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The Environmental Case for the High-Speed Train in the UK: Examining the London–Manchester Route

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ABSTRACT

This article investigates the potential for environmental benefit from the introduction of the High Speed Train (HST) on the London–Manchester route in the UK, focusing on carbon dioxide (CO_2) emissions. The lifecycle carbon emission of HST is assessed, and its sensitivity to demand changes is analyzed for several scenarios. Based on the UK Government demand assumptions, the analysis shows relatively limited potential for reduction in CO_2 emissions. In 2033, overall CO_2 reduction due to HST operation on the route is estimated at 100,000 tCO_2 per annum, which is less than 0.1% of the total UK domestic transport emissions in 2007.

Key Words: carbon dioxide emissions, carbon intensity, electricity generation mix, high-speed train, life cycle assessment

1. INTRODUCTION

This article aims to address the following questions: Will the introduction of the High Speed Train (HST) in the UK result in a reduction of carbon dioxide (CO_2) emissions? How much reduction can be expected? And what are the key determinants that affect emission reduction?

The development of HST in the UK has been widely discussed by policy makers as well as researchers. More generally, the subject of HST has been extensively studied in the literature in terms of its provision of additional capacity, economic

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impacts, travel time savings (Adler, Pels, and Nash 2010), and competition with other modes (Givoni 2006; Clever and Hansen 2008). In addition, much focus has been placed on the potential environmental benefits that HST can bring (Campos and de Rus 2009; Gonzalez-Gonzalez et al. 2010).

HST proponents in the UK suggest that the wider economic benefits of HST must be considered and, overall, result in higher benefits than what could be concluded by a traditional cost–benefit analysis. It is also argued that without significant investment in rail infrastructure, severe transport bottlenecks can be expected on the UK rail network, leading to economic loss, amongst other impacts (Department for Transport 2007).

The opportunity for reduction in CO_2 has also been mentioned in the UK debate on HST development. In particular, this is inspired by the need to meet green-house gas (GHG) emission reduction targets. In this respect, the UK Government has recognised the significant role of the railways and the potential of the industry to play a role by virtue of its efficiency and quality of service, which can result in reducing the transport carbon footprint through mode substitution to rail (Department for Transport 2007).

Carbon emissions can be reduced and air quality improved by achieving a shift of passengers to HST from other modes of transport (Givoni 2007). However, it has also been pointed out that the introduction of HST services could lead to an overall increase in demand for travel, resulting in an absolute increase in CO_2. It is therefore crucial that any assessment should include all modes of transport. Furthermore, it is not sufficient to consider only transport operation but all environmental loads, including construction of the infrastructure and production of the trains. While this is desirable, even essential, there are significant barriers to a full quantitative analysis of all the above elements (Commission for Integrated Transport 2007).

Nevertheless, significant progress has been made in recent years by using Life Cycle Assessment (LCA) in transport. LCA is a systematic, comprehensive process that evaluates the environmental impacts of products, processes and services. LCA is an appropriate method for conducting early-stage environmental assessment of the provision of passenger transport facilities (Kato and Shibahara 2006). Application of LCA in transport has been studied extensively, particularly with respect to road transport. For example, U.S. freight transportation by air, rail, and road was studied using LCA, and air transportation was rated the least efficient in terms of emissions (Fachanha and Horvath 2006). For HST passenger transport, for example, Von Rozycki et al. (2003) estimated a total of 69.4 g CO_2 emissions per passenger kilometer (pkm) when conducting an inventory analysis of rolling stock and infrastructure of the environmental carbon load on the German HST route between Hannover and Wuerzburg. In another case of HST, Kato and Shibahara (2006) compared air transport with HST, including consideration of maglev technology in Japan, and found that the life cycle carbon emissions of air transport is more than 8.7 times that of HST on the Tokyo–Osaka route.

Recent LCA studies in the United States by Chester and Horvath analyzed specific inventory data by comparing road, rail and air modes of transport (2009), and also examined HST in detail (2010). Their analysis showed that varying levels of occupancy rates (i.e., load factor) can easily change the relative environmental performance of different modes. The results of the above and other studies (Givoni 2007) demonstrated that air transport has a relatively high environmental load in comparison to other modes, on air transport's short haul routes (routes from 300 km to 1,000 km). In addition to the occupancy rate, which is very much effected by demand and operational practices, Life Cycle CO_2 (LC_CO_2) emission of transport depends on the route distance, vehicle type and above all the sources of energy used.

A limitation of previous studies is that they normally rely on one emission factor for computation. However, using emission factors that change according to demand on the route will result in more accurate estimation. Also, a crucial aspect to account for is changes in the electricity generation mix, which affects the amount of carbon emission for modes of transport powered by electricity from the grid (Givoni, Brand, and Waitkiss 2009; Tanaka et al. 2010). In addition, demand shift from other modes should be included. The analysis presented in this article accounts for the above.

