HS2 London to the West Midlands Appraisal of Sustainability

Appendix 2 – Greenhouse Gas Emissions

A Report for HS2 Ltd

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1. Introduction

1.1.1. This appendix provides details of the appraisal method adopted to determine carbon[1] emissions associated with the construction of the proposed scheme, manufacture of rolling stock and operation of the proposed route enabling a comparison of three scheme scenarios and the reference case (i.e. the future situation without HS2). Since HS2 Ltd's Report to Government, two key developments have taken place:

- The scheme recommended by HS2 Ltd as 'proposed' has been endorsed by Government, subject to a small number of refinements, as the 'recommended scheme'. Full details on this are described within Section 2 to the AoS Main Report.
- The Government has requested that proposals for extension to HS2 from the West Midlands up to Manchester and Leeds be developed.

1.1.2. A full appraisal of the scheme between London and Manchester and Leeds would be undertaken during the course of 2011 to take account of the more detailed scheme proposals to Manchester and Leeds, as well as any policy revisions with respect to energy, carbon and transport that may have emerged by this stage. For this report, we have considered what the wider network might be in the longer term, up to and beyond Manchester and Leeds, in order to gain an understanding of what the full long term effects might be. Four scheme scenarios considered within this report (including the option for northwards extension) are as follows:

- Proposed route;
- The New Classic Line alternative;
- Extension to Scotland; and
- The Reference Case.

1.1.3. Emissions associated with the operation of HS2 are referred to as operational emissions and include any changes in other transport sectors (i.e. road, rail and air) due to HS2. Emissions associated with construction of the scheme and manufacture of rolling stock are referred to as embedded emissions.

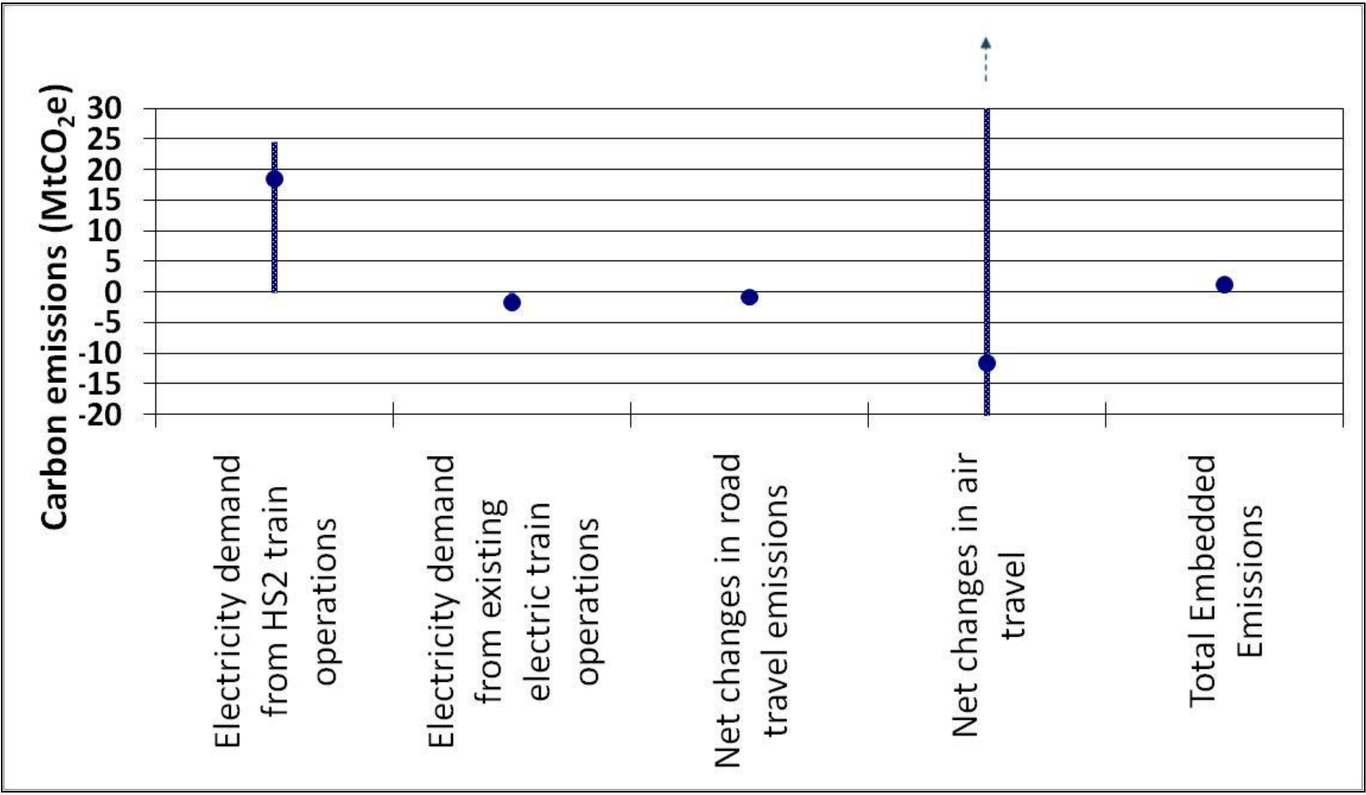
1.1.4. Operational emissions were calculated using initial outputs from the HS2 Demand Model for the proposed route with reference to appropriate emission factors. This study provides a methodology that decouples the carbon calculations from the HS2 Demand Model, allowing for standalone sensitivity analysis of key factors relating to carbon emissions, such as UK Government projections of the carbon intensity of electricity generation. The methodology therefore provides for an evaluation of various policy outcomes relating to the reduction of carbon emissions in the UK, both now and at a later date without the need to re-run the full HS2 Demand Model. These have not been re-appraised at this stage from those assumed at December 2009, since, at the time of writing, policy on energy use and carbon has not changed significantly. A further outcome of the work to date is the identification of the key drivers for reducing carbon emissions and the potential impact they may have in determining whether HS2 would make a significant contribution or otherwise to reducing UK greenhouse gas emissions.

1.1.5. Embedded emissions have been calculated for each scheme scenario using preliminary engineering design details and appropriate emission factors. The results are presented in million tonnes of carbon dioxide equivalent ($MtCO_2e$) and the cost derived in accordance with the latest guidance published by the Department for Energy and Climate Change (DECC).

[1] Although the term 'carbon' is used throughout this report, all carbon emissions are reported in million tonnes of carbon dioxide ($MtCO_2e$) to ensure the numerical values are consistent with reporting of carbon emissions by UK Government and others. This appraisal is limited to CO_2 only and hence, no consideration has been given to convert other greenhouse gases to carbon dioxide equivalent (CO_2e).

