (Melbourn Rock) occurs at base of formation. The upper two-thirds is mostly conspicuously fossiliferous: most beds contain gritty shell debris, commonly pink, and some have mytiloid inoceramid bivalves preserved in three dimensions.
Thickness	up to 15m
Density	Medium dense to High dense
Unconfined compressive strength	1 to 15MPa
Calcimetry	Average 87% Range 60 to 95%
Flint content	<2%
Brash	Rougher, more grainy and rubbly brash, compared with New Pit Chalk. Brash is commonly too hard to be easily broken during normal cultivation, and so tend to develop a rather grubby appearance. In the absence of shell debris, the rather grainy texture of typical Holywell Chalk distinguishes it from the smooth chalks of the succeeding New Pit Chalk
Topography	Forms relatively gently sloping ground in the mid part of the primary escarpment, which can slope either towards or away from the escarpment. Base occurs at a weak negative break of slope, just below a strong positive break of slope.
Zig Zag Chalk (‘Grey Chalk’)	
Typical characteristics	Soft to medium-hard, pale grey, blocky chalk with some thin resistant limestone beds near the base. Basal bed is either a fine-grained phosphatic calcarenite (Totternhoe Stone), or silty to calcarenitic chalk (the Cast Bed)
Thickness	up to 70m
Density	High dense to Very high dense
Unconfined compressive strength	1 to 25 MPa
Calcimetry	Average 77% Range 20 to 95%
Flint content	0%

Brash	Rather sparse angular or blocky fragments of grey chalk.
Topography	Forms relatively steep ground low in the primary escarpment. Base at a negative break of slope.
West Melbury Marly Chalk ('Chalk Marl')	
Typical characteristics	Numerous rhythmic alternations, each consisting of soft off-white to grey clay-rich chalks (marls) passing up into grey clayey chalks and hard grey or brownish grey limestones. Glauconitic, clayrich, locally sandy calcareous siltstone/clay (Glauconitic Marl Member)
Thickness	up to 70m
Density	High dense to Very high dense
Unconfined compressive strength	0.5 to 20 MPa
Calcimetry	Average 70% Range 30 to 95%
Flint content	0%
Brash	Rough, rubbly limestone fragments locally voluminous; commonly fossiliferous. Glauconitic base found as brash in places, but is more proven by hand auger samples.
Topography	Forms relatively gently sloping ground in the lowest part of the primary escarpment. Locally can form a subsidiary escarpment with a dip slope facing towards the primary escarpment. Base occurs at a weak negative break of slope

Appendix D Illustrative Underground Emergency Station

EMERGENCY EVACUATION STATION CAVERNS

SCALE 1:100 @ A3



NOTE:
ESCAPE & EMERGENCY SERVICES CROSS PASSAGES & SMOKE EXTRACTION DUCTS AT 100 METRE SEPARATION STAGGERED BY 50 METRES

Appendix E Cost Model

E.1.1 The cost model and tables below are based on the HS2 Cost and Risk Model (Jan 2012) and the consequent Estimate of Expense presented to Parliament dated 15th November 2013

E.1.2 Where some information is not identified this has been added from previous analysis or reporting undertaken by HS2 Ltd and their consultants when reviewing the submissions for the Full Chilterns Tunnel.

E.1.3 The first table sets out the Reference Route costs and the consequent rates, which are then applied to the other routes, to provide a comparative cost basis.

					Resulting Common rate
Reference Route	dims	tot £m	length (km)	£ m	£m/km
Chiltern Tunnel twin bore	8.80m ID		13.225	839.97	63.51
South Heath Green Tunnel	twin track		1.08	86.66	80.24
Wendover Green Tunnel	twin track		1.28	86.83	67.84
CT South Portal				23.17	
CT North Portal				23.65	
SH GT South Portal				incl	
SH GT North Portal				incl	
Wendover GT South Portal				incl	
Wendover GT North Portal				incl	
CT VS Chalfont St Giles				15.84	
CT VS Chalfont St Peter				17.13	
CT VS Amersham				15.99	
CT VS Little Missenden				16.31	(average)
Retaining Walls				0	
Viaducts Country South (km: £mtot)	25.2	354.59	1.2	16.89	14.07
CT Tunnel systems			13.225	64.86	4.90
SH GT Tunnel Systems			1.08	4.99	4.62
Wendover GT Tunnel Systems			1.28	5.24	4.09
Permanent Way	2 track		23.7	53.87	2.273
OHLE			23.7	12.893	0.544
Sig and comms			23.7	7.584	0.32
Earthworks *					
Embankments (cu.m)	1,160,000			12.78	11.02
Cuttings (cu.m)	2,260,000			63.08	27.91
Viaduct			2	incl above	1072
Other works					
Road diversions				10	
Major utility diversions				50	
Land costs				19.8	
TOTAL				**1447.53**	

Reference Tunnel Route	dims	length (km)	£m
Chiltern Tunnel twin bore	8.80m ID	23.7	1505.28
Intervention Gap	twin track	1	incl above
CT South Portal			23.17
CT North Portal			23.65
IG Portal South			incl above as tunnel
IG Portal North			incl above as tunnel
CT VS Chalfont St Giles			15.84
CT VS Chalfont St Peter			17.13
CT VS 3 Adj A404			15.99
CT VS 4			16.31
CT VS 5			16.31
CT VS 6			16.31
CT VS 7			16.31
CT Tunnel systems		23.7	116.23
Land Costs			2.7
TOTAL			**1785.23**

Reference Intermediate Route	dims	tot £m	length (km)	£ m
Chiltern Tunnel twin bore	8.80m ID		17	1079.7346
Wendover Green Tunnel	twin track		1.28	86.83
CT South Portal				23.17
CT North Portal				23.65
Wendover GT South Portal				incl
Wendover GT North Portal				incl
CT VS Chalfont St Giles				15.84
CT VS Chalfont St Peter				17.13
CT VS Amersham				15.99
CT VS Little Missenden				16.31
CT VS 5				16.31
Retaining Walls				0
Viaducts Country South (km: £mtot)	25.2	354.59	1.2	16.89
CT Tunnel systems			17	64.86
Wendover GT Tunnel Systems			1.28	5.24
Permanent Way	2 track		23.7	53.87
OHLE			23.7	12.89
Sig and comms			23.7	7.58
Earthworks *				
Embankments (cu.m)	1,160,000			12.78
Cuttings (cu.m)	1,350,000			37.68
Viaduct			2	incl above
Other works				
Road diversions				8
Major utility diversions				50
Land costs				17.8
TOTAL				**1582.56**

Green Route	dims	length (km)	£m
Chiltern Tunnel twin bore	8.80m ID	24.7	1568.79
Intervention Gap	twin track	1	incl above
CT South Portal			23.17
CT North Portal			23.65
IG Portal South			incl above as tunnel
IG Portal North			incl above as tunnel
CT VS Chalfont St Giles			15.84
CT VS Chalfont St Peter			17.13
CT VS 3 Adj A404			15.99
CT VS 4			16.31
CT VS 5			16.31
CT VS 6			16.31
CT VS 7			16.31
CT Tunnel systems		24.7	121.14
Land costs			2.7
TOTAL			**1853.65**