As the debate on HST development continues, plans for extensive investments in HST infrastructure are being considered in the United States, UK, and Sweden, for example, and construction of HST lines in China is rapidly progressing, more evidence for the environmental case for HST development are required. This article aims to provide such additional evidence by using LCA to estimate the likely environmental benefits from the proposed new HST line in the UK between London and Manchester, the first route likely to be completed on the future UK HST network. The analysis considers only passenger transport, putting aside the implications that adding rail capacity might have on rail freight transport, including for example possible substitution from road to rail for freight transport.

The remainder of the article is structured as follows. Section 2 explains the methods and data used, together with a brief description of the case study route. Section 3 then presents and discusses the results of the analysis, and Section 4 provides some conclusions.

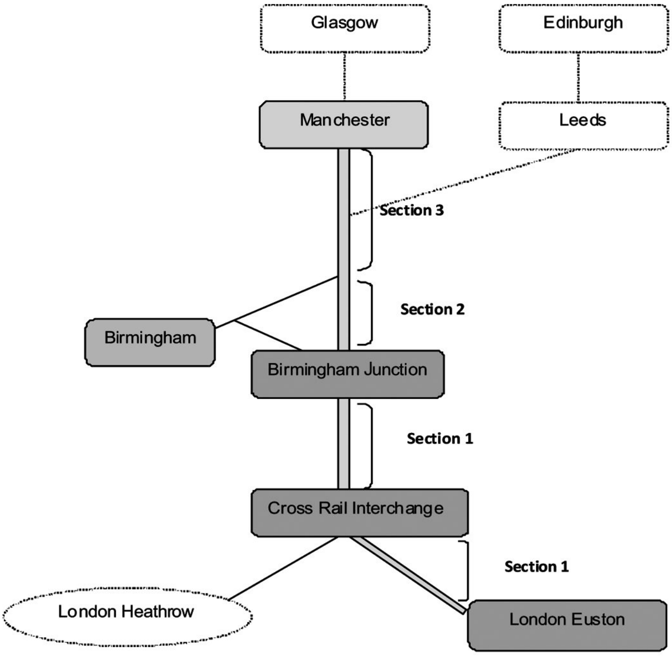
2. METHODOLOGY, DATA AND CASE STUDY

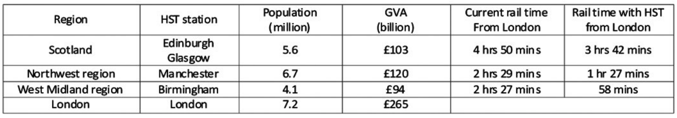
2.1. Methodology for LCA on the London–Manchester Route

In general, LCA consists of three steps: (1) Goal and scope definition, (2) Inventory analysis and impact assessment, and (3) Interpretation. LCA evaluates the environmental impacts through the entire lifecycle of the system. Each component of the transport system consists of three life phases: "construction/production," "operation/use," and "disposal" (Kato and Shibahara 2006).

The current plan for the UK HST network is based on a "Y-shape" network that will link London and Birmingham, and then Birmingham with Manchester on one branch, and Birmingham and the East Midlands, and Sheffield and Leeds on the other. This is expected to be the UK's initial core HST rail network, as suggested by High Speed Two Ltd's (HS2), the company set up by the UK government to consider the case for new high speed rail services between London and Scotland. The lines are also expected to later be extended to serve Edinburgh and Glasgow in Scotland.

London to Birmingham and then Birmingham to Manchester are expected to be the first parts of the proposed network to be completed. At present, the UK





Region	HST station	Population (million)	GVA (billion)	Current rail time From London	Rail time with HST from London
Scotland	Edinburgh Glasgow	5.6	£103	4 hrs 50 mins	3 hrs 42 mins
Northwest region	Manchester	6.7	£120	2 hrs 29 mins	1 hr 27 mins
West Midland region	Birmingham	4.1	£94	2 hrs 27 mins	58 mins
London	London	7.2	£265		

Figure 1. Illustration of the case study route analyzed based on the current plans for the UK HST network.

government reports consider that operation will start in 2026 and will cost approximately £25 billion for the line to Birmingham, and an additional £13 billion for the extension to Manchester (Department for Transport 2010a). This proposed route will link the new HST terminal at Euston in London to Manchester via the Birmingham interchange (see Fig. 1 for illustration).

In this study, only CO_2 emissions and “two life-cycle phases” (construction/production and operation/use) are considered. The former will be referred to as non-operation phase, and the latter as operation phase on the route from London to Manchester. Life cycle periods of 30 to 100 years for the main infrastructure (e.g., railway, bridges, and tunnels) and 30 years for the train carriages are considered. Demand is analyzed for 40 years, from 2026 to 2066. The analysis does not consider the disposal phase in the life cycle due to the lack of detailed data.

The total amount of life cycle CO_2 emission (LC_CO_2) on the London–Manchester route is estimated first, and from this, the amount of life cycle CO_2 emissions per passenger-km [LC_CO_2(g-$CO_{2/\mathrm{pkm}}$)] is computed by accounting for demand on the route. Fundamentally, this study follows the calculation methodology by Chester and Horvath (2009).