1.1.6. The key findings that can be drawn at this time are as follows: (1) there is significant potential to reduce embedded carbon emissions through selection of materials and construction methods; and (2) whether HS2 makes a significant contribution to reducing UK greenhouse gas emissions is subject to: (a) assumptions in modal shift, principally from air to high speed rail, are achieved or can be bettered; and (b) the delivery of existing policies to reduce emissions across the economy. The methodology developed for this study, de-coupling the carbon calculations from the HS2 Demand Model, would enable this to be assessed in more detail in tandem to generating the HS2 Demand Model results as work progresses. The results to date, highlighting the key drivers are illustrated in **Figure 1** below. This illustrates the relative degree of uncertainty related to different determinants in the appraisal. Two sets of assumptions were used for operational carbon emissions (Assumptions A and B). These are described in detail below in section 6.1.1.

Figure 1 – Net Carbon Emissions from Operational and Embedded Sources



2. Key Influences on Carbon Emissions

2.1.1. With limited information available at this time on construction methods, design of the scheme and the materials to be used and only preliminary output from the HS2 Demand Model, the focus of this study was to identify where the greatest reductions in carbon emissions may be expected and what effect this would have in assessing the proposed scheme. These are described below from the most important to the least.

2.1.2. Travel choices and decision making included in the HS2 Demand Model are not dependent on carbon emissions and hence, each of the key drivers to reduce carbon emissions can be assessed in more detail as a standalone exercise. In due course such analysis is important as it would allow a more direct evaluation of the individual and collective effect of policy measures relevant to reducing carbon emissions.

First Order of Magnitude

2.1.3. The greatest potential benefit for HS2 in terms of carbon emissions is associated with people using it in preference to air travel. This benefit would only be realised if any reduction in air passenger numbers results in reduced numbers of flights. This study considers three scenarios: the most optimistic, the worst case, and a no change scenario.

- The most optimistic scenario assumes that the total number of journeys shifting from air to HS2 is divided by the number of seats on the average domestic flight to derive the total reduction in the number of domestic flights. The important assumption is then made that the freed up landing and take-off slots at UK airports would remain unused, resulting in a net reduction in carbon emissions.
- The worst case scenario is that HS2 would result in freed up landing and take-off slots which are then used up to meet demand for international flights, resulting in a net increase in carbon emissions. The magnitude of this potential net increase in emissions has not been quantified at this time as further analysis is required to determine the additional carbon emissions associated with projected international travel demand.
- The no change scenario assumes the reduction in passenger numbers on any individual flight is not sufficient for the airline to discontinue the service and hence, aviation emissions remain unchanged.

Second Order of Magnitude

2.1.4. The Climate Change Act 2008 set legally binding targets to reduce the UK's emissions of CO_2 by at least 34% by 2020 and 80% by 2050, compared with a 1990 baseline. The Committee on Climate Change (CCC) has suggested that the 2050 target can only be met if there is a very substantial decarbonisation of the power sector by 2030, and called for a 90% reduction in the carbon intensity of electricity generation. The Government remains committed to reducing the carbon intensity of electricity generation by 2050, to between 14% and 40% of that achieved today. This would have the effect of reducing both embedded and operational emissions from HS2, reducing the change in emissions associated with a shift from existing electric rail to HS2 and increasing the change in emissions associated with a shift from road to HS2 and air to HS2. The UK Low Carbon Transition Plan outlines how the UK would cut emissions from electricity generation and other sectors[2]. The most optimistic and worst case scenarios were also considered, with the most optimistic scenario being 100% use of renewables and nuclear to generate electricity and the worst case being no change from the current carbon intensity.

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[2] Other papers published in tandem with the Transition Plan include The Low Carbon Industrial Strategy, The Renewable Energy Strategy and Low Carbon Transport: a Greener Future.

Third Order of Magnitude

2.1.5. The increased use of recycled materials in construction e.g. steel, the development of new blends of concrete that are less carbon intensive and use of existing techniques to optimise efficiency of construction would reduce the embedded carbon emissions.

2.1.6. A revised route alignment to minimise tunnel sections would reduce embedded carbon emissions.

2.1.7. Changes to the stopping pattern may also impact upon load factors, modal shift and generated traffic.

Fourth Order of Magnitude

2.1.8. The aviation industry continues to work to reduce the carbon intensity of air travel by increasing passenger loading, using lighter, more fuel efficient aeroplanes and developing aviation fuels blended with bioethanol. A key incentive for this is the inclusion of the aviation sector within the EU Emissions Trading Scheme which would effectively cap carbon emissions from domestic and European flights. These measures would have the effect of reducing the change in emissions associated with a shift from air to HS2.

2.1.9. The UK Government is committed to reducing the carbon intensity of motor vehicles, through promotion of more efficient, smaller engine vehicles, blending of bioethanol in petrol and diesel, and electric vehicles. This would have the effect of reducing embedded emissions from HS2 (or that part linked to construction traffic) but would reduce the change in emissions associated with a shift from road to HS2. Government mechanisms for the reduction of emissions from motor vehicles include: improving the fuel efficiency of vehicles; reducing the fossil carbon content of transport fuel; increasing the care that people take over fuel consumption while driving; and promoting adoption of hybrid and electric vehicles.

3. Previous Studies

3.1.1. Estimating the carbon emissions associated with HS2 has presented a number of challenges. Expectations about the carbon benefits of high speed rail are already high, in advance of any detailed appraisal. HS2 is frequently presented as a low carbon technology.

3.1.2. This may need to be qualified; a study in 2007 by Booz Allen Hamilton and Temple Group for the Department for Transport [3] demonstrated that a key determining variable for carbon efficiency of high speed rail was the geographical scale of such an initiative (city to city routes). The construction (embedded) carbon element was expected to be substantial, and only where significant modal shift (from air to rail) was possible, was a net carbon reduction (embedded carbon less operational carbon) achieved. Proposed routes from London to Birmingham and London to Manchester were found to make a potential net contribution to carbon emissions, as the operational carbon savings achieved through modal shift did not compensate for the construction related carbon emissions. Proposed routes from London north to Scotland would reduce net contributions to climate change where sufficient modal shift was achieved.

3.1.3. A more recent analysis by ATOC for Greengauge 21[4] has found significant carbon benefits associated with high speed rail. The ATOC report argues that the carbon advantage of high speed rail over other methods of travel is likely to improve over time and therefore concerns about the carbon impact of rail at higher speeds needs to be put into context. In particular, the carbon advantage of high speed rail should improve substantially over time and its carbon advantage per passenger-km over new cars would remain at least three times greater. Notwithstanding this, there is an argument that higher quality journey time is enjoyed on high speed rail compared to air travel, with significantly less disruptions associated with security checks, boarding, etcetera, as well as greater potential for wireless communications and use of IT equipment. This may drive modal shift more from air to high speed rail rather than simply accounting for differences in journey time[5].

