

**The Capital Carbon Cost
of
High Speed One**
by

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Fourth-year undergraduate project

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I hereby declare that, except where specifically indicated, the work submitted herein is my own original work.

Signature:

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Technical Abstract

The Capital Carbon Cost of High Speed 1, Yin Lin, N, Group D

The Climate Change Act 2008 contains a binding commitment to an 80% reduction in the UK in terms of greenhouse gas emissions, as measured against a 1990 baseline, by 2025 since domestic transport accounted for 21% of the UK's domestic emissions of CO₂, it is therefore important that the emissions caused by large-scale infrastructure projects are assessed for the purpose of recommendations for future design and enabling carbon emissions of future designs to be controlled and kept to a reasonable value.

High Speed 1 is a railway of 108km between St Pancras London and the Channel Tunnel and connects with the international high-speed routes between London-Paris and London Brussels.

The aim of the project is to evaluate the capital carbon cost of the existing High Speed 1 during construction estimate on how long it will take to pay back the bill of the environmental impact in terms of CO₂ emission due to the construction of the civil infrastructure.

Since there is currently no specific guidance relating to the production of an energy and carbon assessment for large infrastructure projects, such as HS1. Current approaches of assessing the carbon emissions of existing structures of High-Speed Rail such as the California High-Speed Rail were reviewed and by identifying emission sources and both the direct and indirect-arising elements, the boundary of the elements was defined referring to a Carbon Model developed by HS2 Ltd. to assess the carbon impact of proposed HS2- potentially the second High-Speed Rail line in the UK. By categorising the carbon emissions resulting from embodied energy associated with materials (embodied), transport of materials to site and operations of machineries, plants and Tunnel Boring Machines. Each element was assessed with corresponding Carbon Intensity Factor from the Inventory of Carbon Energy provided by the University of Bath. The carbon emissions of each element add up to the total capital carbon cost.

The Capital Carbon Cost from construction of the main civil structures was estimated to be 2.05 million tonnes. This is equivalent to 390,285 annual UK household's carbon emission. The payback period required for the capital carbon cost to payoff and produce positive carbon saving was estimated to be three years. This is considered small compared with the

expected life time and existing estimates on other high-speed rail lines such as the California High-Speed Rail. It can be concluded that HS1 could reduce CO₂ emissions over a relatively short period of time and play a role in meeting the carbon emissions targets. This can be explained by the successful public perception on the project on carbon saving leading to higher ridership as suggested by the increasing trend of passenger number earlier.

The study also analysed the carbon intensity of track designs including ballasted track and concrete slabtrack. This is followed by the discussion of the relative advantages and disadvantages of slabtrack and ballasted track. Although slabtracks were considered to have excellent performance specifically on high-speed the carbon emission per km was assessed to be 10 times greater than ballasted track due to the high carbon intensive bulk material used. Results suggest that TBM operating energy involved in the energy intensive tunnelling activity contributes a significant amount to the plant and machinery use cost of the whole scheme which also led to analysis of differences between open track and tunnels. Mitigation opportunities on High-Speed Rail designs were also discussed.

Variations in HS1 results compared with HS2 average were small. It suggested that designs of HS1 and HS2 are very similar and so far there is no major advance in incorporating any new system in reducing the capital carbon cost of high-speed rail design to reduce the environmental impact. It is suggested that if High Speed 2 is to deliver the environmental benefits intended, there must be robust evidence that it truly divert passenger from car and air transport and that the high speeds intended do not lead to increase emissions.

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1 Introduction

1.1 Background

1.1.1 Energy Policy

The Climate Change Act 2008 contains a binding commitment to an 80% reduction in the UK in terms of greenhouse gas emissions, as measured against a 1990 baseline, by 2025¹. According to the Department for Transport, in 2008, domestic transport accounted for 21% of the UK's domestic emissions of CO₂, transport clearly has to make its contribution to reducing the UK's overall emissions.

Work carried out in 2009 by the Association of Train Operating Companies (ATOC) assessed the carbon emissions of HSR compared with car and travel and was suggested by Green Gauge 21 that high speed rail can play a vital role the future low-carbon transport system. It is therefore important that the emissions caused by large-scale infrastructure projects are assessed for the purpose of recommendations for future design and enabling carbon emissions of future designs to be controlled and kept to a reasonable value.

1.1.2 High Speed 1 Overview

1.1.2.1 HS1 Connections



Figure 1.1 High Speed 1 Route Map

High Speed 1 is a railway of 108km between St Pancras London and the Channel Tunnel and connects with the international high-speed routes between London-Paris and London Brussels. This connection to mainland Europe provides HSR connectivity to the European HSR network, allowing passengers to take services to France,



Figure 1.2 High Speed 1 Rail

Spain, Germany and beyond. HS1 is Britain's first High speed railway and as indicated in Fig.1.1, HS1 has a number of connections to the UK domestic network : at Ebbsfleet and Ashford allowing through services from north and east Kent, with domestic lines to the north of London and a freight connection at Ripple Lane.

1.1.2.2 HS1 Operating Services

The opening of HS1 made a few connection services possible. Currently the services running on HS1 include:

- International passenger services linking St Pancras International, Ebbsfleet International and Ashford International with Paris, Brussels, Lille and Calais using Class 373 rolling stock
- Domestic passenger services operating between St Pancras International and Stratford International using Class 395 rolling stock at speed of 225km/h

There are also limited international freight services operating between London and Poland at night on HS1 at a maximum speed of 140km/h and use Class 92 locomotives.

1.1.2.3 Benefits of using HS1

London is the largest city in Western Europe and is acknowledged as the financial capital of Europe. London also receives top ranking as a city destination for international visitors. As the only connection rail line connecting London and continental Europe, HS1 offers excellent alternative to short-haul air travel. The benefits of using HS1 from a passenger's perspective include:

- City centre to city centre travel (e.g. St Pancras to Gare du Nord)
- Improved working conditions (productivity benefits)

- More reliable services
- Provides good onward connections at city centre stations
- Avoids airport stress and queues with easier and shorter check-in and no waiting for baggage reclaim

The main competitor for international high speed rail is air travel. Since recent estimates have suggested high-speed rail can be competitive on operational carbon emission, producing only 15% of the greenhouse gas emissions of short haul air travel per passenger-km², High Speed Rail has been proposed by many as a mean of recurring our carbon footprint. However, the bases of these comparisons are direct operational carbon cost, neglecting the considerable capital carbon costs resulting from actual construction.

1.1.2.4 Achievement of HS1

Since HS1's opening, the high-standard rail line has been recognised in many national environmental and planning awards and has achieved:

- Over 60% of the route built in transport corridors of existing railways and motorways with 25km of tunnels beneath London
- Minimised impact on sensitive landscapes and achieved a route which also incorporates wildlife habitat creation and biodiversity
- Innovative track with the London Tunnels providing enhanced ground borne noise mitigation for properties above the London Tunnels
- Associated with the development of the Stratford Area in East London. Strong impact on London 2012 bid
- Reduced flooding risk in East London as a result of permanent de-watering at Stratford Station

Travel figures of the Annual traffic volumes³ provided by Groupe Eurotunnel reveal that since the opening of complete HS1 line of commercial services started progressively from 2007, more than 76 million passengers have travelled through the Channel Tunnel High Speed trains, which amount to yearly average of nearly 10 million. The increasing trend on passenger number reveals the popularity of the rail line as an alternative to car and air of travel between London and Paris.

1.1.3 High Speed 2



Figure 1.3 HS2 Proposed Route Map Source: www.architectsjournal.co.uk

Following the success of HS1, the development of a second high-speed line of length 192km was proposed in 2009 by the UK government to connect London, the English Midlands, North West England, Yorkshire and potentially North England and the Central Belt of Scotland.

The investment is a complex decision that includes technical, social, economic and environmental trade off. Climate change concerns have led to a greater focus on carbon costs and the current controversy surrounding HS2's justification suggests that a carbon analysis of the UK's existing High Speed line would be valuable and critical in decision making depending on the total carbon impact of the system.

Although DfT claims that HS2 will be broadly carbon neutral, 51m⁴ pointed out that HS2 is not part of a low carbon future concerning issues regarding

- Consumption of electricity : dependant on carbon intensity of grid electricity
- Change from domestic slots to medium and long haul flights
- Assessment of construction carbon: assessment based on a simple CO₂/£ equation
- Modal shift from domestic air to rail: competing with air travel
- Impacts on road transportation : only 6% from shift road

1.2 Purpose and Aim of the Project

There is currently no specific guidance relating to the production of an energy and carbon assessment for large infrastructure projects, such as HS1.

The aim of the project is to evaluate the capital carbon cost of the existing High Speed 1 to answer questions such as whether the project is net carbon negative and how long

it will take to pay back the bill of the environmental impact in terms of CO₂ emission due to the construction of the civil infrastructure. Since HS2 Ltd. has performed a carbon assessment on a similar scale, comparison on HS1 and HS2 carbon impact possible can be made possible.

Meanwhile, understanding the percentage contribution of various construction materials and manufacturing process give good indications on making informed decisions with regard to the best design option, e.g. bridge type, tunnel type and etc.

The project aims to determine whether it is advantageous to opt to produce more CO₂ emissions at the stage of constructing high speed rail, to create a less energy consuming, and hence CO₂ emitting, infrastructure solution the longer-term. To be more specific, the objectives are to:

- Quantifying the capital carbon CO₂ emissions from construction of the main civil structures involved in the project
- Comparing the difference in designs of HS1 and HS2
- Quantifying the payback period for the capital carbon cost required for HS1
- Understanding the differences between tunnels and open-track
- Understanding the relative advantages and disadvantages in embodied carbon of ballasted track and concrete slab track

Although there is a wide range of environmental impacts resulting from rail, this project is mainly concerned with the embedded carbon in a high-speed rail system, which represents the construction of rail infrastructure, trains and tunneling boring machines. Existing studies suggest that emissions largely arise from the use of high-energy bulk materials such as steel and concrete, and high-energy intensive construction practices such as tunnel boring.

1.3 Structure of the report

The report starts with literature review in Section 2. This section explores the current situation with approaches of assessing the carbon emissions of existing infrastructures. By reviewing current publication relevant to High Speed Rail, the boundary of this project were identified and defined. The key findings and available methodologies and resources that we can adapt into our study are also highlighted.

Section 3 provides an overview of the methodology and approach undertaken, explains how the capital carbon cost can be calculated starting with definition of emission sources, scope of assessment, the process of choosing a boundary for imperative elements that contribute to the total carbon cost followed by the method of performing calculations.

Section 4 presents the results and analysis findings in the environmental impact context. This is followed by discussions concerning comparison between HS1 and the proposal of HS2 and discussions of the significance of the findings hence potential measures to reduce CO₂ emissions that can be implemented in the design stage.

Final part of the report concludes on key findings in meeting the aim and objectives of the project and discusses the mitigation opportunities available.

2 Literature Review

2.1 LCA (Life Cycle Assessment)

The full impact of rail projects with regards to carbon emission is associated with construction, operation and maintenance of infrastructure. Life cycle assessment has gained prominence as the preferred method for accounting for the Green House Gas impacts of building and operating a rail system (Cano and Chester, 2015 ; Gallivan et al., 2014). LCA evaluates the impact of a product from cradle-to-grave; from gathering of the raw materials through final disposal. In building and infrastructure projects the disposal phase of an LCA is often excluded, as the useful life of the analyzing product is long (e.g. more than 100 years design life for typical large scale infrastructure). Accordingly, assessments of such projects are often cradle-to-gate rather than cradle-to-grave.

2.2 High-Speed Rail vs other Modes of Transport

Green Gauge 21⁵'s publication points out the relative advantages of High Speed Rail (HSR) in terms of energy consumption and carbon emissions as followed:

“HSR produces only one-third of the carbon emissions of car travel and one-quarter the emissions of an equivalent trip by air, taking into account the average loadings typically achieved on each mode.”

Other advantages also include the minimal increase in carbon per passenger (up to +10%) of high-speed trains (300km/h+) compared with conventional (299km/h-the speed of existing intercity trains), and the reduced CO₂ emissions by one million tonnes each year by 2055 based on the assumption on shift of passengers from air travel to HSR.

2.3 The Case of California High-Speed Rail

When analysing the environmental effects of planes, trains or automobiles, the normal approach is to measure tailpipe emissions, disagreements about environmental impacts of high speed rail can arise when analysts examine only the most direct effects of the rail system.

California is planning to spend \$40 billion to build a high-speed rail system from San Diego to Sacramento. Although advocates believe that High Speed Rail gives the benefit of diverting the demand of vehicle and rails, critics raise the concerns over the embedded carbon in the high-speed rail system, which represents the carbon emissions associated with construction of rail infrastructure and trains. Chester and Horvath⁶ points out that the Life-Cycle Analysis is needed in evaluating a new rail track that will last for decades as opposed to narrower accounting approach. The study put its focus on estimates and comparison of energy efficiency of different transportation modes transportation carbon emission by taking life-cycle and ridership uncertainty into account. Analysis should include emissions result not only from the direct effects of operating the vehicles but also from indirect effects, such as building the infrastructure, producing the fuels, manufacturing the vehicles, maintaining the system, and disposing of materials at the end of their lives.