The equations for estimating emission from HST are expressed as follows:

$$\mathrm{LC}_{\mathrm{CO_2HST}}\left(\mathrm{g}-\mathrm{CO}_{\frac{2}{\mathrm{pkm}}}\right)=\sum_{i=1}^{n}\frac{CO_2\,non\text{–}operation+CO_{2i}\,operation}{PKM_i} \tag{1}$$

where,

$\mathrm{LC}_{\mathrm{CO_2HST}}$ is the amount of life cycle $\mathrm{CO_2}$ emission (gram per passenger-km–g/pkm) for HST during year *n*;

CO_2 non-operation is the total amount of $\mathrm{CO_2}$ emission per year related to construction and maintenance of infrastructure (including tunnels, viaducts, at grade crossings, the production of rail tracks and rolling stock, but excluding maintenance of the rail tracks and rolling stock);

$CO_{2\mathrm{i}}$ operation is the total amount of $\mathrm{CO_2}$ emission during the operation phase in year *i*;

PKM_i is the number of passenger-km transported by HST in year *i*;

i refers to "a year" from 2026 to 2066, thus n equals 40 in this analysis;

$$CO_{2i}operation = CO_{2i}rolling\ stock + CO_{2i}operationsupport \tag{2}$$

Where *$CO_{2\mathrm{i}}$ rolling stock* is the total amount of $\mathrm{CO_2}$ emission from the operation of the rolling stock in year *i*, which is obtained by multiplying $\mathrm{CO_2}$ emissions of rolling stock per sector and the number of services in year *i*.

$CO_{2\mathrm{i}}$ operation support is the total amount of $\mathrm{CO_2}$ emission from train maintenance and refitting, and operation and maintenance of the stations and rail tracks in year *i*. The allocation of emissions between non-operation and operation support is the result of the available data. The data for train maintenance and refitting is expressed in $\mathrm{CO_2}$ per passenger units, while the data for operation and maintenance of the stations is expressed in $\mathrm{CO_2}$ per train-km units.

Data for operation and maintenance of the rail tracks is expressed in $\mathrm{CO_2}$ per km units.

Based on the data described above and the two equation, two emission factors (EF) can be derived. EF for the operation of HST in year *i*, EF_{HSTi} is estimated as:

$$EF_{HSTi} = CO_{2i}operation/PKM_i \tag{3}$$

and the EF for only the rolling stock operation in year *i*, $EF_{\ HSTrolling\ stock\ i}$, is estimated as:

$$EF_{HSTrollingstock\ i} = CO_{2i}rollingstock/PKM_i \tag{4}$$

The values of the LC_$\mathrm{CO_2}$ emissions per passenger-km largely rely on the assumed demand (Von Rozycki et al. 2003; Chester and Horvath 2009). For this analysis, demand for HST is forecast using a logistic model together with the assumptions of the Department for Transport in the UK (MVA Consultancy 2009; Department for Transport 2010a, 2010b, 2010c).

Thus, the PKM factor in equation (1) is estimated using the following logistic model:

$$\frac{PKM_i}{GDP_i} = K/(1 + a * \exp(-b * i)) \tag{5}$$

where,

k = coefficient to be estimated;
b = growth factor (b is less than 1);
i = time;
a = constant factor;
PKM_i = passenger kilometres in year i, calculated by multiplying the assumed load factor and the seat kilometers supplied in year i;
GDP_i = UK Gross Domestic Product (GDP) in real terms in year i.

The calculation heavily relies on historical data and assumed growth rates. The logistic form of the demand curve is assumed given the nature of market penetration of new products. Since the aim of this article is not to attempt to forecast demand, but to estimate how the environmental performance depends on the assumed demand, a relatively simple approach is adopted combined with a sensitivity analysis.

UK GDP data, in real terms from 2000 to 2009, is used as base data (Office for National Statistics 2010b). GDP from 2010 to 2026 is estimated by using a 2% annual growth rate, based on a business as usual scenario. Sensitivity analysis for variations in demand has been undertaken in order to understand the impacts of changes in demand and load factor on the environmental load. In equation (1), LC_CO_2 of HST largely depends on the denominator (*PKM*), which is demand on the route. The load factor affects LC_CO_2 of HST by determining the PKM (the output level) given the level of available seat-km (ASK), the maximum possible output. Historically, GDP growth has been highly correlated with demand for transport and therefore used as an important predictor of it (Åkerman 2005).

Three scenarios are examined using the variables GDP and load factor for estimating demand: (1) business as usual case, 2% GDP annual growth and 60% load factor in the initial year of 2026, (2) medium demand scenario, 2% GDP growth and 40% load factor in 2026, and (3) low growth scenario, 1.5% GDP growth and 40% load factor in 2026.

A 2% of GDP annual growth is taken because it is the average growth rate between 2001 and 2010, and the forecast growth for EU countries (Gurria and Padoan 2010). The load factor is expected to change over time as demand grows.

2.2. Data Used for the Case Study Route

Data required to perform the above analysis on the London–Manchester route include: inventory data of rolling stock and infrastructure, detailed description of the route and its components (e.g., the length of tunnels, bridges and viaducts), and information on the demand. Fundamentally, this study follows the UK government policy and relies on its studies and plans for the data. Energy consumption and emissions data resulting from rail infrastructure are taken from Network Rail (2010).