3.1.4. The Fourth Carbon Budget views HS2 as an integral part of the climate agenda in the UK by replacing domestic and short-haul aviation. In its review of UK aviation, the Committee on Climate Change states “we assessed a maximum potential emissions reduction of 2 $MtCO_2$ annually through switching from aviation to high-speed rail, with two caveats that this would require a low-carbon electricity system, and would also need complementary levers such as withholding any slots released at capacity constrained airports”. They also state that “we estimate that the effects of the high-speed rail proposals on surface transport emissions (i.e. the combined effect of the increase in emissions from electricity generation and any reduction in car emissions through modal shift) would be negligible[6]".

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[3] DfT (2007) Estimated Carbon Impact of a New North-South Line. Report by Booz Allen Hamilton and Temple Group

[4] Greengauge 21 (2009) Energy consumption and CO_2 impacts of High Speed Rail: ATOC analysis for Greengauge 21

[5] http://business.timesonline.co.uk/tol/business/related_reports/europe_by_train/article6921715.ece

[6] Committee on Climate Change (Dec 2010) The Fourth Carbon Budget. Reducing emissions through the 2020s

4. Appraisal Methodology

4.1. Overview

4.1.1. There is no established methodology for undertaking a study of this type and as a result a variety of assumptions have been made, each of which can tip the balance between potential benefits and dis-benefits. The overall approach has been to use methods and techniques consistent with the UK Greenhouse Gas Emissions Inventory[7].

4.1.2. The scope for this study considered the following elements:

- Modal shift and Demand Modelling inputs, to take account of the switch from other transport modes to both high speed rail and conventional rail as a result of released capacity on classic lines.
- Operational characteristics: service patterns (both high speed and changes on classic line services); number of trains/hour; line speed (km/h).
- Rolling Stock specification: energy efficiencies achievable through time (e.g. rolling stock/regenerative breaking; primary energy supply mix i.e. proportion renewable, nuclear, gas.
- Access to stations: route configuration – access to stations (city centre/parkway) and associated emissions travelling to and from stations.
- Embedded (construction) carbon, which would be a function of alignment type (with major structures such as tunnels likely to have a higher carbon impact than at-grade sections); number of stations, viaducts and any ancillary infrastructure (where information is available), transport of bulk materials and the emissions from the transport of spoil resulting from construction.

4.1.3. The operational carbon impact of the proposed scheme is reported in $MtCO_2e$, aggregated for the assumed 60 year lifetime of the scheme. The carbon impact of HS2 is reported in terms of embedded carbon emissions (expressed in $MtCO_2e$) for the four HS2 scenarios aggregated for the construction period. At this time the embedded emissions for the Reference Case are undefined. The net carbon impact has been determined as the sum of embedded and operational carbon emissions for the proposed scheme.

4.1.4. The operational and embedded carbon impacts of each scenario in $MtCO_2e$ have been valued for the purposes of policy appraisal using monetary values for carbon published by DECC, taking into account non-traded and traded carbon sources.

4.2. Operational Carbon

4.2.1. Operational carbon represents the carbon emissions associated with the proposed operation of HS2 itself balanced against any change in emissions associated with affected journeys by road, existing rail and air.

4.2.2. The appraisal adopted best practice in determining operational carbon emissions, principally by de-coupling the transport model from the carbon calculations. This is an important step as significant changes in carbon emissions are expected across the economy (and hence, from different transport modes) as a result of government intervention. De-coupling from the transport model allows for sensitivity analyses to be undertaken to determine the effect of variations in delivery outcomes of different policies.

4.2.3. The approach used is summarised below:

- definition of emissions sources;

[7] http://www.ghgi.org.uk/index.html

- identification of Demand Model outputs that provide activity data for each emission source;
- identification of appropriate emissions factors; and
- estimation of the carbon impact.

4.2.4. Details of each emission source and calculation method are presented in **Table 1** overleaf. Emission factors for current activities were generally obtained from the National Atmospheric Emissions Inventory (NAEI) to be consistent with international reporting of greenhouse gas emissions. Projections of emission factors for future years were based on publications from either the DfT or DECC. Note that further details of underlying assumptions and calculation procedures are provided in the Demand Model documentation.

4.2.5. A preliminary appraisal of the uncertainty in estimating operational carbon emissions was undertaken, partially fulfilling the standard methodology used in compiling emission inventories based on Monte Carlo analysis. The full analysis of uncertainty requires estimating the range of values expected for each component of each variable and the distribution within that range. For each component of each variable, a random value within the range is generated and the total carbon emissions calculated. This is repeated to provide 10,000 calculations of total carbon emissions for each variable. The uncertainty of estimated carbon emissions from each source and from all combined is determined as the mean ± 2 x Standard Deviation (SD). The former can be used to identify key assumptions for optimising the HS2 project in terms of carbon emissions (as noted above) and the latter used for overall reporting purposes. Preliminary output from the Demand Model precluded this detail of analysis at this time and a single range of values[8] was assigned for each carbon source to collectively represent the uncertainty in individual variables. This analysis is considered appropriate at this stage as it reinforces the concept that the carbon emissions are an estimate only and provides a mechanism for reducing uncertainty. Where uncertainty can be reduced, decisions can also be made on how best to reduce carbon emissions and priorities determined accordingly.

[8] Defined in this study as either high (±75%) medium (±50%) or low (±25%).