The study has developed a life-cycle inventory of high-speed rail, automobiles, heavy-rail and aircraft in the California high-speed rail corridor from San Diego to Sacramento. Results for high-speed rail showed that accounting for infrastructure

construction and electricity production adds 40 percent to the energy consumed by the trains operation alone. Greenhouse gas emissions increase by about 15 percent, primarily because of the concrete used in construction.

In addition, several environmental assessments have been performed, and focus on European and Japanese systems. The International Union of Railways (UIC) assessed the GHG emissions of four different HSR lines: the SE Atlantic; the LGV Mediterranean; Taipei-Kaohsiung; and Beijing-Tianjin (International Union of Railways 2011). For each of these lines, a cradle-to-grave analysis was carried out on earthworks, material transportation, structures, track, signalling equipment, stations and rolling stock. In a comparison of these lines by tCO₂ due to construction per km of line and year, the two French lines compare similarly, at around 60tCO₂/km/yr. The Taipei-Kaohsiung and Beijing-Tianjin lines are considerably higher at around 175tCO₂/km/yr and 140tCO₂/km/yr respectively. The large difference between these two lines and the two French lines is predominantly due to the use of bridges, tunnels and viaducts on the Taipei-Kaohsiung and Beijing-Tianjin lines.

2.4 The HS2 Context

Similar controversy on the environmental impact was raised on the proposal of the High Speed 2. Looking in more detailed at the proposed new London-West midlands high speed line, the reports by HS2 Ltd provide a detailed analysis of the operational and embedded carbon effects of HS2 and is valuable reference for our study to carry out carbon assessment for the completed project HS1 as there are no systematic way of evaluating at this stage.

2.5 Current Studies on HS1

The evaluation of embodied carbon of HS1 infrastructure include the embodied energy evaluation for sections of the UK Channel Tunnel rail link was conducted by Chau et al.⁷ The study evaluated the embodied energy of two built sections of High Speed 1 and found that in geotechnical structures, the embodied
In the process of achieving the conclusion, the study categorized geotechnical structures into two types including (a) structures of which the materials are totally dominant 90% of the total energy, such as pile-slab; and (b) more direct energy-

intensive construction, where the transportation and installation can collectively account for as much as 40% of the total, such as tunnel and embankment. It was also found that the embodied energy of the structures analysed are equivalent to 10,000 UK annual households' consumption and revealed the large scale of energy involved in the two section of HS1 construction, compared to activities in everyday life. The large figure called for more attention in evaluating the embodied energy of geotechnical constructions as part of design evaluations.

The study gives recommendation on optimizing designs by reducing the use of energy-intensive materials. Since embodied energy and embodied carbon are correlated, conversion is possible with corresponding conversion factor depending on forms of energy used. The study provides background to our calculation of tunnel construction carbon cost.

2.6 Current Approach of Carbon Assessment

For such assessment, the most commonly used database is the Inventory of Carbon Energy (ICE) developed by Bath University. The boundaries within the ICE database are cradle-gate which simply describes the energy required to produce the finished product without any further considerations. Although a cradle-to-grave approach which defines embodied energy as that 'consumed' by a project throughout its life more useful one when looking the project historically, coefficients are much more complex to estimate.

However, even within these boundaries there are many possible variations that affect the absolute boundaries of study. In our study, the upper and lower bound analysis will be included in our case study together with an adopted ICE value of our choice based on design and construction context.

2.7 Capital Carbon Cost

Capital Carbon Cost is the emission accrued as a result of the infrastructure's construction. In rail projects, stations, bridges, viaducts, tunnels, tracks, rolling stock and earthworks contribute substantially to CO₂ emission. Life cycle carbon cost

assessments of infrastructure projects are becoming more common, evidenced by the recent assessment of HS2 in London and four HSR case studies including (Paris and Silva, 2010; International Union of Railways, 2011).

LCA completed in advance of a project are necessarily based on projections; careful documentation of material use, shipping distance, site energy use and waste should be carried out to allow confirmation of the analysis and to facilitate more accurate future work.

So far, no calculation was performed to assess the capital carbon cost of the completed and operating high-speed line HS1. Most researches on carbon emissions of high-speed rails have focused on a life-cycle assessment of the rail lines including operational life and maintenance such as the assessment and comparison on carbon footprint on HSR in South Europe Atlantic and LGV Mediterrean France, Taipei-Kaoshiung in Taiwan and Beijing-Tianjin in China performed by the UIC⁸. The study of capital carbon of HS1 offers an opportunity to compare the carbon assessment of the newly proposed scheme of HS2 and indicate the corresponding environmental impacts of rail transportation infrastructure against vehicle and air travel.

3 Methodology

3.1 Scope of Assessment

Fig. 3.1 shows the route of High Speed 1 and the large-scale civil structures on the line including 5 stations, 5 major viaducts and 5 tunnels including 4 bored tunnels and 1 cut & cover tunnel. Rest of the line consists of a significant number of small civil structures including cuttings, retaining walls, embankments, road, links, roundabouts and etc.

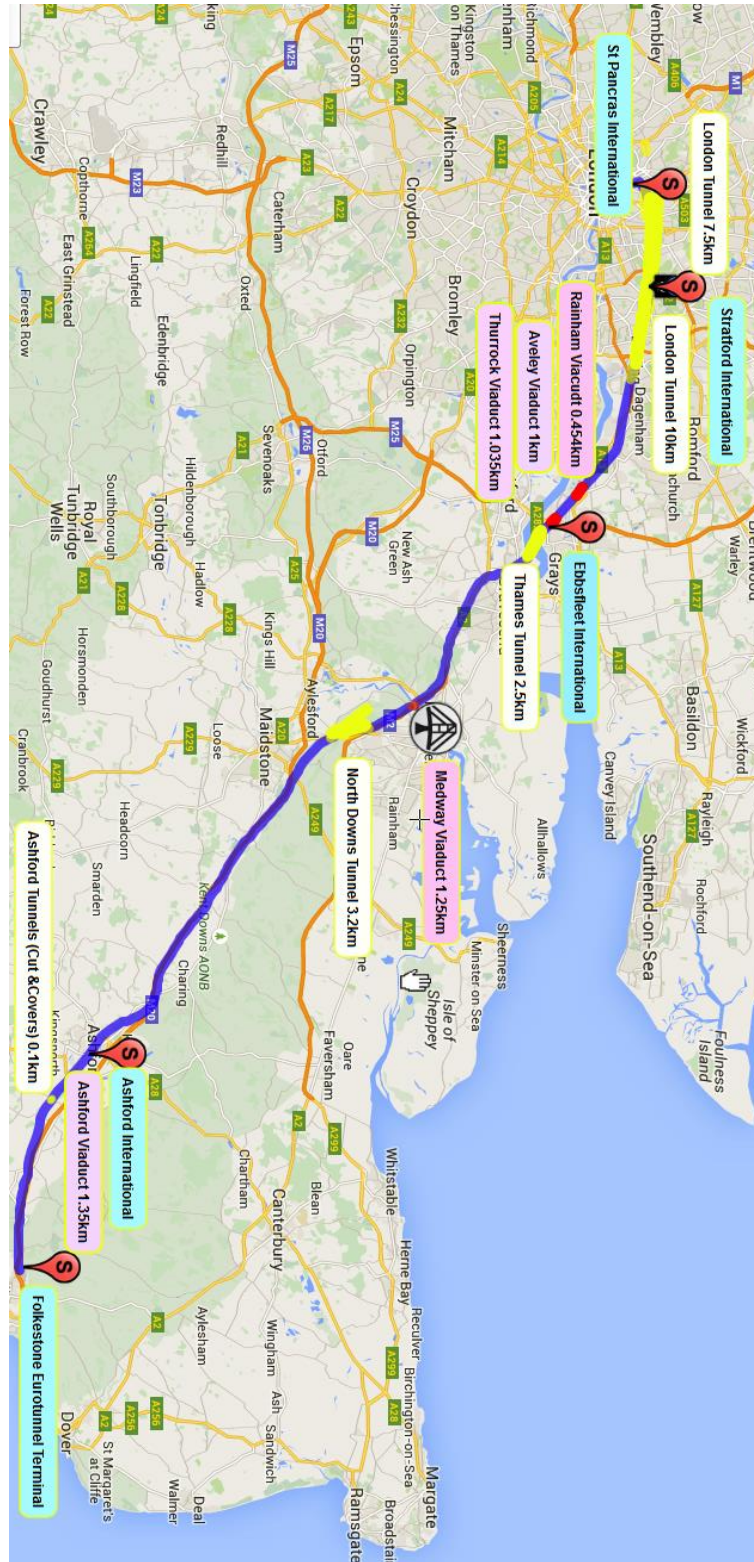


Figure 3.1 High Speed Rail Line and Large Civil Structures 2015 Google Map Data

3.2 The Approach to the Carbon Assessment

Understanding the potential carbon impacts of a high-speed rail is a complex process that relies on numerous factors, some under the direct influence, some not, and all with various degrees of uncertainty. The HS2 Carbon Model on Construction Phase was studied and used the reference for developing the methodology and boundary for our study. The HS2 methodology provided the most detailed, transparent and thorough framework to base this research on.

3.2.1 Study Boundary

3.2.1.1 Embodied Material CO₂ (Indirect Source)

The construction industry consumes a massive amount of new and recycled materials, such as concrete, steel, wood and plastics and each material must be extracted, processed and transported to site. Each stage in the process has CO₂ impacts. The largest CO₂ cost is associated with the CO₂ embodied in the materials themselves plus the emissions during their placement⁹.

The three main construction materials used in rail are track ballast, concrete and steel. Reinforced concrete is used in the tunnel sections, retaining walls and floor slabs. Steel reinforcing bar is used in most concrete elements and steel beams and columns of bridges and viaducts.

3.2.1.2 Construction Site Carbon Emission (Direct Source)

This stage considers the carbon emissions of energy consumed during construction activities associated with machineries and plants operations (diesel and electricity). This also includes the transport emissions arising due to the removal of excavated material.

3.2.1.3 Emission Source

The assessment of the capital carbon starts with identification of emissions sources. Collection of activity data and corresponding emissions coefficients are then required for the estimation of carbon impact. These elements are listed in Fig. 3.2. Emissions source can be categorized into direct-arising during operation of the power plant and indirect-arising during other non-operational phase of life cycle.

Initially it was intended to achieve an estimate a capital carbon cost covering all the elements as suggested in the HS2 Carbon Assessment to facilitate direct comparison between the two projects. However, as the project progressed, it was realised that the time constraint and the difficulty in data acquisition make it impossible to complete estimation for a scope covering all the elements listed below. The boundary of the carbon assessment changed overtime and the final scope is shown within the yellow box.

3.2.1.4 What were included

Recent studies show that the greatest contribution of the embodied energy results from the high carbon intensive bulk materials, hence large-scale civil structure elements such as bridges, tunnels, tracks, stations were imperatively chosen to be included for a realistic CO₂ emission estimate. For the elements of main civil infrastructure including bridges, viaducts and tunnel, the focus is primarily on the CO₂ associated with the materials

With earthwork activities, there is no CO₂ associated with manufacturing the materials. Hence the dominant carbon emission comes from the fuel consumed by the machines and plants operating on sites. As indicated in it was intended to be excluded in our assessment due to lack of robust tools for such analysis in estimating the extent of earthwork activities. However, since it can contribute a moderate amount to the total carbon emissions, (11.1% of total according to HS2), in order to achieve a closer estimate to the total for payback period, calculations were performed with the HS2 results based on our findings in comparing design similarity on major civil structure designs.

3.2.1.5 What was excluded

As grouped in the grey box, a number of elements box were excluded from the study due to incomplete detailed information with restricted time. Small civil structures such as cuttings, embankments were not assessed despite their use along the rail line. Other elements such as people mover were also excluded as we assume the contribution is small.

Other indirect CO₂ factors to be excluded for example, the assessment of LULUCF (Land-Use, Land-Use Change and Forestry) measures the total carbon emissions or removal due to land take and forestland converted to rail lines. Due to high speed rail's very high transport capacity, the land needed for the large traffic volumes carried is much reduced. This can also be reflected from the HS2 assessment indicating the least carbon emission accounting for 0.75% of the total. In addition, the impact on land use can be significantly reduced if new high speed lines are laid out parallel to existing motorways, which is usually the case. Moreover, the exclusion can also be explained by the fact that the land use impacts of High Speed Rail compared to aviation is predominantly a comparison of land use near an airport and a train station. HSR stations often share services with local and regional services, such as King Cross-St Pancras.