The London–Manchester HST route is divided here into three parts (Fig. 1): Euston–Birmingham junction, Birmingham section, and Birmingham Junction–Manchester. Engineering data was obtained from the route engineering report and drawings by the Department for Transport (2010d). The total construction length is about 351.7 km (including the lines to Birmingham city centre, 24.7 km).

Inventory data of components for construction and maintenance are summarised in Table 1. Due to the characteristics of inventory data and to simplify the calculation, the rail infrastructure has been divided into two categories: open section, and tunnel section. According to the data in Table 2.10 (p. 22) of the report by Network Rail (2010), emissions for electric rail infrastructure for open section are 162.1 tonnes CO_2 per rtkm (rail track km) per year, and 906.7 tonnes for tunnel section. The data include emissions from the stations.

The length of the open section and tunnel section are estimated as 331.22 km (section 1: 168.15 km; section 2: 24.7 km; and section 3: 138.37 km) and 20.45 km respectively (Department for Transport 2010d). The total amount of LC_CO_2 for the non-operation phase is estimated at 72,233 tonnes CO_2 per year, which is 205.4 tonnes per rtkm per year. A summary of components and inventory data is presented in Table 1.

The following information from Department for Transport (2010a, 2010b, 2010c) is used here for estimating demand of HST on the route between London and Manchester. The details are summarized in Table 2. The year 2033 is used as a milestone in this analysis since demand data for this particular year is given by Department of Transport (2010a).

The following data is used to estimate the demand:

1. 94,800 passengers per day from/to London to Birmingham and Manchester areas in 2033.
2. In terms of supply, up to 14 train services per hour, rising to 18 an hour in the future. The train vehicle will be 200 meters in length, carrying up to 550 passengers. It will be later increased to 400 meters (1,100 passengers).
3. HST demand is assumed to be 16.2 million passengers in the initial year (2026), with an average load factor of 60%.
4. Other assumptions used in order to estimate the demand (equation 5) are:
5. Utilisation of 10 hours per day and 350 days operation per year.
6. 44,301 passengers per day (16 million per annum) in 2026 (the initial year) (Department for Transport 2010a, 2010b).
7. Train services will increase to 18 per hour, from 14, with the 200 meters train vehicle in 2029.
8. The train vehicle will be upgraded to 400 meters in 2033.
9. The number of passengers will be 35 million per annum in 2033 (Department for Transport 2010c).
10. The number of passengers will grow by 5% from 2035 to 2040.

Table 1. Life cycle CO_2 emissions inventory data for construction and maintenance.

Components	Life Cycle (year)	Length (km)			LC_CO_2 (construction) Tonnes CO_2 per year	LC_CO_2 (maintenance) $kgCO_2/rtkm$ per year
		Section 1	Section 2	Section 3		
Open section		168.15	24.7	138.37	53,691⁽¹⁾	0.514 $kgCO_2/rtkm$
Tunnel section		20.45	0	0	18,542⁽²⁾	
	Total LC_ CO_2 (tonnes CO_2 per year)				72,233	
Breakdown⁽³⁾					LC_Carbon (infrastructure): 205.4 tonnes CO_2 per rtkm	
Tunnel	100	20.45				
Tunnel portal	30	1.75				
Bridge	50	1.285	0.51			
Viaduct	50	24.7	7.674			
At grade	30	140.42	16.56			
Total		188.6	24.7	138.37	351.7 km	

		Number of units		LC_CO_2 per unit (tonnes)	
Rolling stock	30		108	1,722 (5)	0.266004 (6) $kgCO_2$ /tdkm
Station(4)	100	2	2	1	0.0001088 $kgCO_2$/passenger (7)

Source: Network Rail (2010), Department of Transport (2010d).

Notes:
1. Open sections: 162.1 tonnes CO_2 per rtkm (rail-track km) per year. Data includes stations.
2. Tunnel sections: 906.7 tonnes CO_2 per rtkm per year.
3. The breakdown of length of infrastructure is estimated based on drawings published by Department of Transport (2010d). The total rail length becomes 351.7 km.
4. The number of stations is assumed based on the White Paper CM 7176, “Delivering a Sustainable Railway” and “Route engineering study final report: a report for high speed two Ltd” (Department of Transport 2010d). Five stations are used, namely London Euston (section 1), Cross Rail Interchange (section 1), Birmingham Junction (section 2), Birmingham (section 2), and Manchester (section 3).
5. The type of rolling stock used in this study is “Alstom AGV,” by following the assumption and data of the report (National Rail 2010). This rolling stock is considered as a successor of the current Eurostar. The lifecycle is 30 years and data from Siemens in case of the typical annual travel of 500,000 km according to the report.
6. Data is estimated energy and water consumption for train maintenance and refitting. It is based on the assumption that there are no large differences between the figures for conventional rail and HSR. In addition, CO_2 emission from maintenance for rolling stock is 0.266004 kg per train-drive km (tdkm) based on the report (National Rail 2010).
7. 0.0001088 kg CO2 per passenger is taken for emission from maintenance at station. These data include maintenance of buildings (concrete and bricks) assuming the requirements for HST and conventional railway stations are broadly similar (National Rail 2010).