Table 1 - Operational Carbon Emissions Sources and Appraisal Approach

Emission classification	Emissions Source	Determination	Variables	Assumptions / Limitations	Sensitivity and Scope for reduction
Direct at source (on-site emissions)	Electricity demand from HS2 train operations	For each plant type: carbon emissions = annual mean electricity demand (KWh)[9] x relevant emissions factor (Kg CO_2/KWh)[10]	Annualised electricity demand, projected carbon emission factors	No consideration is given to variations in the carbon intensity associated with marginal increases in electricity demand. The annual mean is used as sufficient lead time is available for the electricity supply industry to meet future demand from HS2 through installation of new plant, reducing marginal effects	There is scope to reduce the electricity demand for HS2 using trackside storage infrastructure to increase the potential savings associated with regenerative breaking. This source is very sensitive to policy delivery of reductions in the carbon intensity of the electricity supply industry
Direct remote (off-site emissions)	Electricity demand from existing electric train operations	For each plant type: carbon emissions = annual mean electricity demand (KWh)[11] x relevant emissions factor (Kg CO_2/KWh)[10]	Annualised electricity demand, projected carbon emission factors	See above	See above
	Net changes in road transport emissions	For each vehicle type: carbon emissions = total vehicle kilometres travelled in each year[11] x emission factor (year, petrol/diesel/electric split/vehicle speed)[12]	Total vehicle kilometres travelled, year, proportion of petrol, diesel and electric vehicles, vehicle speed	No consideration given to local traffic	This source is very sensitive to policy delivery of reductions in the carbon intensity of road transport
	Net changes in air travel	For domestic flights: carbon emissions = total passenger air kilometres travelled[11] x emission factor for domestic flights[13] / domestic aeroplane seat capacity[13]	total passenger air kilometres travelled	The assumptions are made that: (a) there is a direct link between the number of passenger air kilometres reduced and the number of domestic flights reduced; (b) for the most optimistic scenario, freed up landing and takeoff slots are *not* used by new (international) services; and (c) for the worst case scenario, freed up	The key drive for modal shift in the Demand Model is journey time. Consideration of journey quality time may induce greater shift from air to HS2

[9] Provided as a direct output of the HS2 Demand Model and checked with reference to a study by Imperial College (Watson R *et al* (2009) Final Outputs of Traction Energy Modelling, Imperial College, London).

[10] Carbon emission factors, current and projected, are included in 'The UK Low Carbon Transition Plan: National strategy for climate and energy', DECC (2009).

[11] Provided as a direct output of the HS2 Demand Model.

[12] Annualised vehicle emission factors and split in petrol, diesel and electric vehicles provided by Department for Transport.

[13] Published by DECC.

Emission classification	Emissions Source	Determination	Variables	Assumptions / Limitations	Sensitivity and Scope for reduction
				landingand take-off slots *are* used by new (international) services	
Secondary	Emissions from secondary development induced around HS2 stations and along existing lines (through released capacity)	Not applicable	Not applicable	Excluded as the business case for HS2 assumes no over development	Not applicable

4.3. Embedded Carbon

4.3.1. Embedded carbon represents the carbon emissions associated with construction operations such as constructing the rail infrastructure and trains, as well as the embedded energy[14] within the bulk construction materials.

4.3.2. The appraisal of embedded carbon has included the carbon impact of the construction phase of each scheme scenario. No details are available at this time of any construction associated with the Reference Case.

4.3.3. The appraisal adopted a similar approach as set out in the Environment Agency's (EA) carbon calculator for construction activities[15], the Highways Agency's (HA)[16] carbon calculator and industry best practice. In addition, the methodologies outlined in both the Booz and Temple 'Estimated Carbon Impact of New North-South Line, 2007,' and Network Rail's 'Comparing environmental impact of conventional and high speed rail', 2009[17] were adhered to.

4.3.4. The approach used is summarised below:

- definition of emissions sources;
- collation of data and appropriate emissions factors; and
- estimation of the carbon impact.

4.3.5. Details of each emission source and calculation method are presented in **Table 2**.

4.3.6. Given the preliminary stage of the design for the scheme, only the main bulk construction materials were estimated, and included within this appraisal. The carbon emissions for construction materials relate to the quantity of materials required for tunnels, at grade sections, viaducts, track, stations and platforms. Carbon emissions from the transport of bulk materials, transport of spoil material, energy from the manufacture of new trains and the energy consumed during tunnel boring were also included.

4.3.7. In defining the emissions boundaries, a number of data limitations were identified and necessary assumptions were made, which have also been set out in **Table 2** below.

4.3.8. A preliminary appraisal of the uncertainty in estimating embedded carbon emissions was also undertaken.

4.3.9. Embedded carbon has also been reported in the Appraisal of Sustainability (AoS) Frameworks (see Volume 2 Plans and Appraisal Framework) for the purpose of the sifting the different routes during scheme development. Carbon emissions reported in the Frameworks relate to the quantity of materials required for tunnels, at grade sections, viaducts, stations and energy from tunnel boring. No statistical analysis has been carried out on the carbon emissions reported in the Frameworks.

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[14] Embedded energy is all energy expended in the extraction and processing of materials up to the factory gate: Cradle to Gate. This definition applies to all the bulk construction materials.

[15] Carbon calculator for construction activities, version 2.1, 2007

[16] Highways Agency Calculation for Major Projects, version 4b, 2009

[17] Comparing environmental impact of conventional and high speed rail, Network Rail, 2009

Table 2 – Embedded Carbon Emissions Sources and Appraisal Approach

Emission classification	Emissions Source	Determination	Variables	Assumptions / Limitations	Sensitivity and Scope for reduction
Direct at source (on-site emissions)	Emissions from construction plant equipment used on site	For each plant type: carbon emissions = distance travelled by plant type x relevant emissions factor (Kg CO_2/km)	Number and type of plant equipment, distance travelled (km)	This source contribution has been set at zero as reasonable estimates of the number and type of plant equipment used on site is not available at this time. The estimation of construction costs is expected to include a schedule of construction plant equipment e.g. dump trucks, bulldozers, diggers, etcetera	This source is subject to uncertainty but with considerable scope for reducing emissions through selection of efficient plant equipment, use of efficient techniques, etcetera. To illustrate this, an uncertainty of +/-25% can be applied to the total estimate. No sensitivity analysis has been undertaken at this time
Direct remote (off-site emissions)	Emissions from the carriage of bulk construction materials to site	For each bulk material: carbon emissions = total volume of material (tonnes) x % carried by road, rail / carrying capacity of vehicle x distance from point of manufacture to site (km) x relevant emissions factor (Kg CO_2/km)	Volume of each bulk material (tonnes), % carried by mode of transport (road, rail), distance from point of manufacture to site (km)	Given the preliminary stage of the design only the emissions from the transport of bulk construction materials (steel, concrete and aggregate) would be estimated. For illustration, steel is assumed to be sourced from Scunthorpe, cement from Rugby, sand from local sand and gravel pits and aggregate from hard stone quarries in Scotland. All materials assumed to be transported by road (HGV), except in the case of aggregate where it is assumed that 25% of the journey would be made by rail. Return journeys have been assumed	This source is subject to uncertainty but with considerable scope for reducing emissions through reducing the volume of materials required e.g. recycling on site, use of rail rather than road, etcetera. To illustrate this, an uncertainty of +/-50% has been applied to the total estimate
	Emissions from the carriage of spoil from site	Carbon emissions = total volume of spoil (tonnes) x % carried by road, rail / carrying capacity of vehicle x distance travelled to landfill site(s) (km) x relevant emissions factor (Kg CO_2/km)	Volume of spoil (tonnes), distance landfill site(s) (km), % by mode of transport (road, rail)	It is assumed that spoil is dominated by tunnel spoil, with a balance achieved between cuttings and land raising elsewhere and demolition waste being a small contributor. At this stage all tunnel spoil is assumed to be disposed of by landfill. The average distance to four landfill sites (Calvert, Park Lodge, East Burnham and Pitstone) have been used as illustration. Return journeys have been assumed. Tunnel spoil was estimated as $\pi r^2 L$, where L = length of tunnel and r = 4.25m (i.e. an estimated 8.5m diameter bore of the tunnel). There is a mixture of single bore and twin bore tunnels along the proposed route. For the classic line a similar methodology was used, although the bore diameter of the tunnels was	This source is subject to large uncertainty with extensive scope for reducing the export of spoil by re-use on site. The selection of landfill would need to be based on availability and tariff rather than proximity. The export of materials to outside the UK can be excluded. To illustrate uncertainty, the proportion of spoil exported by rail was increased from 0% to 75% and, in a second case; the distance by road was doubled (with 0% by rail). An uncertainty of +/-50% has been applied to the total estimate