Demolition waste at the end of construction activities was considered to be outside our study boundary with the long life time of large scale structures such as stations and rails despite HS2 shows this element accounts for 1.89% of the total emission.

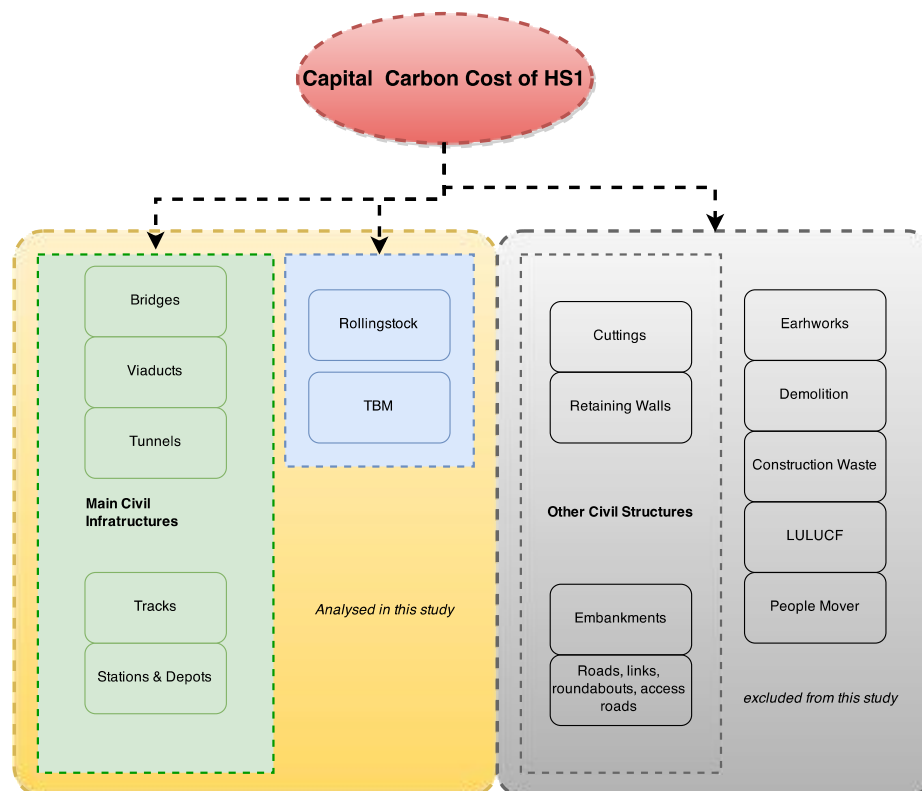


Figure 3.2 Study Boundary compared with HS2

Note the life cycle stages such as operational and End of Life carbon emission is not included in our scope of study. The end of life was excluded as rail lines are often used far beyond their design life, for example the Victorian lines are still widely used in London today.

3.3 Data Collection

For detailed case study analysis and calculations, ARUP has given permission to access to past documents on the project from the stage of Preliminary Design to Operational Drawings and Reports. Since the calculation on carbon emissions of a project is dependent on very detailed record keeping, specifically from the quantity of concrete used, to the shipping/transport distance of construction materials and the energy source (electricity and fuel) use on site equipment. When technical drawings could not be located for estimation based on designs released for construction, standards drawings were referred to and studied. As LCA is relatively new to rail infrastructure projects and the documents provided by ARUP are incomplete within several sections. Assumptions were made where information required is not available.

As shown in Appendix Fig. 6.5, different intensity factors in terms of the potential differences between the infrastructure requirements can lead to different carbon emissions. Inspections on the carbon intensity of materials used showed uncertainty due to the materials energy (depending on choice of materials and to carbon emission intensity itself) is very large. The same applies to carbon emissions on worksite construction activities and transport methods.

The uncertainty means that some parts of the carbon footprint may be best represented as a range. However, with the limited time and resource, average carbon intensity factor was taken in the calculation due to limited time.

3.4 Assumptions

An assessment of carbon emissions requires completeness of data within the scope. However, in a completed project of this size where the boundaries have been defined, good documentation is necessary. Where information gap is presented, assumptions have to be made. Some key assumptions in calculations are listed below:

- Since the information on construction traffic impacts is scarce, assumptions were made for construction traffic and the subsequent emissions. Examples of transport distance are shown below
 - Transport distance for tunnel boring machines from manufacturing site to tunnel location is assumed to be 200 km.
 - Default values with the CO2sT Tool of transport distance for Steel, precast concrete and in-situ concrete were allocated the distances of 50,70 and 10km respectively (these reflect the typical plant requirements and subsequent energy consumption values.)
- No assumptions were made regarding the way carbon emissions may have changed over the period of time since the construction of HS1 started.
- No improvements in emissions produced through production of materials (eg concrete, steel) have been assumed over the period of analysis which is conservative.

3.5 Stations



Figure 3.3 London St Pancras Source: en. Wikipedia



Figure 3.2 Ebbsfleet International

Referring to Fig. 3.3.1 Map of HS2 with large-scale Civil Structures, there are four international stations along the HS1 route, two in London and two in Kent. The London terminus of HS1 is the magnificently refurbished St Pancras International (Fig. 3.2). It is assumed that the requirements of stations are broadly similar for high-speed in terms of size for Stratford International, Ashford International and Ebbsfleet (Fig. 3.2) despite that the construction of Stratford is likely to have greater contribution to the total carbon due to the presence of the massive concrete box. According to Chester, 2008; Paris & Silva, 2010, the average station construction greenhouse gas emissions is estimated to be 24647 tCO₂, the number was taken as the average of rest of the three stations including Stratford International, Ashford International and Ebbsfleet International.

3.6 Rolling stock

Three types of rolling stock operating for HS1 include Class 373 Euro Star, Class 395 and Class 92 giving a total of 103 vehicles. Table 3.1 is the extract of comparisons between different types of rolling stock procured and operating in HS1. Comparison of these models of rolling stock shows similarities in design between Class 373 and Class 395 vehicle in train dimension and operational speed reflecting the similar types of service.

Table 3.1 Comparison between different types of rolling stock

Rolling stock	Type of Service	Length/m	Width	Height	Maximum Speed km/h	Car body
Class 373	International Passenger	121.3	2.81	3.817	300	Steel
Class 395	Domestic high speed passenger	18.7(middle) 22.15(driving) 21,84(powered middle)	2.81	/	225	Aluminium
Class 92	Conventional freight	21.34	/	/	140	/

Despite different rolling stock models, the manufacturing process of rolling stock is assumed to be the same for each single vehicle due to the same requirements on operating such as speed and capacity. A standardized CO₂ value of carbon emissions was used.

An estimate of the construction carbon footprint accounting for materials used only was performed by HS2. Details on fit out of the train (i.e. seats, tables etc.) or energy used at the manufacturing plant where the train was put together, or the transport of the train to the rail line were not available. This result of construction carbon cost is shown in Table 3.2 and included in the calculation performed in this study.

Table 3.2 Construction Carbon Footprint of Rolling Stock¹⁰

	Quantity (t)	EF (kg CO ₂ e/t)	Carbon footprint (t CO ₂ e)
Aluminium	90	9,160	824
Steel	322	1,950	628
HDPE and glass fiber reinforced plastic	155	1,930	299
Copper	34	2,170	75
Glass	50	1,350	68
Construction Total	651		1,894

3.7 Tracks

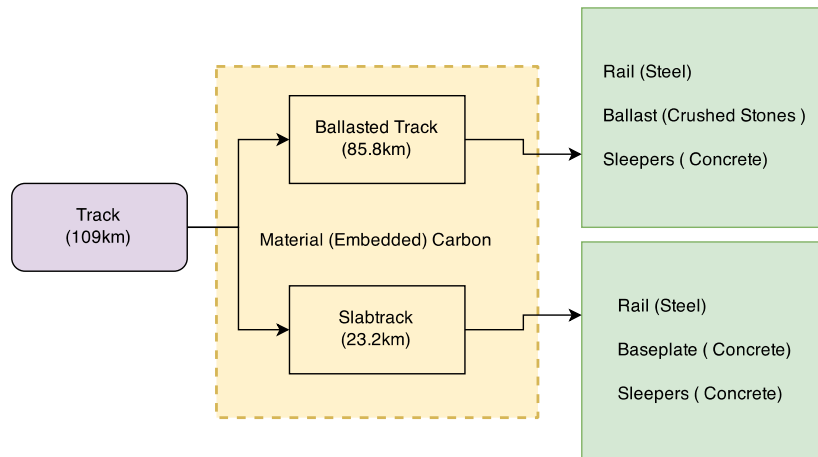


Figure 3.4 Track Embedded Carbon Calculation Flowchart

The 109km long track of HS1 consists of ballasted track and concrete slab track. The embedded carbon of rail is determined by the quantities of steel, in forming the rail section, quantities of sleepers and ballast. In slab track, ballast is replaced by concrete in function for better track performance required by high-speed rail.

As shown in Fig.3.2, estimate of track emission started with analyzing standard detail drawings of the two types of track work to obtain the cross sectional area of rail for the quantity of steel.

It was specified in the track work document under Construction Standard of data provided by Arup that the distance between sleepers are 60mm. Quantity of sleepers needed was then calculated by dividing the length of rail by the sleeper distance. Carbon intensity was then determined by looking up from ICE database referring to the standard requirement of construction materials documents.

The following assumptions were made for the calculation:

- The assumed minimum number of tracks is two.
- HS2 has assumed for ballasted track except in tunnels where slab track was assumed¹¹. The same assumption was made in deciding the proportion of length of ballasted tracks and slab tracks. I.e. the length of track in slab track and ballasted track is 23.2km and 85.8km respectively.
- Using a slab reinforcement ratio of 1.5% for concrete as suggested in Slab Track Design for High –Speed ¹²
- Total length of track is assumed to be 109km by neglecting the effect of gradient of track. (It is specified in HS2 Project Specification that “The rising and falling

gradients of the new high speed line shall be limited to a maximum of 35%; typically gradients should be less than or equal to 25%”. With every 1km’s track on a slope, an increase of track length approximately 0.1km. This increase in length is neglected in our calculation)

With the above assumptions, embedded carbon of steel, concrete and ballast used in track construction can be obtained with the correct quantities and appropriate carbon intensity factors as stated below:

Table 3.3 Track Component Material Properties

Component	Material	Density kg/m ³	Carbon Intensity Factor kgCO ₂ /kg
Rail	Steel	7840	1.293
Sleeper	Concrete	2400	0.214
Base Slab	Concrete	2400	0.214
Ballast	Crush Stones	1954	0.004321

As shown above, ballastless track is expected to lead to significantly higher embedded emissions due to the higher carbon intensity (6 times greater) despite the reduction in depth compared with ballasted track.

3.8 Tunnels

Over 25km of the HS1 route is in tunnel, particularly the more urbanized sections closer to London and there were two types of tunnels in HS1.

Bore Tunnels

- Shield type machines with precast segmental tunnel lining
- Used when surface access is very limited at depths typically below one tunnel diameter
- Longer tunnel lengths where economical to use machine

Cut & Cover Tunnels

- Typically concrete box structures constructed in excavated ground
- Used at shallower depths where there is good surface access

In this study, only bored tunnels were assessed due to the greater scale in lengths and more energy intensive tunneling method where a TBM is required.

Figure 3.3 shows the calculation method for the carbon emissions associated with the construction of twin-bored tunnels adding up to a total length of 23.2 km. The

contribution can be divided into two parts including the tunnel segment materials emission and tunnel boring activity emission.

Details of the material carbon for the tunnel segments were taken from a study of Chau et al (2011)¹³. In determining the manufacturing and transport carbon emission in fabricating concrete segments from energy used in the study mentioned above, conversion factors as published in (2013 Government GHG Conversion Factors for Company Reporting: Methodology Paper for Emission Factors)¹⁴ have been used depending on the energy source consumed such as fuel/gas/electricity. Table.3.1 shows examples of Conversion Factors used in this study.

However, as technology advances the efficiency of different energy source might have changed and results may not reflect the true emission during the actual time of construction.

On the other hand, quantities of the raw materials consumed in tunnel construction were multiplied directly with the corresponding carbon intensity factor. The sum of manufacturing concrete segments and raw material contribution is then divided by the length of tunnel assessed in the study to give an average value in material carbon cost per km.

Designs in bored tunnels varied slightly. For examples, North Downs tunnel has sprayed concrete lining whereas London Tunnels are constructed with fibre reinforced segments. Assuming for similar tunnel designs for all the twin-bored tunnels, this value is used to evaluate the total material carbon cost of the HS1 tunnels of length 23.2km. Further study is needed to understand the embodied energy and carbon of different tunneling types.