Table 2. Summary of assumptions used to calculate demand and emission factors.

	1 (Base line)	**2 Medium growth**	**3 Low growth**
GDP growth	2%	2%	1.5%
Load factor in the initial year (2026)	60%	40%	40%
Passenger demand between London and Manchester			
in 2026 (initial year)	16.2 million per annum (44,301 per day)	10.8 million per annum (29,534 per day)	10.8 million per annum (29,534 per day)
in 2033	34.6 million per annum (94,800 per day)	20,5 million per annum (5,6034 per day)	
Passenger growth from 2035 to 2040	5% annual growth	4% annual growth	3% annual growth
Operation	10 hours per day and 350 days per annum		
Frequency	14 train services per hour in 2026 and increasing to 18 in 2029		
Train vehicle	200 meters train vehicle (550 passengers) in 2026 and upgrade to 400 meters (1,100 passengers) in 2033. The number of vehicle sets: 108 for 40 years		
Energy consumption	Alstom AGV: 21.45 KWh per km, 0.45 kg CO_2 per kWh, 9.65 kg CO_2 per km. CO_2 per sector: 3,394 kg (9.65 kg × 351.7 km)		
Emission factors ($EF_{HSTrollingstock}$)* in 2026 (load factor)	30.5 g/pkm (60%)	45.7 g/pkm(40%)	45.7 g/pkm (40%)
Emission factors (EF_{HST})** in 2006	41 g/pkm	61.5 g/pkm	61.5 g/pkm
Emission factors ($EF_{HSTrollingstock}$)* in 2033 (load factor)	18.3 g/pkm (52%) 1,100 passengers rolling stock	31 g/pkm (57%)	31 g/pkm (57%)
Emission factors (EF_{HST})** in 2033	23.4 g/pkm	39.5 g/pkm	39.5 g/pkm
$LC_{CO_2\,HST\left(g-CO\frac{2}{PKM}\right)}$*** for 40 years	26.6 g/pkm	43.9 g/pkm	44.5 g/pkm

*($EF_{HSTrollingstock}$) is emission factor (g/pkm) for the rolling stock operation.

**(EF_{HST}) is emission factor (g/pkm) for the HST operation, which includes the rolling stock operation and the operation support (see also Fig. 2).

***$LC_{CO_2\,HST\left(g-CO\frac{2}{PKM}\right)}$ is the life cycle emission factor (g/pkm) for the HST operation and non-operation for 40 years. This is used to derive the total column in Figure 2.

The emission factor for HST per passenger-km is estimated using energy consumption data of 21.45 kWh (Kilowatt hours) per km, which is 0.033 kWh/seat-km for the Alstom AGV trains, which is a train prototype designed as the successor to the current French TGV. This energy consumption information was specifically calculated for the UK HST, accounting for the speed, acceleration patterns, gradients and tunnels characteristics of the route (Network Rail 2010). This is slightly higher than that of the Japanese Shinkansen 700 trains (0.029 kWh/seat-km, 38.36 kWh/km) but lower than Class 373 Eurostar trains operating between London and Paris and London and Brussels (0.041 kWh/seat-km, 30.75 kWh/km) (Network Rail 2010). The differences between the estimates for the UK and Japan partly stem from the assumptions in the UK that constructions of the stations and some other infrastructure will be similar to that on the conventional UK rail network (Network Rail 2010), while in Japan all the infrastructure elements of the HST are different from that of the conventional Japanese network (Yukizawa et al. 2002).

For energy consumption of the rolling stock on this route (351.7 km), the amount of 3,394 kg CO_2 per sector is estimated based on the assumption of 180 train services per day with 94,800 passengers per day from/to London to/from Manchester. Hence, a value of 18.3 g/pkm is estimated for the emission factor of the rolling stock ($EF_{HSTrollingstock}$) in 2033 using the expected train energy consumption (21.45 kWh per km) and the UK electricity carbon intensity (0.45 $kgCO_2$ per kWh, 9.65 kg CO_2 per km).

The emission factor per passenger of the rolling stock ($EF_{HSTrollingstock}$) is, however, different depending on the assumptions such as demand and the energy intensity.

If HST demand is very low, for example, only 10,000 passengers per day on the route, the emission factor becomes 135 g/pkm in case of 14 train services per hour, and 185 g/pkm for 18 train services per hour. At such a low level of demand, 3.6 million per year (10,000 per day), the emission factor on the route becomes larger than that for air transport (see below). On the other hand, the emission factor becomes 21 g/pkm for 18 train services per hour, when demand is 90,000 passengers per day.

In this analysis, the emission factor of 18.3 g/pkm is adopted for the business as usual scenario. The results of the analysis are discussed next.