Emission classification	Emissions Source	Determination	Variables	Assumptions / Limitations	Sensitivity and Scope for reduction
				estimated to be 7.25m	
	Emissions from construction personnel travel to and from the site	Mode of transport characteristics i.e. private transport or public transport	Mode of transport specification /efficiency	This source contribution has been set at zero as reasonable estimates of the number and type of vehicles used by personnel are not available at this time. Information of this type is limited although the Highways Agency (HA) has a research programme to address this. Consultation with the HA is recommended to determine likely emissions from this source	This source is subject to large uncertainty with extensive scope for reducing emissions through use of Green Travel Plans, etcetera. How cost effective this may be can be determined through discussions with the HA. No sensitivity analysis has been undertaken at this time
	Generation emissions from construction plant power use (e.g. Tunnel Boring Machines (TBM))	Carbon emissions = electrical demand of TBM (MWh/km) x tunnel length (km) x relevant emissions factor (Kg CO_2/KWh)	Electrical demand of TBM (MWh/km), number of TBM, tunnel length (km), twin or single bore tunnels	TBM are energy intensive and typically represent one of the primary sources of carbon emissions from a construction project of this nature. Mains electricity consumption data are available from TBM suppliers in terms of MWh/km of tunnel bored. Operating hours is principally a function of tunnel length but also geology (hardness of rock). Electrical consumption data is provided as 12,125MWh/tunnel km. Tunnels assumed to be 11.6m diameter, twin bore, with two earth pressure balance TBM operating at 90% capacity	This source is subject to uncertainties in: tunnel length; geology (hardness of rock); and carbon intensity of mains electricity used. To illustrate this, an uncertainty of +75% to -50% has been applied to the total estimate
Indirect	Emissions from the manufacture (cradle to gate) of bulk construction materials (embedded energy), for each type of track feature (i.e. rail, rail driveway, viaducts, tunnels, stations, OHLE structures and wires)	Carbon emissions = tonnes of steel x relevant emissions factor (Kg CO_2/tonne)	Tonnes of steel	Standard multipliers for steel requirements per unit length of rail, rail driveway, OHLE, tunnels, viaducts and stations, were derived from previous studies. (Rail = track - assumed two tracks, 2 rails per track, Rail Driveway = sleepers, ballast, OHLE = Overhead line electrification, tunnels = tunnel structure, assumed twin bore duplex lining. Due to design limitations, concrete and steel requirements for stations and viaducts were estimated using standard factors for major structures, i.e. 2,000m^3 / 4,800 tonnes concrete required for major structures. Concrete from platforms for each station was also estimated based on number of platforms and length, with a minimum length assumed of 400m. It was assumed that 25kg reinforced steel is used per m^3 concrete for tunnels, viaducts and stations. For the OHLE, embedded carbon from copper and aluminium was also estimated	No sensitivity in the emissions factors was considered. Carbon emissions from this source would be reduced with increasing proportion of recycled steel used. An uncertainty of +/-75% has been applied to the total estimate
		Carbon emissions = tonnes of concrete x	Quantity (tonnes) and	Standard multipliers for concrete requirements per unit length of rail, rail driveway, OHLE, tunnels, viaducts	No sensitivity in the emissions factor was considered. An uncertainty of

Emission classification	Emissions Source	Determination	Variables	Assumptions / Limitations	Sensitivity and Scope for reduction
		relevant emissions factor (Kg CO_2/tonne)	grade (% of cement) of concrete used	and stations, were derived from previous studies. (Rail = track - assumed two tracks, 2 rails per track, Rail Driveway = sleepers, ballast, OHLE = Overhead line electrification, tunnels = tunnel structure, assumed twin bore duplex lining. Due to design limitations, concrete and steel requirements for stations and viaducts were estimated using standard factors for major structures, i.e. 2,000m^3 / 4,800 tonnes concrete required for major structures. Concrete from platforms for each station was estimated based on number of platforms and length, with a minimum length assumed of 400m. It was assumed that 25kg reinforced steel is used per m^3 of concrete for tunnels, viaducts and stations. For the OHLE, embedded carbon from copper and aluminium was also estimated	+75% to -75% has been applied to the total estimate
		Carbon emissions = tonnes of ballast (aggregate) x relevant emissions factor (KgCO_2/tonne)	Quantity (tonnes) of aggregate required	Due to overriding safety concerns only virgin aggregate has been considered although the potential for recycled ballast remains. Standard multipliers for aggregate requirements per unit length of rail, rail driveway, tunnels, viaducts and stations were derived from previous studies	No sensitivity in the emissions factor was considered. An uncertainty of +/-75% has been applied to the total estimate
	Emissions from the manufacture (cradle to gate) of trains (embedded energy)	Carbon emissions = number of trains x tonnes of steel per train x relevant emissions factor for steel (KgCO_2/tonne)	Number of trains	All of the embedded carbon in train manufacture is assumed to be represented by steel production at this stage	No sensitivity in the emissions factor was considered. To account for the gross assumption of trains being wholly made of steel, an uncertainty of -25 to +75% was included
	Emissions from the manufacture of vehicles and associated infrastructure	Carbon emissions = number of vehicles x tonnes of bulk material per vehicle x relevant emissions factor (KgCO_2/tonne of bulk material)	Number of vehicles	This source contribution has been set at zero as reasonable estimates of the number and type of vehicle is not available at this time	This source is subject to uncertainty. No sensitivity analysis has been undertaken at this time
	Emissions from the manufacture of airplanes and associated	Carbon emissions = number of airplanes x tonnes of bulk material per vehicle x relevant	Number of airplanes	This source contribution has been set at zero as reasonable estimates of the number and type of airplanes is not available at this time	This source is subject to uncertainty. No sensitivity analysis has been undertaken at this time