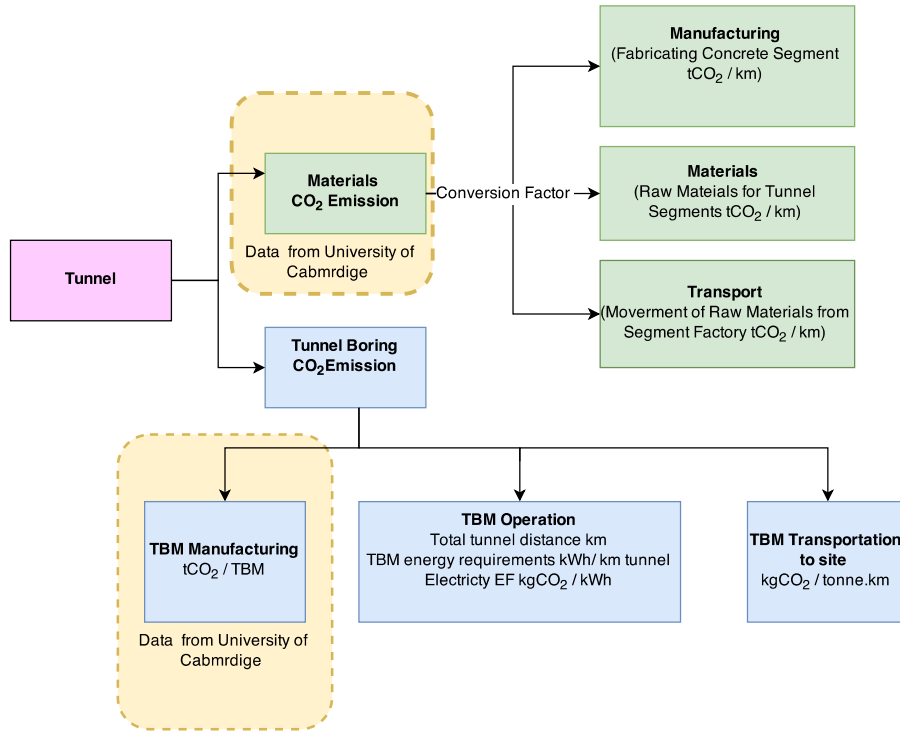


Figure3.3 Tunnel Calculation method

Fuel	Indirect/WTT EF(kgCO ₂ e/GJ, Net CV basis	Source of Indirect/WTT Emission Factor	Assumption
Coal (industrial)	15.61	JEC WTW (2011)	Emission factor for coal
Other Petroleum Gas	6.96	Estimate	Based on LPG ¹⁵ figure, scaled to direct emission ratio
Diesel	15.80	JEC WTW (2011)	
Gas Oil	15.80	Estimate	Assume same as factor for diesel

Table 3.3.4 Examples of conversion factors used in this study for fabrication of tunnel segments

With respect to TBM operational CO₂ due to tunneling activities for each of the identified tunnel, the calculation is based on tunnel length, operation hours (24 hours / 7 days working) and grid factor source selected. Since cut-and-cover tunnels do not require tunnel boring, it is hence not included in our calculation. The calculation process is shown in the flowchart as followed:

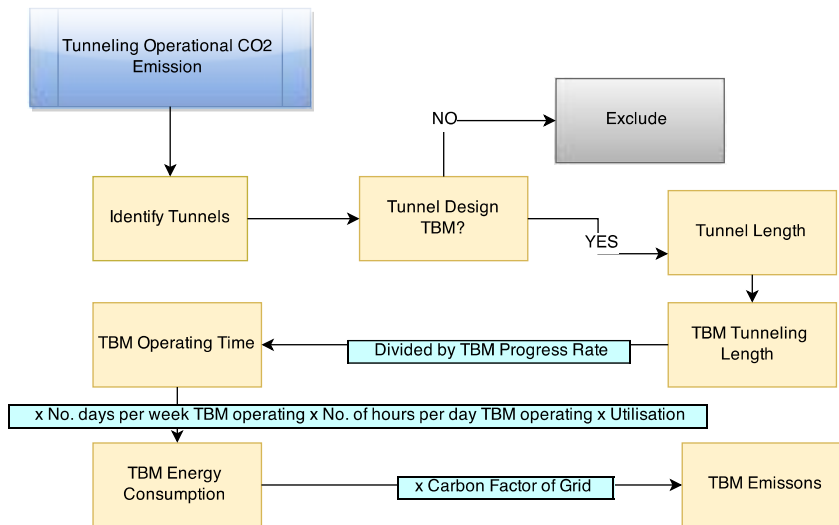


Figure 3.5 TBM Operational CO2 Emission Calculation Process

The assumptions on factors to be used are also tabulated below:

Assumptions	
No. days per week TBM operating	7
No. hours per day TBM operating	24
Utilisation	80%
TBM Apparent power (MVA) (MW)	6.25
TBM Power factor	0.98
Carbon Factor of Grid gCO2/kWh	317

3.9 Bridges and Viaducts

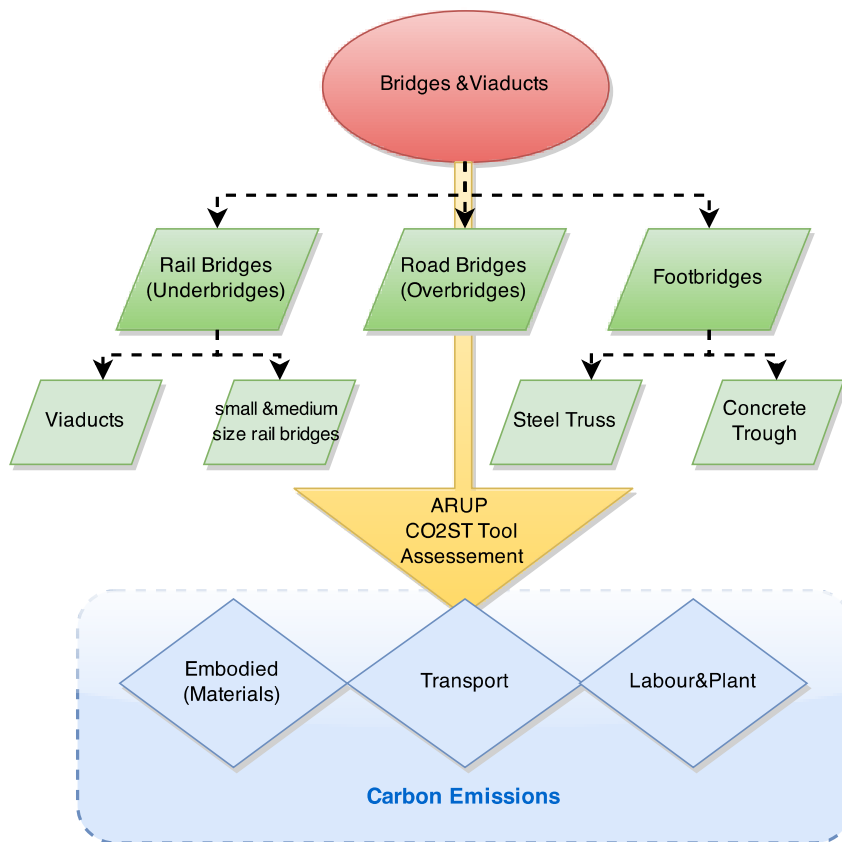


Figure 3.4 Bridges & Viaducts Calculation Method

Bridge designs were categorized into Road bridges (Overbridges), Rail bridges (Underbridges) and Footbridge. According to the Preliminary Design Report, there were 74 road bridges, 43 rail bridges, and 34 footbridges including off-line structures proposed. 57 road bridges, 23 rail bridges and 23 footbridges were identified in the drawings. By locating to detailed drawings and measuring using Google Map, length and width of each bridge was obtained and gave a value for total deck area for bridges.

3.9.1 CO₂ST Tool

The Arup CO₂ST tool was used to calculate the CO₂ emission associated with the construction of the bridges and viaducts. CO₂ST Tool gives output of carbon cost of Materials (Embodied), Transport of construction materials to site and Labour & Plant emissions of machineries operated on site. Quantities were estimated from detailed drawings.

Due to the large number of structures to be accounted for, typical designs according to various types of bridges were chosen and analysed. All major viaducts, 2 underbridges, 4 road bridges and 2 footbridges were included in the CO₂ST Tool assessment. Through assessment of operational drawings it is found that within each type of bridge structure there is a diversity of geometric constraints such as span, length and skew. Additionally there are constraints imposed on pier position. However, extract from preliminary design documents specified that “optimization of design effort was required to be achieved during detail design where possible by: ‘Re-use of designs and drawings at multiple sites.’” Hence average values for each type of bridge were used in establishing a total by multiplying this value by the total deck area.

CO₂ST Tool calculates and categorizes the carbon cost resulting from the extraction and manufacturing of construction materials, transportation of construction materials to site and the carbon associated with machinery and plant usage involved with the construction activities.

Elements automatically included specifically for the bridges calculations are: road restraint systems, drainage and service ducts, earthworks, piling and embedded retaining walls, structural concrete, steelwork and waterproofing for structures.

An example of the background calculations of CO₂ST Tool for a bridge is presented in the Appendix Table. 6.6.

CO₂ST Tool operates on its own Carbon Intensity Factors Library built based on the ICE database and some other sources and an example of carbon intensity factors used can also be found in Appendix.

3.10 Pay Back Period

The payback period evaluates the upfront energy or emission investment in deploying high-speed rail infrastructure against the potential reductions over time.

The carbon payback period for HS1 can be estimated by comparing the energy associated with its construction with the resulting carbon savings in its operation.

Based on the record on Eurotunnel traffic volumes for the past 10 years provided by Eurotunnel Group¹⁶, extracts can be found in Table 6.2 in Appendix Table. 6.4, the total number of passengers on high-speed rail can be calculated. With the assumption that emission for Eurostar per passenger¹⁷ is 6.6kg CO₂ and 102.8kg per passenger for

aviation respectively (The figures are the most detailed ever produced and are based on actual passenger numbers, exact distances of rail and air routes, actual aircraft types in use on different routes, and the mix of electricity sources used by Eurostar trains.), the difference of the two CO₂ emissions represents the net carbon saving per passenger per trip. This figure can then be multiplied by the cumulative passenger counts assuming high-speed rail is the only alternative for the journey between London-Paris and to aviation, the payback period can be estimated by comparing the capital carbon cost with the cumulative carbon saving due to mode shift from aviation to rail.

However, the estimates for carbon footprint per passenger per trip are obtained with assumption on ridership estimate. Although this issue was addressed by studying the ridership forecasts conducted for the CAHSR Authority¹⁸ (with assumptions such as steady increasing ridership) for the case of carbon assessment of California High-Speed rail, the uncertainty in ridership is difficult to deal with.

4 Results & Discussions

Numerical results of each assessed elements as specified in the boundary are shown in

Table 4.1Summary of Carbon Emissio Results

Construction	Embodied	Transport	Labour & Plant	Operation	Total tCO ₂	% of total
bridges	133,854	9,391	8,576	/	151,821	7.4%
viaducts	176,845	14,472	11,804	/	208,951	10.2%
tunnels	160,578	4,891	1,377	140,915	307,761	15.0%
stations	/	/	/	/	667,501	32.6%
track	176,449	/	/	/	176,449	8.6%
rolling stock	107,958	/	/	/	195,082	9.5%
TBM	10,920	163	/	/	11,083	0.5%
Earthworks	/	215,787	110,660	/	326,447	16.0%
Total	766,603	244,702	273,333		2,045,094	

4.1.1 Bridges & Viaducts

Carbon Emission for bridges and viaducts were estimated to be 360,771 tonnes and accounted for 17.6% of the total emissions.

Bridges and viaducts were designed and constructed where ground features and topography requires. The use of bridges and viaducts seek to minimize length and height to mitigate impacts on land shape and rivers. The designs are usually sensitive to sit in specific environments.

The total CO₂ resulting from the CO₂ST Tool analysis of the 14 bridge structures are shown in Figure 3.1 and total CO₂ is separated into embodied, transport and Labour and Plant carbon emissions. Materials appeared to dominate the carbon cost yet Labour and Plant were found to be similar for each viaduct assessed due to the fixed energy input at the startup stage of the construction. The CO₂ resulting from the viaducts are significantly higher than the other types of bridges analysed hence contribute greatly to the total CO₂ emissions due to its greater span and the need for more adequate structural standards which may also leads to higher degree of reinforcement required.