3. THE POTENTIAL FOR ENVIRONMENTAL BENEFITS FROM A NEW HST LINE BETWEEN LONDON AND MANCHESTER

3.1. the Environmental Impacts of Constructing and Operating HST Services Between London and Manchester

The results reveal that the operation phase Life cycle carbon emissions (LC_CO_2) of HST accounts for more than 88% of the total LC_CO_2 (607,800 tonnes per annum—the middle and upper parts, together, of the columns in Fig. 2), and the non-operation (infrastructure and most of its maintenance; see section 2.1) LC_CO_2 for less than 12% (72,233 tonnes per annum—the bottom part of the columns in Fig. 2) over the 40 years period. Therefore, the environmental

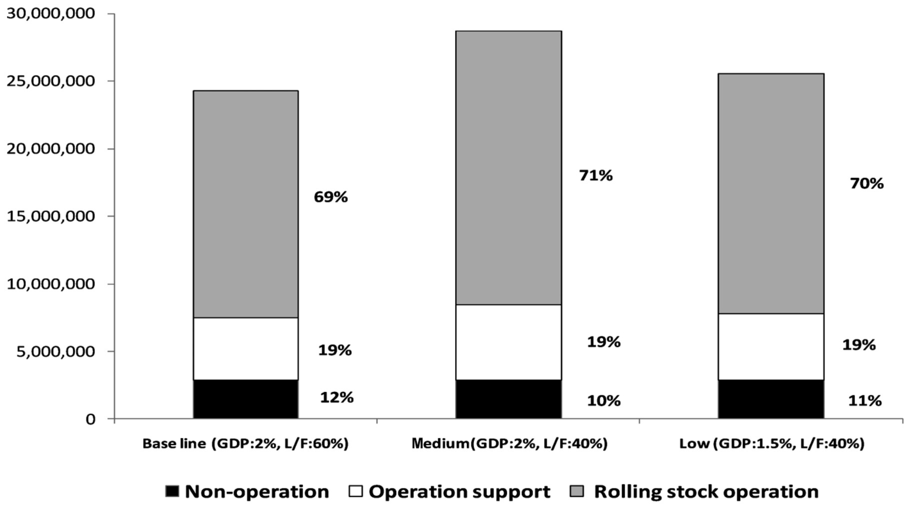


Figure 2. Life cycle CO_2 emissions (tonnes) from the operation and non-operation phases on the London–Manchester route over 40 years. *Source*: Department for Transport (2010a and 2010c), and Office for National Statistics (2010a). *Note.* GVA (gross value added) is the measure to assess the contribution to an area of the industry to an economy.

impact in terms of CO_2 is largely determined by the operational efficiency, especially by emissions associated with the rolling stock operation (upper part of the columns in Fig. 2).

In 2033, the emission factor for the rolling stock operation ($EF_{HSTrollingstock}$) is 18.3 g/pkm in the business as usual scenario (base line), and 31 g/pkm in the other scenarios (medium growth and low growth). This results in a LC_CO_2 of HST (g/pkm, for both operation and non-operation) of 26.6 g/pkm in the base line scenario. The result is much lower than that for other countries, such as Germany (69.4 g/pkm) (Von Rozycki et al. 2003) and the Tohoku line in Japan (57 g/pkm) (Kato and Shibahara 2006). The differences can be explained by the fact that the route distance in the German case is shorter (325 km) and demand much lower (7.1 million per annum). In the Japanese Tohoku Shinkansen case (the line connecting Tokyo and Hachinohe which is 495 km long), annual demand is also much lower at 24.5 million. In terms of LC_CO_2, the London–Manchester line is similar to the Tokaido HST line between Tokyo–Osaka which is 515 km long with demand of 77.7 million resulting in LC_CO_2 of 20 g/pkm (Kato and Shibahara 2006). Overall, the importance of demand in determining the environmental performance of HST lines is clear.

The effect of the load factor on the LC_CO_2, is widely discussed in the literature. Chester and Horvath argue that the load factor is an important factor in determining the environmental impact of a mode and the main factor determining which mode of transport has a better environmental performance (Chester and Horvath

2009,). The load factor, in essence, shows how well the operator is matching supply to demand, but also to what extent demand is equal in both directions of the route at the same time of operation.

In addition to the load factor, the electricity generation sources are a key factor in determining the LC_CO_2 load from HST operation. In this analysis, a value of 21.5 kWh per km (0.45 kg CO_2 per kWh) is used in the base line scenario assuming the future energy intensity of electricity for HST. The current carbon intensity of electricity in the UK is 0.5 kg CO_2 per kWh. The UK Government predicts that the energy intensity of the electricity would fall to under 0.4 kg CO_2 per kWh by 2025 if policies to decrease the carbon intensity of electricity are implemented. These include increasing the energy produced from gas and renewable sources and reducing reliance on coal and nuclear (Department of Trade and Industry 2007). Depending on fuel prices, the impact of the EU Emission Trading Scheme (EU ETS), and carbon prices, it is assumed that the carbon intensity will fall by 4% to 28% between 2005 and 2020. Table 3 shows the change of carbon load of the rolling stock operation, depending on different levels of carbon intensity and demand on the London–Manchester route.