Emission classification	Emissions Source	Determination	Variables	Assumptions / Limitations	Sensitivity and Scope for reduction
	infrastructure	emissions factor ($KgCO_2$/tonne of bulk material)			
Secondary	Emissions from construction of secondary development induced around HS2 stations and along existing lines (through released capacity)	Not applicable	Not applicable	Excluded as the business case for HS2 assumes no over development	Not applicable

4.4. Carbon Valuation

4.4.1. The UK Climate Change Act 2008 includes legally binding targets to reduce greenhouse gas emissions (i.e. carbon) to 34% below 1990 levels by 2020 and to 80% below 1990 levels by 2050, to be achieved through action in the UK and abroad. Achieving this requires a whole range of measures underpinned by a robust approach to include climate change impacts in appraising and evaluating public policies.

4.4.2. The approach adopted by UK Government is to assign a monetary value to carbon emissions and include this within existing methodologies for cost benefit analysis of public policies in accordance with HM Treasury requirements. The Government's guidance to valuation of carbon has developed since 2002, from an approach based on estimating the social cost (defined as the lifetime damage costs associated with incremental greenhouse gas emissions) to the current approach, based on calculating the cost with reference to the marginal abatement costs consistent with a given emissions reduction target (as defined by the Climate Change Act 2008). This is referred to as the non-traded cost of carbon.

4.4.3. In the longer term, from 2030 onwards, the cost would be set equal to the market price of carbon observed in an emissions trading scheme such as the EU Emissions Trading System (EU ETS). This is referred to as the traded cost of carbon. In the short to medium term, the principal advantage of using a target based approach is that the marginal costs for abatement can be more robustly determined compared to estimating social costs[18].

4.4.4. For the purposes of carbon valuation for HS2, emissions have been defined in terms of being traded or non-traded with different costs assigned to each, enabling the total cost of carbon for the proposed scheme to be determined and used within the overall cost benefit analysis.

4.4.5. Carbon emissions associated with industrial activities within the EU Emissions Trading Scheme (EU-ETS) including electricity generation the manufacture of steel and concrete and aviation, for example, are capped with trading allowed between industrial operators. The Department of Energy and Climate Change (DECC) has forecast the traded price (low, central and high) of carbon up to the year 2050 in £/tCO_2e in 2009 prices.

4.4.6. Carbon emissions associated with activities outside the EU-ETS (i.e. non-traded) include those associated with road and rail (diesel powered units). DECC has published projected low, central and high non-traded carbon costs up to 2050 in £/tCO_2e in 2009 prices. The traded and non-traded costs of carbon are projected to converge in 2030.

4.4.7. The majority of embedded carbon costs are traded whereas the majority of operational carbon costs are non-traded. There is an expectation that carbon cost associated with transport fuel may become traded in the future. This appraisal designates traded and non-traded costs on the basis of current inclusion within the EU-ETS.

4.4.8. Each source of carbon included in the model for HS2 is listed in **Table 3** and defined in terms of being traded or non-traded.

[18]Carbon Valuation in UK Policy Appraisal : A Revised Approach, Department for Energy and Climate Change, July 2009

Table 3 - HS2 Sources of Traded and Non-Traded Carbon

	Traded	**Non-traded**
Embedded	Steel manufacture Concrete manufacture Site plant use of mains electricity (e.g. tunnel boring machines (TBM)) Electricity generation emissions from construction plant power use (e.g. TBM) Emissions from manufacture (cradle to gate) of bulk construction materials (embedded energy of steel and concrete), for each type of track feature (i.e. rail, rail driveway, viaducts, tunnels, stations, OHLE structures and wires) Emissions from manufacture (cradle to gate) of trains (embedded energy of steel)	Diesel emissions from construction plant equipment used on site Diesel emissions from the carriage of bulk construction materials to site Diesel emissions from the carriage of spoil from site Petrol and diesel emissions from construction personnel travel to and from the site Diesel emissions from construction of secondary development induced around HS2 stations and along existing lines (through released capacity)
Operational	Electricity demand from HS2 train operations Electricity demand from existing electric train operations Electricity demand from electric road vehicles Electricity demand from secondary development induced around HS2 stations and along existing lines (through released capacity Net changes in air travel (aviation fuel*)	Petrol and diesel for road vehicles Net changes in road transport emissions (petrol and diesel) Natural gas combustion emissions from secondary development induced around HS2 stations and along existing lines (through released capacity)

Notes:

The aviation sector will become part of the EU ETS on 1 January 2012, before the HS2 opening year of any new high speed line

The traded operational carbon costs have been included within the appraisal outlined in HS2's economic case

4.4.9. The July 2009 DECC guidance includes projections of traded and non-traded costs of carbon up to the year 2050 at 2009 prices. These projections include low, central and high estimates. The traded cost increases from £21 in 2009 (within the range £12 to £26) to £70 in 2030 (within the range £35 to £105). The non-traded cost increases from £50 in 2009 (within the range £25 to £75) to £70 in 2030 (within the range £35 to £105). From 2030 onwards the traded and non-traded costs are the same, rising to £200 in 2050 (within the range £100 to £300). For the purposes of this appraisal, costs are assumed to remain at £200 after 2050. The difference in traded and non-traded costs are significant during the construction period (2020 - 2026) but unlikely to be significant over the operational lifetime of the scheme (2026 - 2086).

5. Assumptions, Limitations and Information Gaps

5.1.1. During the later stages of preparing the AoS it became apparent that a full set of results from the HS2 Demand Model would not be available. Subsequently, the approach agreed with HS2 Ltd was to adapt the detailed methodology to reflect current availability of the HS2 Demand Model results.

5.1.2. No comparison can be made at this time of the proposed scheme with either the Reference Case (do-minimum) or the three alternative scenarios. Preliminary results from the Demand Model were available only for the proposed scheme.

5.1.3. The preliminary results were only available in summary form with no results of sensitivity analyses provided. Consequently, the results do not provide any indication of the range in values for each parameter or of the expected distribution of values within the range (e.g. normal, log-normal, etc.).

5.1.4. The preliminary results allow for decoupling the transport model from the calculation of carbon emissions associated with electricity generation, road fuel consumption and aviation at a macro level. The results of carbon calculations are only available in terms of UK wide annual mean totals.

5.1.5. No Demand Model results were available at this time to enable the results of carbon calculations to be expressed in terms of seat-kilometre or passenger-kilometre for different modes of transport.