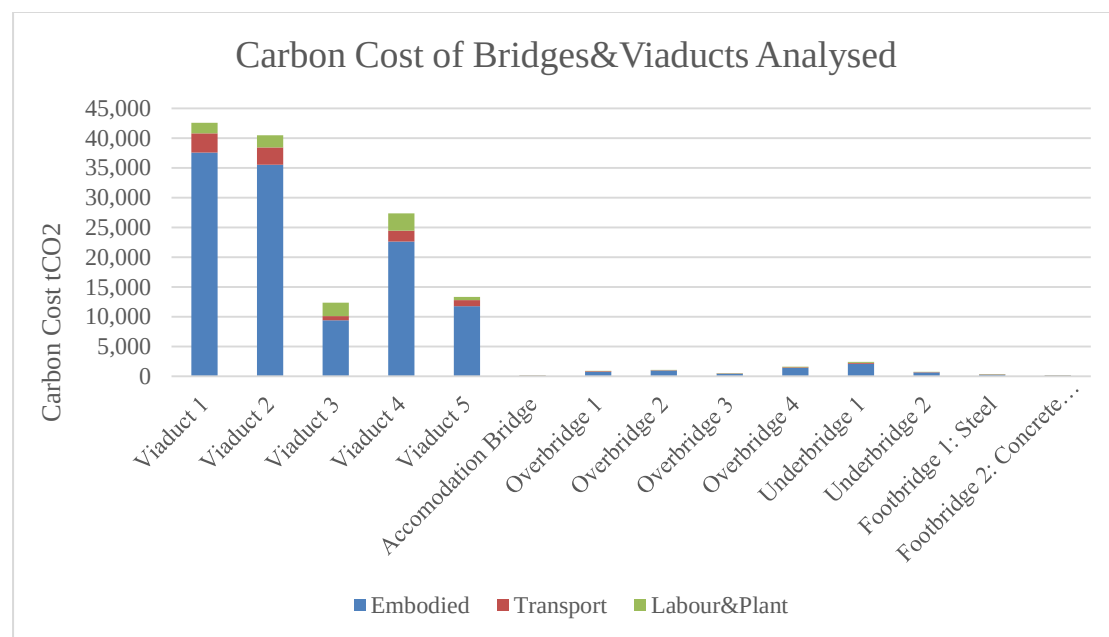


Figure 3.1 Total CO₂ Cost for Bridges & Viaducts Assessed in Tonnes

As shown in Fig. 3.1, similar pattern was found for overbridges, underbridges and footbridges despite the lower total emissions. (10-20 times smaller than viaducts).

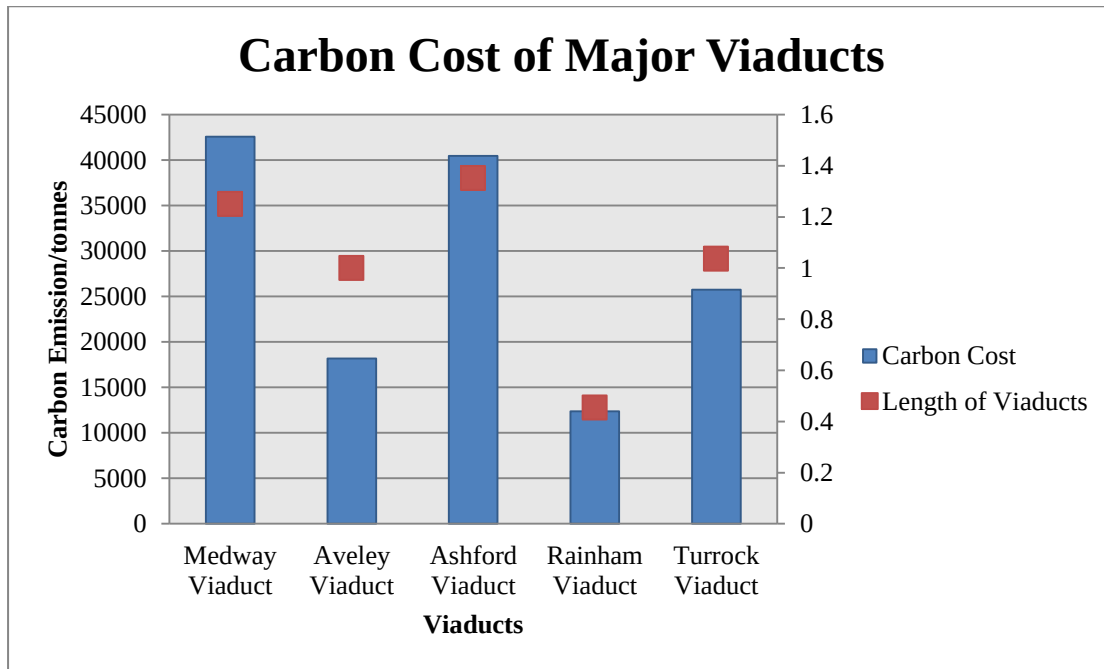


Figure 4.1.2 Carbon Cost of Major Viaducts with Lengths

The carbon costs of different bridge type based on the assessed structures including 4 viaducts, 2 underbridges, 2 highway bridges, 1 accommodation bridge and 2 footbridges are shown below in Fig 3.4.2 below. By comparing results from the work of Hughes¹⁹ (also assessed with CO₂ST Tool), the bridges were chosen from the same category. It can be seen that variations in carbon cost is common due to differences in designs resulting from factors including locations, geographic limitations and etc.

Comparison of these results and the wide range of variation in bridges carbon analysis published by the HS2 Ltd indicate the benefit to analyse every single structure of this project for an accurate estimate of the environmental impact. However, since these analyses are both resource and time intensive, this presents a trade off between degree of accuracy and substantial efforts required within limited time.

According to our study, as presented below in Fig. 3.4.2 underbridge is a slightly more energy intensive structure. Viaducts and highway bridges have similar values. Footbridge gives relatively small carbon emission despite the common use of steel as a carbon intensive material. This can be explained by the nature function of footbridge for pedestrians' passage requiring smaller deck thickness and reduced width.

The similar results compared with HS2 also revealed the resemblance in bridges and viaducts designs.

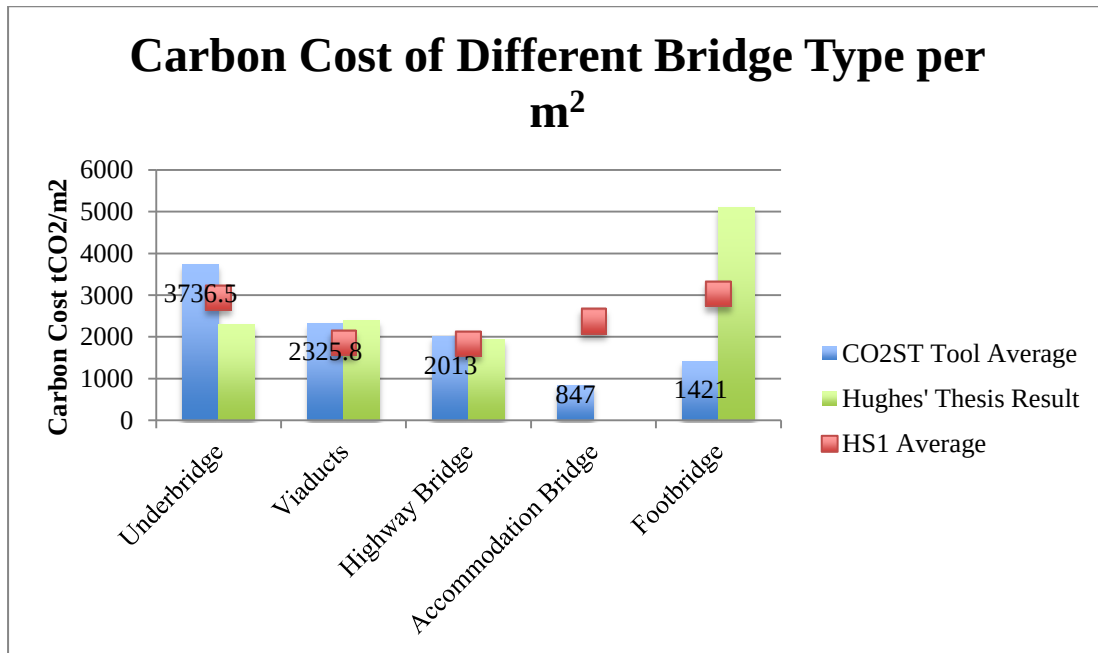


Figure 3.4.2 Comparisons of CO₂ST Tool HS1 Results, HS2 Averages and Hughes's Thesis Results

4.1.2 Tunnels

Carbon Emission for construction of tunnels were estimated to be 307,761 tonnes and accounted for 15% of the total emissions.

Different types of tunnels are used in different types of terrains. Shallow tunnels are often dug by the “Cut-and-cover” method, which involves excavating a long trench, adding reinforced slides, roof and floor, and then covering the whole thing over with spoil (the original excavated material). Where shallow cut-and-cover tunnels are not possible, deep tunnels must be bored using tunnel boring machines.

Figure 3.3 showed the carbon cost of major tunnels assessed including the London Tunnel, Thames Tunnel and North Downs Tunnel with breakdown of TBM Operation, Manufacturing, Materials and transport. As indicated from the Fig. 4.3, TBM operation as part of the tunnel construction process can dominate more than 40% of the total emissions from tunnel constructions.

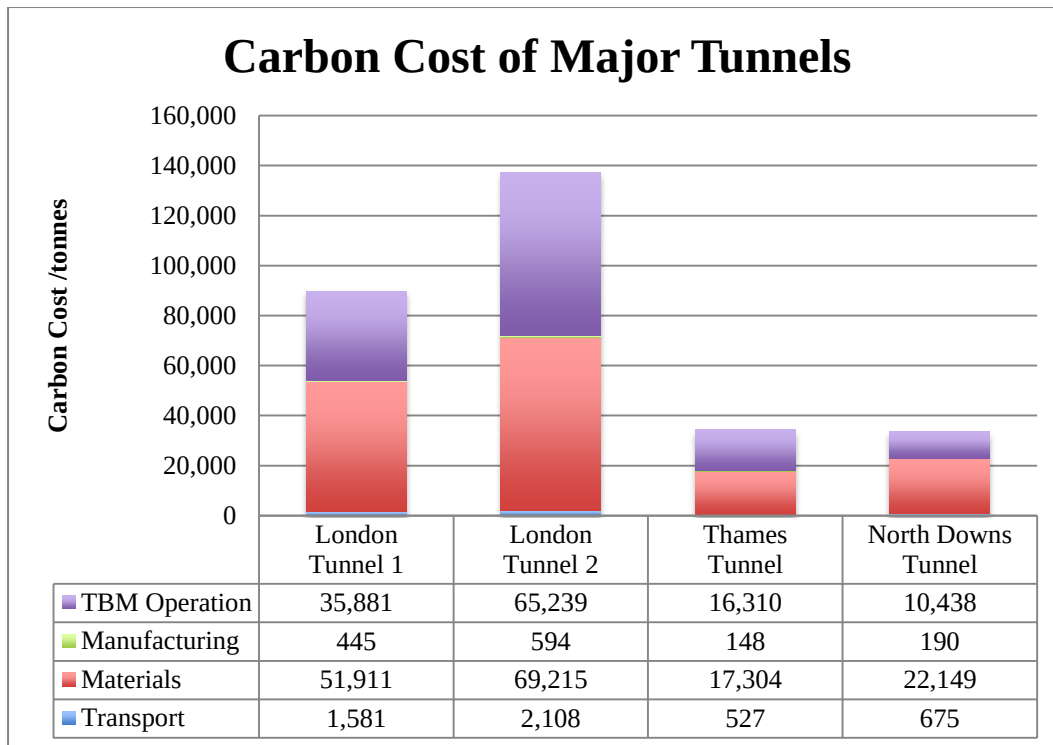


Figure 4.3 Carbon Cost of Major Tunnels Assessed

It is shown from the result that the principal impact from the tunnels construction is the CO₂ emissions is embodied carbon in materials, being over 50% of the total emission, with emissions from construction plant, machinery and tunnel boring activities being as high as 47% for one of the tunnels.

Shorter tunnels or more efficient operations could help in reduction in TBM activity and hence less significant effect on the construction phase electricity consumption. Hence while designing alignments of tunnels, efforts should be made into achieving a shorter tunnel yielding a greater carbon saving.

4.1.3 Tracks

Carbon emissions due to construction of track were estimated to be 176,449 tonnes and accounted for 8.6% of the total.

The three main construction materials used in rail are track ballast, concrete and steel and Table 4.1 below gives a summary of Track Carbon Emissions. Typical designs of track include two options: slab track and ballasted track, with the majority of the rail line track was ballasted track and the rest of the line in tunnel sections constructed with slab track.

Table 4.2 Summary of Track Carbon Emission

Track Type	tCO ₂ /km	Length/km	tCO ₂
Slab track	4,018.9	23.2	93,238.3
Ballasted Track	483.6	85.8	41,494.2
		Total CO ₂ /t	134,732.5

The assessment of track CO₂ accounts for 9% of the total carbon. We expect this represents an underestimate of the track emissions as the level of assessed embedded emissions for the line of route can vary considerably, depending on

- The nature of the route: single track/double track
- Gradient
- Curves
- Length of tunnels (has an influence on type of track to meet operation standard)
- Construction method used
- Additional platform tracks in stations

For example, based on the effect of gradient along, with the assumption of average slope of 25%, every 1km on slope increases the track length by 0.1km. Assuming 20% of line on slope, this will lead to extra track length of 22%.