A 0.1 kg CO_2 per kWh difference results in a saving of a 4 g CO_2 per pkm, when daily demand exceeds 90,000 passengers on this route. Approximately 49,000 tonne of CO_2 per annum will be saved as a result. Given that an 8 g CO_2 per pkm is saved by the successful implementation of the Energy White Paper Policy, approximately 100,000 tonnes of CO_2 per annum could be saved. To put the above in perspective, 47,000 tonnes of CO_2 were produced by air transport operation on the London–Manchester route in 2006, based on this analysis (see below). The contribution of improvement in the energy intensity to the reduction in emissions during the operating phase, which account for almost 88% of LC_CO_2 (see Fig. 2) is substantial and it is an important determinant of the potential for environmental benefits from HST.

Table 3. The change of CO_2 load for the rolling stock operation due to changes in the carbon intensity and demand on the London–Manchester route (CO_2 g/pkm).

	Carbon intensity			
Daily traffic in 2033	**2006 level (0.5 kg CO_2 per kWh)**	**Baseline (0.45 kg CO_2 per kWh)**	**Without energy white paper policy options (0.4 kg CO_2 per kWh)**	**With energy white paper policy options (0.3 kg CO_2 per kWh)**
Base line (94,800)	20.4	18.3	16.3	12.2
Medium and low (56,958)	33.9	31	27.2	20.4

3.2. The Potential for Environmental Benefits From a New HST Line Between London and Manchester

The potential for environmental benefits from the introduction of HST services between London and Manchester depends on the environmental performance of the HST but also on the performance of other modes and the level of substitution between modes on the route. The environmental implications of mode substitution are examined below. Only the environmental impact from the rolling stock operation is assessed, due to the lack of LC inventory data for other modes such as conventional trains, automobiles and air transport. Furthermore, it is difficult to see how the introduction of the HST will affect the supply of infrastructure for other modes as it is largely already built, although it can be argued that the construction of the HST will save the need to construct, for example, additional runway capacity. CO_2 emission and energy data for conventional rail operation and cars are taken from a study by the Association of Train Operating Companies (ATOC 2007). CO_2 emissions for air transport are estimated using the UK Civil Aviation Authority (UK CAA) traffic data (2006) and aircraft performance data from Eurocontrol (2006).

The current average CO_2 emission for cars is 160 g per vehicle km or 160 g/pkm assuming a load factor of 1, which is used for cars on the London–Manchester route (distance: 267 km). The train type Class 390 Pendolino (9 cars, electric, tilting train operating on the London Manchester route) is selected to calculate the current emission factor of conventional rail, which is 51 g/pkm assuming a 40% of load factor (ATOC 2007). This value is slightly lower than the UK average (76 g/pkm) which also rely on diesel powered trains and many shorter routes with significantly lower levels of demand (Department for Environment, Food and Rural Affairs 2010). For estimating the base line scenario in 2033, Hitachi Super Express train type is used as a future conventional train (0.45 kg CO_2 kWh, 9.65 kg CO_2 per train km in case of 10 cars with 649 seats (Network Rail 2010) resulting in an emission factor of 29.7 g/pkm with a 50% load factor.

The emission factor for air transport for the operation mode depends heavily on the distance flown, aircraft type and the load factor (Miyoshi and Mason 2010). Based on actual traffic data released by the UK CAA for 2006 and aircraft performance data published by Eurocontrol in 2006, the emission factor of air transport for the operation mode on this route has been modelled using seven aircraft types used on the route between London Heathrow/Gatwick airports and Manchester airport. The average emission factor (g/pkm) on these sectors (distance flown: 291 km) is estimated at 210 g/pkm.

In addition, the potential energy efficiency improvement for each mode needs to be considered. The UK Government aims to improve energy intensity of rail transport by 20% by 2025 (Department for Transport 2010c). Automobiles' fuel efficiency is also expected to improve to 100 g/pkm due to greater usage of alternative fuels and technology improvement (Department of Trade and Industry 2007). The air transport industry aims to reduce emissions by at least 30% of the current levels by using alternative fuels and improving air traffic control (International Air Transport Association 2009).

Table 4 shows the amount of carbon mitigated by the introduction of HST on the route examined for three scenarios: (1) the current case (0.5 kg CO_2 kWh),

Table 4. Daily demand and the estimated CO_2 (tonnes) per year in 2033.