5.1.6. The methodology framework for the appraisal of carbon emissions includes a statistical description of the range in uncertainty in emission estimates using Monte Carlo analysis consistent with the methodology adopted for the UK Greenhouse Gas Emissions Inventory. However, this requires describing a range of expected values for each input parameter and the type of distribution this range is expected to exhibit. It rapidly became clear that defining such a distribution, particularly in the aviation sector would be difficult. As a result a simplistic approach was adopted assuming a gross range of error defined as either large (±75%) medium (±50%) or small (±25%) and assuming a normal distribution within the simply defined range of values. HS2 Ltd also undertook some simple sensitivity testing on key input variables of grid intensity of carbon and vehicle efficiency. This is also reported below. Within the methodology framework, this simplified approach is considered sufficient to ensure a range of values is presented for discussion and evaluation of carbon emissions.

5.1.7. This study has been carried out in the absence of detailed design and information regarding the construction of the scheme and, for example, station or viaduct design.

5.1.8. Given the preliminary stage of the design for the scheme, only the main bulk construction materials were estimated, and included within this appraisal. The emissions for construction materials relate to the quantity of materials required for tunnels, at grade sections, viaducts, track, stations and platforms.

5.1.9. Estimates have been made on the range in values for each parameter associated with embedded carbon based on experience on similar projects. This includes, for example, distance to spoil disposal sites and aggregate sources and quantities of bulk materials.

5.1.10. These estimates are available for defining input parameters for the purposes of statistically describing the uncertainty in estimating embedded carbon emissions using Monte Carlo analysis. However, the analysis undertaken to date has been simplified to be consistent with the approach adopted for operational carbon emissions.

5.1.11. It is envisaged that the carbon appraisal would be refined over time as the scheme design and operating model are developed and the HS2 Demand Model work completed and, in particular, as work progresses to include extensions to Manchester and Leeds. Notwithstanding these limitations, the simplifications to the methodology made at this time still allow for the implications of external policies specific to carbon (i.e. number of flights in the UK and the carbon intensity of both electricity generation and road fuel) to be determined in terms of HS2.

6. Results

6.1. Operational Carbon

6.1.1. **Table 4** summarises the operational carbon emissions for the proposed scheme, including two sets of assumptions (labelled A and B).

- Assumption A used a range of assumptions about key drivers for each category of impact. Outputs reflected a reasonable worst case, a theoretical best case (figures reported in brackets in the table) and a reasonable best case.
- Assumption B used a simplified statistical analysis to demonstrate the degree of uncertainty expected if a full analysis was undertaken based on each component of each variable being defined (see paragraph 4.2.5). The results are a range of carbon emissions the breadth of which reflects the degree of confidence in each assumption.

6.1.2. The operation of HS2 would result in carbon emissions through electricity generation. These emissions would be offset by reductions in emissions associated with the electricity demand from existing rail services and a reduction in emissions from road transport. These emissions are overshadowed by the range in uncertainty associated with the potential for net changes in emissions from air travel.

6.1.3. Assuming the most optimistic scenario for HS2 displacing air travel, the net reduction in air travel related carbon emissions is 23.2 $MtCO_2e$ over 60 years, assuming any freed landing and takeoff slots are not re-used. The worst case scenario would result in a net increase in carbon emissions, primarily associated with international flights using the freed up landing and takeoff slots. This increase is expected to be at least an order of magnitude greater than the reduction associated with substituted domestic flights. For the purposes of completing this appraisal, a zero net change in air travel related carbon emissions was used as the midpoint.

Table 4 – Comparison of Individual Emissions Sources for the Proposed Route

Primary source	**Key assumptions**	**$MtCO_2e$**	**Ranked by $MtCO_2e$**	**Ranked by Uncertainty[1]**
Electricity demand from HS2 train operations	A – carbon intensity ranges from 0 (100% renewables / nuclear) to that achieved today	+18.5 (0 to +24.6)	2	2
	B – carbon intensity of electricity is reduced to between 14% and 40% of that achieved today	+18.5 (+13.0 to +23.9)		
Electricity demand from existing electric train operations	A – see above	-1.7 (-2.3 to +0.03)	3	3
	B – see above	-1.7 (-2.2 to -1.2)		
Net changes in road transport emissions	A – range in emissions reflecting variations in speed associated with reduced vehicle kilometres travelled	-1 (-2.2 to -0.8)	4	4
	B – range in emissions reflecting variation in speed and take-up of electric vehicles	-1 (-1.3 to -0.7)		
Net changes in air travel	A – From a maximum reduction in domestic flights, no re-use of freed up slots, to no change in domestic flights	-23.2 (-23.2 to 0)	1	1
	B - From a maximum reduction in domestic flights, with landing /take-off slots either not re-used or re-used for international flights	0 (-23.2 to (note 2))		
Total	**A**	**-7.4 (-27.7 to +23.8)**	-	-
	B	**+15.7 (-13.7 to (note 2))**		

Notes:

1. 1 = Highest level of uncertainty, with 4 being the lowest.

2. The upper range of net changes in air travel is unknown as the international destination of flights using take-off slots freed up by HS2 diverting domestic flights is not known at this stage. As an illustration, flights from London to either New York or Shanghai would be one order of magnitude greater than typical UK domestic flights. The value of the upper range is expected to be large and positive resulting in a net increase in carbon emissions and aggregated carbon costs from HS2.

6.2. Embedded Carbon

6.2.1. The results of estimating embedded carbon emissions for each of the routes are summarised in **Table 5**. This includes the mean and range of uncertainty derived from the Monte Carlo analysis.

Table 5 - Embedded Carbon Emissions for all Scheme Scenarios

Route	**Carbon Emissions MtCO2e**
Proposed route	+1.2 (+0.29 to +2.12)
The New Classic Line alternative	+1.17 (+0.25 to +2.10)
Extension to Scotland	+5.36 (+1.16 to +9.56)
The Reference Case	0 (0 – 0)

Notes

Carbon emissions are expressed as the mean and range of uncertainty (see **Table 2** for details of assumed uncertainty parameters).

No details are available at present for embedded carbon emissions associated with the Reference Case.

6.2.2. Emissions from embedded carbon are largely due to the use of high energy bulk materials such as steel and concrete, and high energy intensive construction practices such as tunnel boring.

6.2.3. Total embedded carbon emissions for the proposed route are reported as 1.2 $MtCO_2e$ (within the range of +0.29 to +2.12 $MtCO_2e$).

6.2.4. **Table 6** below gives a more detailed breakdown for the proposed route only, taking into account individual emissions sources, in terms of their carbon emissions and the upper and lower ranges of uncertainty. These emissions sources are also ranked by carbon emissions and uncertainty.