In terms of extra platform lengths, detailed analysis on each station has led to an extra track length of 10.38km, which is 10% of the overall rail length.

Since we have only assumed for a total track length of 109km, a more accurate estimate of track emission requires more detailed study on the factors mentioned above.

4.1.4 Tunnel Boring Machines (TBM) Manufacturing

According to engineers from ARUP, a total of 5 tunnel boring machines were used for Stratford Box, Easterly drives, Westerly Dives (Barking Portal), Thames Tunnel and North Downs Tunnel separately. The total carbon emission due to TBM manufacturing and transportation to site was estimated to be 11,082.5 tonnes, 0.7% of total. Although the contribution is small, the significant tunneling operational carbon emission indicates a high degree of urge in improvement of TBM design in yielding a lower construction carbon cost.

4.1.5 Rolling stock

Carbon emissions due to construction of track were estimated to be 195,082 tonnes and accounted for 9.5% of the total.

Carbon emission induced by the manufacturing of rolling stock only accounts for a considerate portion of the total. The effect of variation in rolling stock designs need to be studied to achieve a better estimate.

4.2 HS1 Carbon Emissions in Context

4.2.1 HS1 Summary

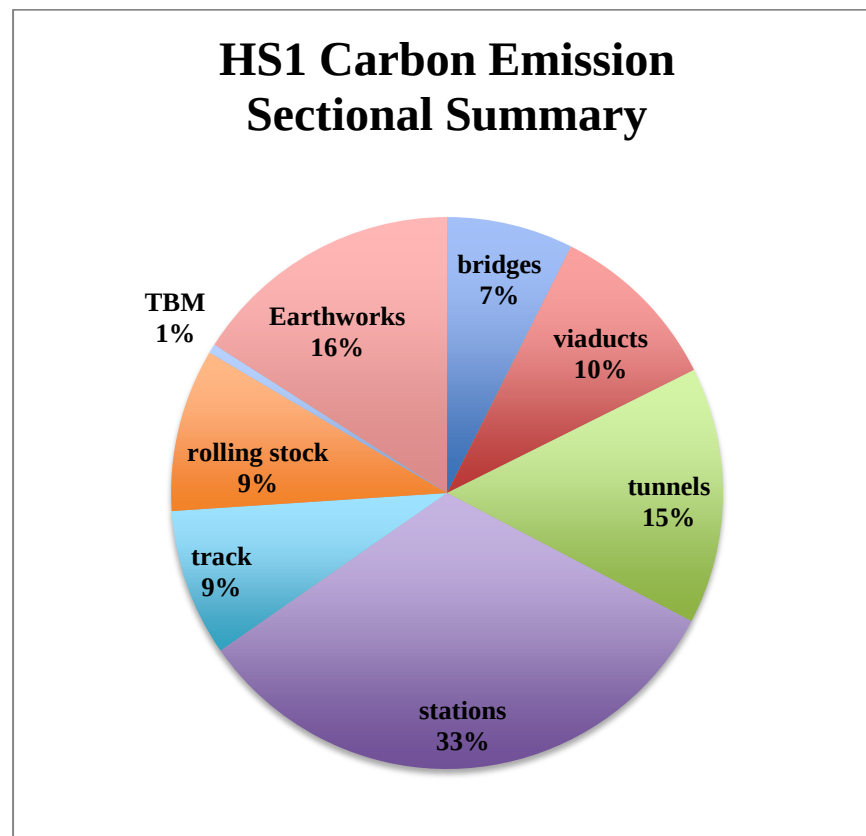


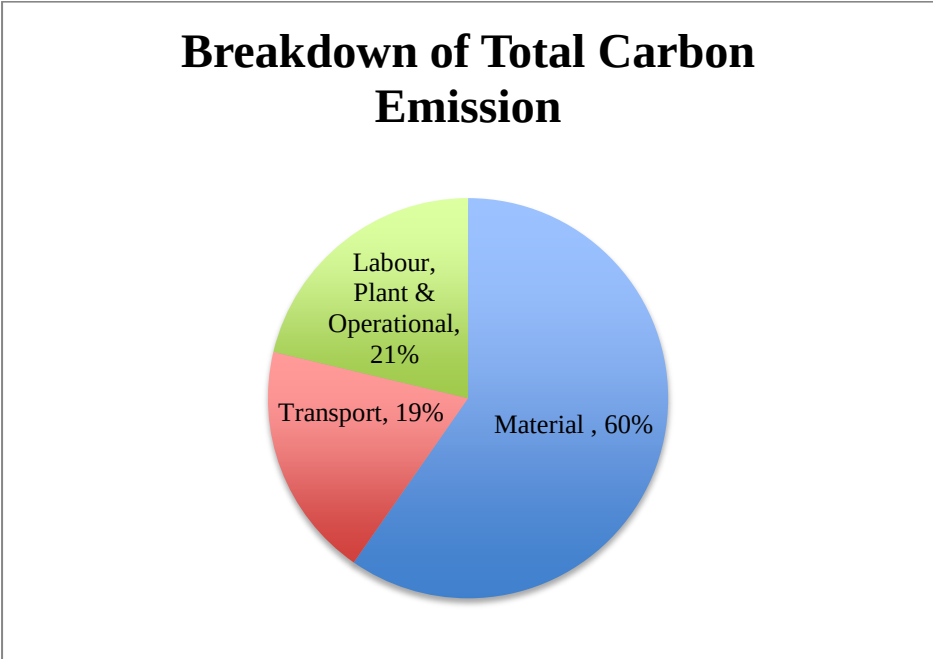
Figure 4.4 HS1 Carbon Emission Sectional Summary

The capital carbon cost of the scope as described in section 3.2.1 was estimated to be 2.05 million tonnes. Although this figure represents a narrow scope of the structures exist on the whole rail line, it is equivalent to 390,285 annual UK household's carbon emission based on the Carbon Dioxide Emissions per Household Estimate²⁰. In achieving the total, we have estimated the carbon emission of earthworks to a shorter

length with HS2 estimate based on our findings in similarity on major civil structure designs of HS1 and HS2 and included the number to our total.

Fig. 4.1 below shows the breakdown of total carbon emissions of HS1. The majority of the CO₂ (79%) result from the materials used within construction, the CO₂ associated with the plant and machinery use is the next largest contributor (18%), with the transportation contributing a relatively small amount of CO₂ (3%).

Table 4.3 Breakdown of Total Carbon Emission



In comparison, this agrees with the HS2 assessment overall. According to the HS2 Ltd assessment, two-thirds of the embedded carbon is associated with materials, particularly steel and concrete. Whereas transportation of the bulk materials accounted for 19% of the embedded carbon.

This result implied that potential reduction in total material use, particularly concrete and steel, should be examined and studied to reduce the CO₂ impact of rail and HSR construction by seeking innovations in design. However, the engineering requirements cannot be sacrificed in pursuing lower material used.

Further initiatives to reduce the embodied carbon in materials through the use of cement substitutes are being investigated and will contribute to greater savings. For example, the use of PFA at a higher cost can reduce the embodied carbon for up to 20%²¹ varying construction type and specification. The reduction in CO₂ can also

potentially be achieved by using higher recycled content or with lower transport-related carbon emissions (e.g. locally-sourced aggregates).

4.2.1.1 Operational Energy

As indicated in the chart above, operational carbon contributes 18% to the total carbon. It is possible to seek for innovations in construction method and plant use such as Hybrid Equipment to reduce energy used for construction so as to achieve a more environmental friendly approach in construction. This is mainly dominant by the energy intensive tunneling activities although it only accounts for approximately 20% of the total rail length.

4.2.2 Tunnels vs Open Tracks

Tunneling is often necessary on railway lines where, due to the rolling nature of the landscape, it would not be possible to align the track without steep inclines. This was the case for HS1 and hence there were more than 25km of tunnels constructed on the rail line.

Tunnel provides solutions for no viable surface route due to topography or population density. However, problems with tunnels include the complexity of design, construction and operation and maintenance together with the high cost, noise and vibration provision of access and ventilation shafts.

4.2.2.1 Tunnel Boring Machines

Advanced design TBMs are essentials are crucial for the tunneling activity. Operation is for 24 hours 7days a week.

Carbon emissions involved in manufacturing and transportation of TBM to site were estimated to be 11,083 tonnes and accounted for 0.5% of the total emission. The TBM was purpose-built depending on specific designs and ground conditions on site to increase reliability of performance and to reduce ground movement. Hence they could not be reused for tunneling on other site and could only be buried in ground after its use. Although construction carbon emission incurred from manufacturing TBMs was not insignificant, the considerable amount of energy required and the single-use nature of the machine is undesirable as they were manufactured as a package with tunneling activities.

Since tunnel account for a significant part of the total capital carbon cost (15%), mainly dominated by materials and operational emissions, it suggests that any reduction in TBM activity will have a significant effect on the carbon emissions arise during the tunnel construction. There is a potential to greatly reduce the carbon impact hence shorter tunnels and more efficient operations will be preferred in rail alignment design to reduce the need for plant and machinery, particularly tunnel boring machines.

4.2.3 Ballasted Track vs Slab Track

4.2.3.1 Traditional Ballasted Track

Traditionally, railway track consist of rails lying on concrete sleepers and supported by ballasted bed. The function of the ballast is to provide longitudinal and lateral stability. The main advantages of ballasted tracks include relatively low construction cost, high elasticity, high maintainability at relatively low cost, high noise absorption and as indicated above, significantly less carbon intensive compared with slab track. However, there are also major shortfalls of this system. Recent study performed by the University of Southampton on HS1 ballasted track²² reveal the problems of ballast migration (ballast circle) and ballast flight (flying ballast)²³ with increasing stress due to increasing train speed. These ballast problems may cause rail to deflect and damage to rolling stocks. Other disadvantages also include limited non-compensated lateral acceleration in curve and increased costs of supporting bridges and viaducts due to ballast's heavy weight.

Approximately 80km of HS1 is constructed as ballasted track except in tunnel sections where slab track was used instead. This is because ballasted track is relatively high, which would lead to greater tunnel diameter. Although this is not the case for us, the reduction in height gives a major argument in favour of slab track as a part of the structure on some bridge designs.

4.2.3.2 Advantages of Slab Track

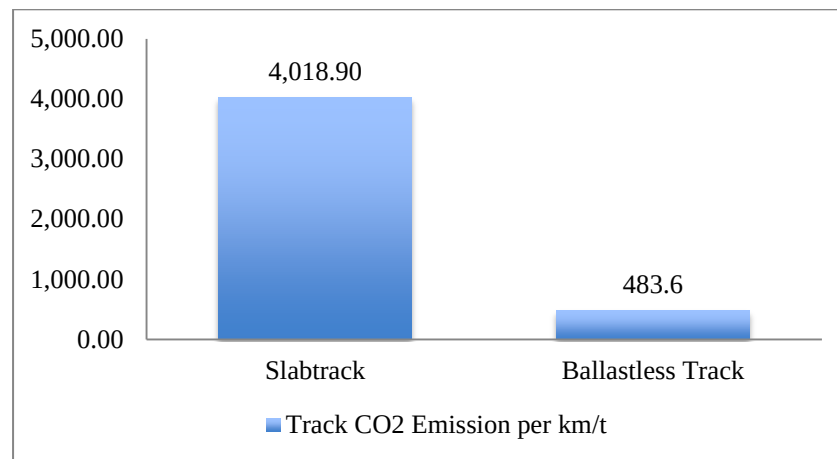
In general, ballastless tracks were designed and developed to improve track performance with the increased train speeds on both new and classic railway lines. The advantages of slab tracks compared with ballasted track include:

- Low maintenance requirement
- Shallow construction depth (embedded rail systems and resilient baseplate track types require the least depth as in HS1 slabtrack design this facilitates tunnel design where headroom and gauge clearance are particularly important)
- Higher speed operation due to the greater trackbed stability of concrete
- Less noise and vibration nuisance
- Preventing the release of dust from the ballast into the environment
- Lower maintenance requirement and increased service life

Fig. 4.3 shows a comparison of CO₂ per km for slab track and ballasted track. Result suggests slab track design is significantly more carbon intensive than ballasted track. This can be explained by the use of concrete which is more energy intensive in substitution of ballast despite shallower depth, to facilitate for better performance in the operation of high-speed rail. Slabtrack were only assumed to present on the line where there were tunnel sections.

As suggested in Slab Track Systems for High-speed Railways²⁴, “The application of slab track in tunnel is very efficient in terms of construction, durability, strength and economy.”

Table 4.4 Track CO2 Emission per km



Slab tracks are now widely used throughout the world for high-speed lines, heavy rail and tram systems. However, the high level of investment required has held up the wide-spread use of slab track on open line so far. The decision to build slab track for tunnel sections could be a trade-off between savings in total life cycle costs and high investment cost. For high speed trains, the need for better performance ensures that the track is maintained to a very high standard. Although the design of slabtrack represents a higher value in carbon emission, other effects including maintenance and life cycle performance underpinned by sustainability as well as construction method need to be taken into consideration in deciding the type of track to adapt.

4.2.4 Payback Period

As indicated in Fig.4.6, since the opening of the complete HS, over 10 million passenger on average have travelled on HS1 through the CTRL with a trend of steady increase.

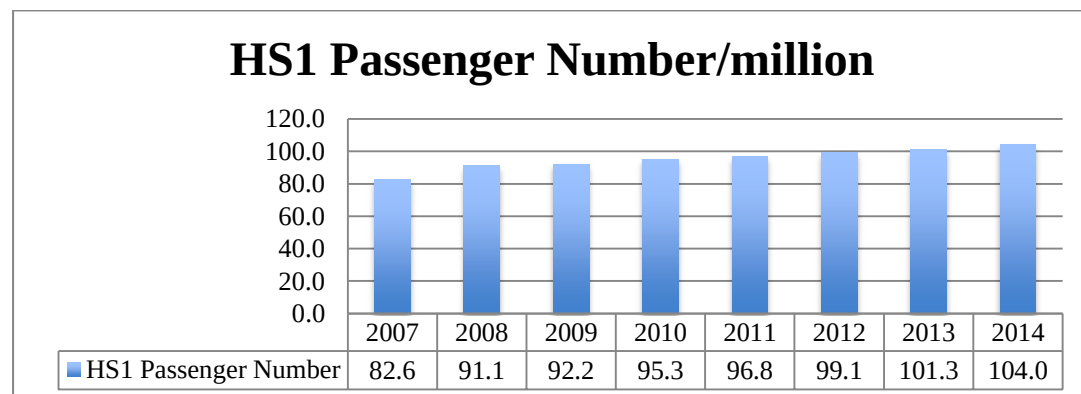


Figure 4.5 HS1 Passenger Number

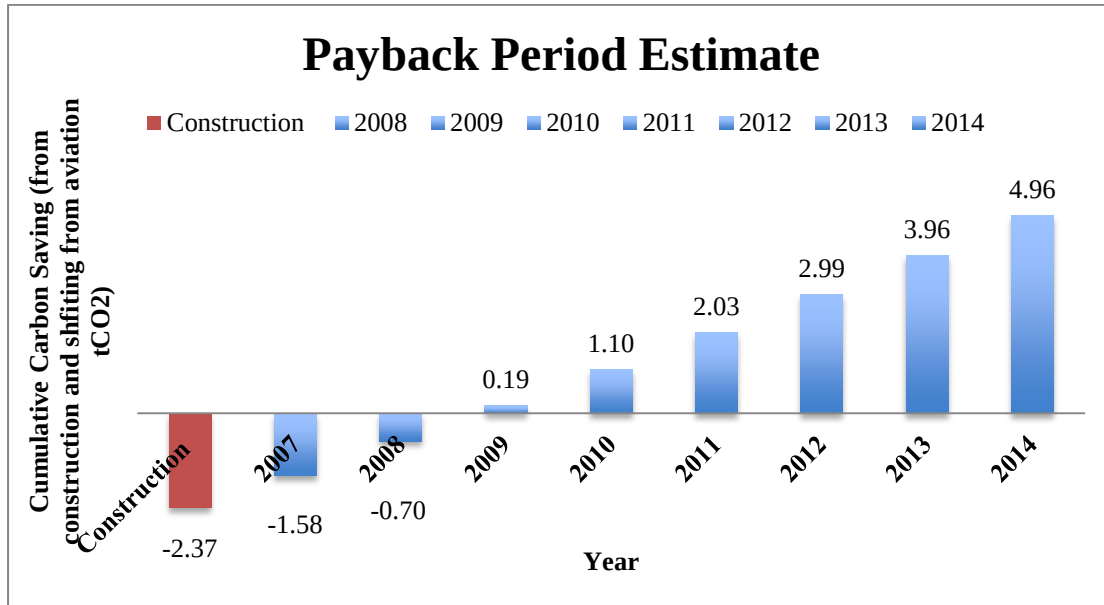


Figure 4.6 Payback Period Estimate

As indicated in Fig.4.6, the first occurring positive cumulative carbon saving in 2009 indicates in the estimated carbon payback period is three year since the opening of the whole life for HS1. This means, if the assumption on ridership prove accurate, the operational HS1 only gave rise to net carbon emission during the first two years of operation. Despite the restricted scope, the time to payback for a significant part of capital carbon cost for construction is considered to be relatively short compared with the expected operational life of 60 years. Existing study on California High Speed Rail²⁵ gave an estimate of the payback period of 6 years for the 1300km rail system based on the high ridership estimate as strong adoption of high-speed rail at the expense of auto and air travel provided by the California High-Speed Rail Authority. Table 4.4 showed the summary of comparison between payback Period of HS1 and California HSR. The different scale in length and the uncertainty in ridership leading to a wide range of payback period of California HSR. This has made direct comparison difficult. Although the capital carbon cost of HS1 is high, by comparison, HS1 could reduce CO₂ emissions over a relatively short period of time and play a role in meeting the carbon emissions targets. The relatively short payback period can be explained by the successful public perception on the project on carbon saving leading to higher ridership as suggested by the increasing trend of passenger number earlier.

Table 4.5 Comparison of payback Period between HS1 and California HSR

Rail	California High-Speed Rail		UK High Speed 1
Length/km	1300		109
Payback Period/ years	High Ridership	6	3
	Mid-Level Ridership	70	
	Low Ridership	Never	

However, as indicated in the Payback Period calculation method, this is a simplified estimation with ridership assumption on carbon saving. Difficult in a good estimate due to great uncertainty in predicting how long the carbon has paid back depending on how the transport and power sectors will perform over the period of time after construction. Significant carbon saving is involved on high-speed 1 per passenger as the option of Eurostar replaces the short-haul flight between London and Paris as majority of the carbon emissions were associated with taking off and landing.

The dominant benefits are CO₂ saving, other benefits also include reduced overcrowding by releasing capacity by aviation and simplifying the journey connecting the two important cities in Europe.

Table 4.6 Net Operational Carbon Saving with Shift from Aviation

High Speed Emissions Rate	6.6	kgCO ₂ /trip.passenger
Aviation Emission Rate	102.8	kgCO ₂ /trip.passenger
Carbon Saving rate	96.2	kg/trip.passenger
High Speed Operational Emission in 8 years	503,218	tCO ₂
Aviation Emission with Equivalent passenger count in 8 years	7,838,000	tCO ₂
Total Carbon Saving form Aviation to Rail in 8 years	7,837,497	tCO ₂

As shown in Table 4.4, the net carbon saving in 8 years' time has achieved 7.8 million tonnes of CO₂ since HS1's completion in autumn 2007. It is believe this result with the quick payoff period of carbon cost resulting from the construction of the rail line will make the environmental advantages of Eurostar even more attractive to passengers.

With the assumption that the shift from other modes such as cars and aviation is high, it is likely that building the high speed 1 is way is going to be a sensible way to

reduce UK emissions despite it involved high-cost and energy-intensive investment of this scale and complexity. Hence it can be concluded that the capital carbon cost of HS1 is out weighted by the less environmentally damaging nature of high speed rail compared with aviation. This is especially important when we consider the strategic importance of the HS1 link and its opening up of the UK to the EU HSR network. The potential for HS1 to enable more modal shift, for more journeys from aviation is great. The imminent introduction of new direct services from London to Amsterdam is a testament to this. Discussion are ongoing to provide direct services to Berlin, Barcelona and Madrid, Significant carbon savings are possible here. On the other hand, the total capital carbon cost as a result of the assessment has also called for improvements of the new rail line design on:

- Low carbon specification and construction
- More energy efficient designs
- More energy efficient train design
- Reduced carbon footprint for grid power involved in the construction process of plant & machinery usage.

4.2.5 HS1 vs HS2

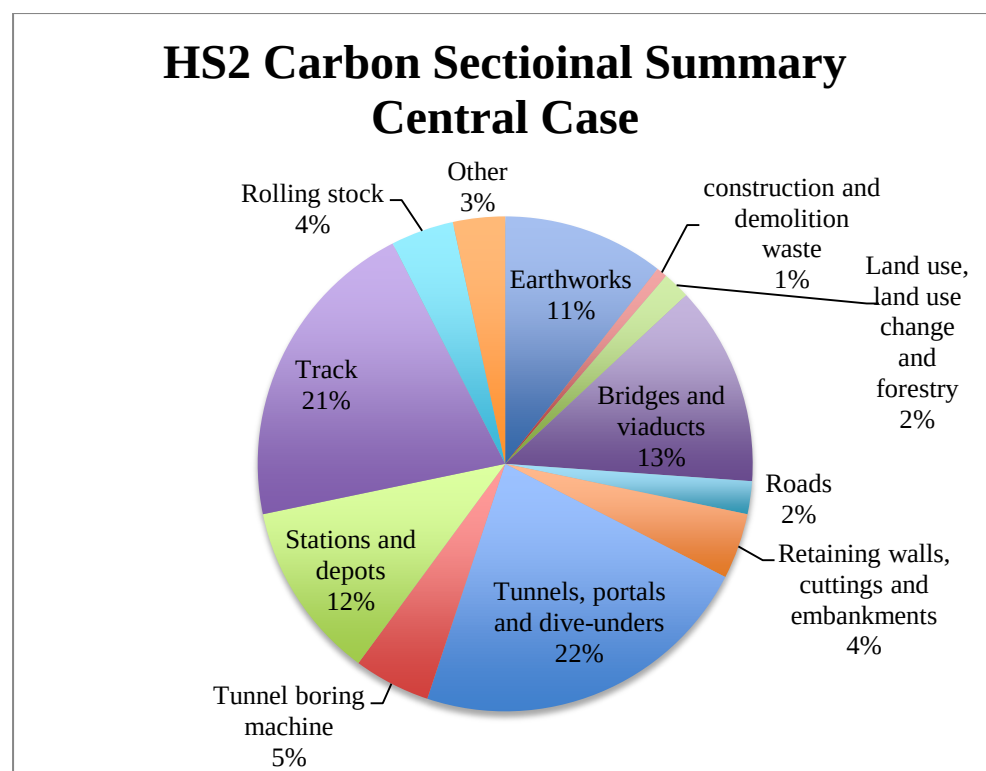


Figure 4.7 HS2 Carbon Sectional Summary Central Case

Total embedded carbon emissions for HS2 were assessed at 5.58 millions tonnes CO₂ in total whereas total embedded carbon emissions for HS1 were assessed to be 1.96 millions tonnes CO₂ in total.

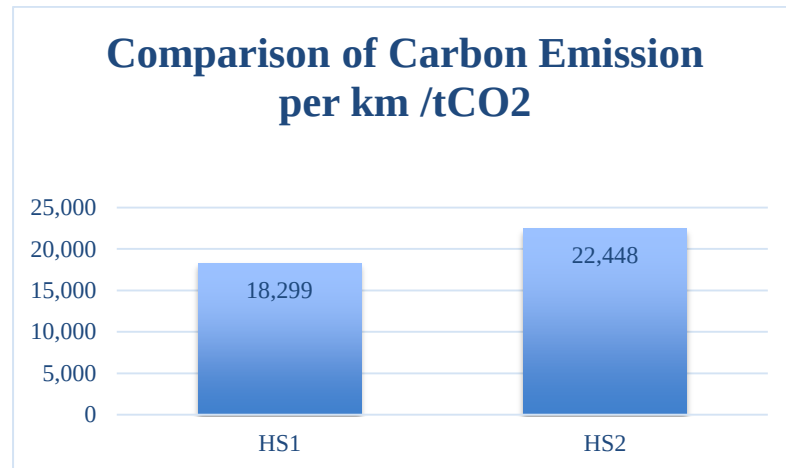


Figure 4.8 Comparison of Carbon Emission per km between HS1 and HS2

As indicated in Fig. 4.8, the carbon emission per km for HS1 is 18% smaller compared with HS2. This can be explained by the narrower scope of our study compared with the HS2 scope. It is believed that the elements we have chosen account for the dominant elements of a carbon assessment and as discussed in the Bridges & Viaducts sections, detail calculations, no evidence showed significant variation in design of the two schemes.

By comparing the assessments of the two rail lines with respect to breakdown of different elements, the following conclusions in common can be achieved:

Comparison in the two rail lines specifically in bridges & viaducts, tracks and tunneling reveal similarities in designs hence similar carbon cost associated with the construction of these elements. This has led to an argument that the HS2 design is duplicating solution of HS1 with no major advance in technology or improvements on controlling the CO₂ cost to a lower level.