Table 6 – Comparison of Individual Emissions Sources for the Proposed Route

Primary source	$MtCO_2e$	Ranked by MtCO2e	Ranked by Uncertainty
Construction Plant on Site	0 (0 to 0)	-	-
Transport of Materials	+0.23 (+0.10 to +0.36)	2	3
Emissions from Spoil Transport	+0.05 (+0.03 to +0.07)	7	7
Personnel Travel	0 (0 to 0)	-	-
Tunnel Boring	+0.10 (+0.04 to +0.17)	6	6
Embedded Carbon Materials			
• Concrete	+0.16 (+0.02 to +0.30)	3	2
• Steel	+0.37 (+0.05 to +0.69)	1	1
• Aggregate	+0.01 (+0.001 to +0.02)	8	8
• Aluminium	+0.14 (+0.02 to +0.26)	4	4
• Copper	+0.13 (+0.02 to +0.24)	5	5
Embedded Carbon - Trains	+0.01 (+0.005 to +0.013)	9	9
Emissions from the manufacture of vehicles and associated infrastructure	0 (0 to 0)	-	-
Emissions from the manufacture of airplanes and associated infrastructure	0 (0 to 0)	-	-
Total	**+1.2 (+0.29 to +2.12)**	-	-

Note: 1 = Highest level of uncertainty, with 9 being the lowest.

6.2.5. Emissions from the use of steel in constructing the scheme account for 31% of the total embedded emissions for the proposed scheme, and gives rise to the most emissions. The transport of the bulk materials is ranked second with carbon emissions of approximately +0.23$MtCO_2e$ (within the range +0.10 to +0.36 $MtCO_2e$).

6.2.6. Carbon emissions associated with concrete and steel account for 44% of the total embedded emissions and have the greatest uncertainty, indicating that there is the greatest potential to reduce emissions from these sources.

6.2.7. Identified ways of reducing the impacts of steel would be the use of recycled / scrap steel where technically feasible. In terms of material transport, it has been assumed that all materials would predominantly be transported by HGV. In reality it may be possible to use rail as a mode of transport, which again could make a significant contribution to reducing the overall carbon emissions.

6.2.8. Total embedded carbon emissions for the proposed scheme are reported as +1.2$MtCO_2e$ (within the range +0.29 to +2.12 $MtCO_2e$). In comparison, the Booz and Temple 2007 study reported a figure of approximately +10$MtCO_2e$ of embedded carbon for a route between London and Scotland (approximately 8-10 times the length).

6.3. Carbon Valuation

6.3.1. The carbon costs and benefits of the proposed route are summarised in **Table 7** and **Table 8** using the key assumptions A and B respectively, as detailed in **Table 4.** The results include the expected range of emissions for each source, whether the emissions are traded or non-traded and the range in terms of carbon costs (shown as negatives in the tables) and benefits (shown as positives in the tables).

6.3.2. These figures are absolute numbers based on projected DECC costs of carbon, expressed in terms of 2009 prices. In order to compare with the costs presented in HS2's economic case, they would need to be converted to present values. It is important to note the economic case includes the traded operational carbon costs, as identified in **Table 3**.

6.3.3. Using the A set of assumptions, the net benefit of embedded and operational carbon emissions is expected to be £870M at 2009 prices within the range £392M to £1,370M , assuming the central projected cost of carbon. A much wider range in costs and benefits is expected if the low and high projected costs are included.

6.3.4. Using the B set of assumptions, the net cost of embedded and operational carbon emissions is expected to be -£2,022M at 2009 prices within the range -£3,162M to -£882M, assuming the central projected cost of carbon. A much wider range in costs and benefits is expected if the low and high projected costs are included.

Table 7 - Traded and Non-Traded Carbon Cost and Benefits for the Proposed Route – Key Assumptions Set A

Source	Emissions ($MtCO_2e$)	Carbon cost (£/tCO2e) (averaged for the stated period)	Aggregated carbon benefit (£M) (assuming central cost)	Aggregated carbon benefit (£M) (low - high range in cost)
Construction Phase (2020 - 2026) - Traded	+0.82 (+0.11 to +1.53)	-43.8 (-50.0 to -16.5)	-35.9 (-41.0 to -13.5)	-76.5 to -1.82
Construction Phase (2020 - 2026) – Non Traded	+0.36 (+0.14 to +0.58)	-62.5 (-94.0 to -31.5)	-22.5 (-33.8 to -11.3)	-54.5 to -4.41
Operational Carbon (2026 - 2085) – Traded	-6.4 (-25.5 to +24.6)	-125 (-188.0 to - 63.0)	+800 (+403 to +1,203)	-4,630 to +1,606
Operational Carbon (2026 - 2085) – Non Traded	-1 (-2.2 to -0.8)	-128 (-192.0 to - 64.0)	+128 (+64 to +192)	+153 to +422
Total	**-6.22 (-27.5 to +25.9)**		**+870 (+392 to +1,370)**	**-4,608 to +2,022**

Table 8 - Traded and Non-Traded Carbon Costs and Benefits for the Proposed Route – Key Assumptions Set B

Source	Emissions (MtCO2e)	Carbon cost (£/tCO2e) (averaged for the stated period)	Aggregated carbon benefit (£M) (assuming central cost)	Aggregated carbon benefit (£M) (low - high range in cost)
Construction Phase (2020 - 2026) - Traded	+0.82 (+0.11 to +1.53)	-43.8 (-50.0 to -16.5)	-35.9 (-41.0 to -13.5)	-76.5 to -1.82
Construction Phase (2020 - 2026) – Non Traded	+0.36 (+0.14 to +0.58)	-62.5 (-94.0 to -31.5)	-22.5 (-33.8 to -11.3)	-54.5 to -4.41
Operational Carbon (2026 - 2085) – Traded	+16.8 (-12.4 to (note 1))	-125.0 (-188.0 to - 63.0)	-2,096 (-3,153 to - 1,056)	Note 1 to +779
Operational Carbon (2026 - 2085) – Non Traded	-1 (-1.3 to -0.7)	-128.0 (-192 to -64)	+133 (+66.7 to +200)	+141 to +259
Total	**+16.9 (-13.5 to (note 1))**		**-2,022 (-3,162 to - 882)**	**(note 1) to +1,032**

Note 1: The upper range of net changes in air travel is unknown as the international destination of flights using take-off slots free up by HS2 diverting domestic flights is not known at this stage. As an illustration, flights from London to either New York or Shanghai would be one order of magnitude greater than typical UK domestic flights. The value of the upper range is expected to be large and positive resulting in a net increase in carbon emissions and aggregated carbon costs from HS2.