Currently many countries have developed high-speed rail to connect major cities. The Japanese have just opened a maglev line operating train with world speed record of 600km/h test run, operating at a higher speed compared with high speed rail yet. The UK is yet to start HS2 which is based upon last century's technology with no improvement in designs to reduce carbon emission despite HS2 Ltd.'s effort into carbon assessment of the project.

In fact, studies suggest Maglev requires construction of a continuous elevated concrete structure, resulting in a significantly larger carbon footprint for construction than a conventional or high speed rail new Line²⁶ (1.5 times higher including operation and construction carbon cost). The expensive maintenance and security upkeep. Costs with constructing the train and rail line appeared to be the biggest hurdle for a similar proposal to HS2 in an 800km-plus maglev to connect London, Newcastle, Liverpool, Glasgow, Edinburgh, Manchester, Leeds and Birmingham.

For HS2, life-cycle analysis will offer a way to identify tradeoffs early in the policy development and planning phases. It is suggested that if High Speed 2 is to deliver the environmental benefits intended, there must be robust evidence that it truly divert passenger from car and air transport and that the high speeds intended do not lead to increase emissions. In terms of the feasibility of the HS2 scheme of carbon impact, HS2 was criticised on the uncertain assumption on the mode shift from aviation and cars. Unlike HS1, being a more efficient in a way of travelling from London to Paris compared with the other options available, HS2 has no direct advantages of attracting passengers from roads or flights due to the complex nature of the route and the many different modes available.

In general, comparison in the construction carbon cost has proved difficulty. This is because interpretation of results on assessments depends on a common methodology and benchmark information is not available. .

Since extensive use of concrete and other materials, transportation of parts and materials in the supply chain, and the electricity generation for many interrelated processes will consume much energy and produce CO₂ before trains begin transporting passengers. Accounting for these life-cycle effects and for the larger range of potential ridership This includes the construction, operation, maintenance and end-of-life of the high speed rail life cycle. Life- cycle assessment including high ridership coupled with planning for system-wide energy and emission reductions are necessary for a high-speed rail network to improve the environment impact.

The major flawed argument the HS2 is the assumption on mode shift from other modes of transport which is in a different context compared to HS1 with the nature of services providing, i.e. domestic and international. Only in this can the effects of

mode shift from other modes of transport be assessed in order to make decision on development of the new rail line.

4.2.5.1 Tunneling Length

	HS1	HS2
Twin Bored Tunnel Length/km	23.2	39.1
% of Rail length	21.3%	19.7%
Cut & Cover Tunnel Length/km	1.7	7.9
% of Rail length	1.6%	4.0%
Rail Length	109	198

Table 4.7 Tunnel Length Comparison between HS1 and HS2

As shown in table 4.5, both HS1 and HS2 involves the construction of a considerable percentage of tunnel as compared to the total length of rail. Although comparison shows that HS2 is slightly lower in percentage of twin bored Tunnel compared with HS1. The tunneling length is almost double the length required for HS1. This has direct impact on the amount of construction materials needed, together with the quantity of excavated materials that need to be transported away from the sites and the amount of tunneling required by the energy intensive Tunnel Boring Machines. The need for tunnels on route design and alignment of a high-speed rail depend on a number of factors including terrain, surface disruption and connectivity. For the case of high-speed rail, faster trains requires straight tracks hence more tunnels, earthworks and high viaducts if terrain does not help. The designer of HS2 faces the challenge in cutting down on tunneling length to reduce the energy intensive tunneling activities

4.2.6 Recommendations

Despite the quick payback period, efforts can be made into reducing the capital carbon cost of a civil infrastructure of this scale covering the following aspects:

- Reduce the fundamental need for materials
- Investigate alternative low carbon materials
- Reduce energy consumption, particularly for tunnel boring activities.
- Reduce energy consumption, this can potentially be achieved by:
 - Introduction of measures to decrease consumption

- Exploring low-carbon energy generation to meet the project's need.

Putting the results above into the environmental policy context, if the assumptions made in this study are correct, with the relatively short payback period, it can be put forward that the biggest energy impact over the lifetime of HS1 will be the operation and maintenance of the rail line hence measures should also be taken in ensuring these costs are controlled to an acceptable level. Other measures could potentially include reducing on station energy consumption and etc.

5 Conclusions

5.1 Assessing the Capital Carbon Cost of HS1

In order to evaluate the environmental impact of the project, the capital carbon cost has been evaluated. The calculation was based on existing operational documents provided by ARUP and public available and validated carbon emission factors. Whilst a preliminary assessment of the impacts have been carried out in this study accounting for the main civil infrastructures together with the emissions of manufacturing and transport of Tunnel Boring Machines and rolling stock, a more in depth life cycle assessment is desirable. Research into the potential for minimization of the embodied carbon in the whole project of new rail infrastructure through sourcing of less carbon intensively produced materials would also seem worthwhile.

5.2 Findings

The Capital Carbon Cost from construction of the main civil structures was estimated to be 2.05 million tonnes. This is equivalent to it is equivalent to 390,285 annual UK household's carbon emission. The payback period required for the capital carbon cost to payoff and produce positive carbon saving was estimated to be three years. This is considered small compared with the expected life time and existing estimates on other high-speed rail lines such as the California High-Speed Rail.

Study also analyses the carbon intensity of track designs including ballasted track and concrete slab track. Although slab tracks were considered to have excellent

performance on high-speed rail in due to its track stability, noise reduction, shallower slab depth and lower maintenance requirement, the carbon emission per km was assessed to be 10 times greater than ballasted track due to the high carbon intensive bulk material used. This could be the reason why only tunnels sections where space is important slab track will be used for HS2.

Results suggest that TBM operating energy involved in the energy intensive tunnelling activity contributes a significant amount to the plant and machinery use cost of the whole scheme.

Assessment showed that carbon impacts of the project directly result from infrastructure design, train design, construction energy emission, and waste & materials use. Material was found to be the greatest contributor to carbon emissions, followed by plant and machinery use, with transport emission accounting for the least carbon emissions. Hence investigations into lower carbon intensive materials may offer opportunities to reduce the overall carbon emissions of the whole project. However, the engineering requirements must not be compromised in pursuit of reducing CO₂ emissions.

By comparing the carbon emission on major civil structures assessed, specifically for bridges and viaducts emissions per deck area, variations in HS1 results compared with HS2 average were small. All results were found to be within the range of HS2 designs. It suggested that designs of HS1 and HS2 are very similar and so far there is no major advance in incorporating any new system in reducing the capital carbon cost of high-speed rail design to reduce the environmental impact before the operation of such rail lines.

Although HS2 was claimed to be a broadly carbon neutral project, the key is in determining whether HS2 will deliver a reduction in emissions by taking travellers off the roads and planes. It is suggested that if High Speed 2 is to deliver the environmental benefits intended, there must be robust evidence that it truly divert passenger from car and air transport and that the high speeds intended do not lead to increase emissions. It is believed that the CO₂ emission per passenger will be significantly underestimated with the uncertain assumption on mode shift. Extensive

use of concrete and other materials, transportation of parts and materials in the supply chain, and the electricity generation for many interrelated processes will consume much energy and produce CO2 before trains begin transporting passengers. For infrastructure construction, the environmental impacts of certain materials, like concrete, should be minimized. Furthermore, mode shifting behavior and indirect effects including reduced congestion should be considered.

6 Appendix

Table 6.1 Carbon Emission of Bridges & Viaducts Assessed

Bridge	Embodied Carbon	Transport Carbon	Labour&Plant Carbon	Total
350 Medway Viaduct		37,551,743.00	3,226,819.00	1,802,627.00
430 Ashford Viaduct		35,546,392.00	2,867,554.00	2,042,790.00
310 Rainham Viaduct		9,404,591.00	691,328.00	2,263,023.00
310 Aveley Viaduct		22,628,943.00	1,832,744.00	2,872,808.00
Thurrock Viaduct		11,771,475.00	1,022,466.00	546,255.00
420 Valley Accommodation Overbridge		123,136.00	9,640.00	6,777.00
Downs Road overbridge No.3		774,670.00	73,003.00	41,251.00
420 Hospital Road Overbridge		656,552.00	31,630.00	49,013.00
420 Old Ham Lane Overbridge		944,619.00	85,735.00	61,586.00
430 Newland Roadbridge		425,690.00	5,272.00	29,055.00
430 Egerton Roadbridge		1,389,245.00	143,663.00	68,860.00
330 Wrotham Road Underbridge		2,084,545.00	193,908.00	144,972.00
430 Cattle Market Footbridge		279,193.00	12,649.00	15,664.00
430 Lodge Wood Footbridge 3-span		156,870.00	13,787.00	10,357.00

Table 6.2 Reinforcement Ratio Applied to CO2ST Tool Calculation

Description	Steel (tn/m3)
Deck	0.25
Deck Support	0.28
Cantilever slabs	0.27
Abutments	0.18
Abutment Foundations	0.16
Abutment Piles	
Wing Walls	0.18
Piers	0.2
Pier Foundations	0.16
Pier Piles	

Table 6.3 List of Major Tunnels and Viaducts

Name	Description/ location	Length
Tunnels		
London Tunnel 1	Twin bore single track tunnel from St Pancras to Stratford	7.5km
London Tunnel 2	Twin bore single track tunnel from Stratford to Ripple Lane	10km
Thames Tunnel	Twin bore single track tunnel under the River Thames between Thurrock and Ebbsfleet	2.5km
North Downs Tunnel	Double track single bore tunnel at Blue Bell Hill (between Maidstone and Rochester in Kent)	3.2km
Ashford Tunnels	Three cut and cover tunnels	1.5km
Bridges and viaducts		
Medway Viaduct	Twin track viaduct spanning the river Medway in north Kent	1.2km
Thurrock Viaduct	Twin track viaduct spanning the m25 and providing access to the Thames Tunnel	1.2km
Aveley Viaduct	Twin track viaduct adjacent to SSSI freshwater wetlands	1.0km

Table 6.4 High Speed Trains Passengers Count

Year	High Speed Trains Passengers
2007	8,260,980
2008	9,113,371
2009	9,220,233
2010	9,528,558
2011	9,679,764
2012	9,911,649
2013	10,132,691

Material			Used			% Difference
Concrete	<i>Concrete: C35/45 50% Fly Ash</i>		0.09100	0.14006	0.09100	<i>z</i>
	<i>Concrete: C35/45 25% GGBS</i>		0.12900	0.14006	0.12900	-0.07897
	<i>Concrete: C28/35 25% Fly Ash</i>		0.12000	0.14006	0.12000	-0.14323
	<i>Concrete: C28/35 30% Fly Ash</i>		0.12400	0.14006	0.12400	-0.11467
	<i>Concrete: C28/35 50% Fly Ash</i>		0.08700	0.14006	0.08700	-0.37884
Cement	<i>Cement: general</i>		0.83000	0.83000	0.83000	0.00000
	<i>Portland cement: average CEM1</i>		0.95000	0.83000	0.95000	0.14458
	<i>Portland Cement: semi-wet kiln</i>		0.93000	0.83000	0.93000	0.12048
	<i>Portland Cement: dry kiln</i>		0.74000	0.83000	0.74000	-0.10843
	<i>Portland Cement: semi-dry kiln</i>		0.84000	0.83000	0.84000	0.01205
	<i>Fibre Cement</i>		1.09000	0.83000	1.09000	0.31325
	<i>Portland Ash Cement</i>		0.58500	0.83000	0.58500	-0.29518
Steel	<i>Steel: general (virgin)</i>		2.89000	1.46000	2.89000	0.97945
	<i>Steel: bar & rod</i>		1.40000	1.33458	1.40000	0.04902
	<i>Steel: pipe</i>		1.45000	1.33458	1.45000	0.08649
	<i>Steel: section</i>		1.53000	1.33458	1.53000	0.14643

Table 6.5 Comparison of Carbon Intensity Factors

Description	Quantity	Unit	Rate	Cost	Material(Embodied)	Transport	Labour & Plant
Establishment of plant for cast-in-place concrete piles ne 600mm diameter (single rig)	-	item	8,318.13	-	0.00	-	607.37
Establishment of plant for cast-in-place concrete piles exc. 600mm diameter (single rig)	2	item	#####	20,571.53	0.00	-	755.84
Moving piling plant for cast-in-place concrete piles ne 600mm diameter	-	no	34.66	-	0.00	-	2.53
Moving piling plant for cast-in-place concrete piles exc. 600mm diameter	816	no	52.48	42,822.37	0.00	-	3.86
Vertical cast-in-place piles, 300mm dia, ne. 5.0m in depth	-	m	38.40	-	25.27	-	2.47

Table 6.6 Example of Background Calculations of CO2ST Tool

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1

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