	HST total	From rail	From road	From air	Generated
Daily demand (share of HST demand)	94,800 (100%)	66,800 (70.5%)	4,000 (4.2%)	2,700 (2.8%)	21,300 (22.5%)
(1) Current electricity generation mix: 0.5 kg CO_2 per kWh					
Emission factor g/pkm	20.4	51	161	210	20.4

		Emission (saved) from other modes/generated traffic			
	HST Emission	**Conventional rail (Pendolino)**	**Road**	**Air**	**Generated demand**
CO_2 (t. p. a.)	+248,258	−437,333	−62,761	−60,224	55,780*
Net CO_2 (t) p.a.	−312,059				
(2) Base line case including energy efficiency improvement: 0.45 kg CO_2 per kWh					
Energy efficiency improvement	0.45 kg CO_2 per kWh	0.45 kg CO_2 per kWh	47% reduction	30% reduction	0.45 kg CO_2 per kWh
Emission factor g/pkm	18.3	37.1	85.3	147	18.3

		Emission (saved) from other modes/generated traffic			
	HST Emission	**Conventional rail Hitachi super express**	**Road**	**Air**	**Generated demand**
CO_2 (t. p. a.)	+222,702	−251,193	−33,263	−42,157	50,038*
Net CO_2 (t) p.a.	−103,911				
(3) Further energy efficiency improvement case: 0.3 kg CO_2 per kWh					
Energy and carbon efficiency improvement	0.3 kg CO_2 per kWh	0.3 kg CO_2 per kWh	As (2)	As (2)	0.3 kg CO_2 per kWh
Emission factor g/pkm	12.2	24.7	85.3	147	12.2
CO_2 (t. p. a.)	+148,468	−206,584	−33,263	−42,157	33,358*
Net CO_2 (t) p.a.	−133,535				

*Included in the amount of CO_2 generated by the HST (the figure in the 2nd column).

(2) base line case in 2033 (carbon intensity 0.45 kg CO_2 kWh and fuel efficiency improvement for the other modes), and (3) further improvement in the energy intensity of electricity used by rail transport (0.3 kg CO_2 kWh). Daily demand on the London–Manchester route for HST is estimated at 94,800 passengers per day. This level of demand results from 66,800 passengers per day shifting to

HST from the conventional rail (representing 70.5% of the demand for HST), 4,000 passengers per day from road transport (4.2%; which will mean 22 million fewer car km in 2033 directly associated with the introduction of HST), 2,700 from air transport (2.8%), and 21,300 passengers as a result of new, generated demand (22.5%) (Department for Transport 2010a; see Table 4).

The report by Department for Transport (2010a) estimates that HST on the London–Manchester route will emit around 330,000 tonnes of CO_2 per year. At the same time, the reduction in Pendolino train services (the current rail service) will save 30,000 tonnes CO_2, and the savings due to mode shift from car will be between 2,000 and 6,000 tonnes CO_2 per year. They also consider a reduction of around 400,000 tonnes CO_2 per year due to substitution from air transport in 2033. Therefore, the report concluded that HST is unlikely to result in a large impact on overall emissions from transport, which will be less than 100,000 tonnes CO_2 per year, and that there is large uncertainty with respect to the actual impact (Department for Transport 2010a).

The results of this study similarly show small environmental benefits from HST in terms of CO_2 emission reduction in 2033 under the base line scenario (Table 4, scenario 1). The total amount of CO_2 generated by HST is estimated at 248,258 tonnes per year in 2033, of which 55,780 tonnes per year are the result of generated demand for HST. The demand shifted to HST from the conventional rail will save 437,333 tonnes CO_2 per year from conventional rail operation, demand shifted from road will result in 62,761 tonnes CO_2 per year reduction and finally demand shifted from air transport will result in emission reduction per year from aircraft operation of 60,224 tonnes CO_2. Thus overall, HST will result in net savings of 312,059 tonnes CO_2 per year (Table 4). The emission savings as result of mode substitution will only take place if capacity released as a result of HST on the conventional rail, road and air networks will not be taken up by new generated demand, an unlikely outcome given the likely increase in demand for transport.

The small net benefit found is mainly because rail transport is already highly utilised on the London–Manchester route and the introduction of HST services, therefore, would not result in substantial mode substitution from air, and not from road. Any improvements in the electricity generation mix, which will reduce its CO_2 intensity, will improve the environmental performance of the conventional rail as well as that of HST thus reducing the benefits from the introduction of HST to only 103,911 tonnes net savings of CO_2 (Table 4, scenario 2). Table 4 suggests therefore that from an environmental perspective, and considering the London–Manchester route, environmental benefits from HST will result from using cleaner energy to generate electricity than from modal shift. However, using cleaner energy to produce electricity will likewise generate environmental benefits from conventional rail operation. The fact that improvements in the energy intensity of electricity result in larger CO_2 reduction from HST than conventional rail operation (the difference between scenario 2 and 3 in Table 4), indicates to some extent the environmental penalty of moving from conventional to high-speed electric rail transport.

4. CONCLUSIONS

This study aims to investigate the possible environmental benefit from the construction of HST in the UK, based on the UK Government demand assumptions.

The reductions in CO_2 emissions due to demand shift from other modes, and improvement to the energy intensity have also been considered. The analysis is limited to the route from London to Manchester since details of the full HST network are not yet available. It is also limited to a somewhat simplified LCA due to lack of data related to the disposal phase of the LCA of HST, which result in somewhat underestimation of the full environmental load of HST on the route. Furthermore, a relatively simple demand-forecasting method is used that follows the UK Government demand assumptions, and rely on the assumed GDP growth in order to examine the environmental benefits at the level of demand the Government is forecasting.

The total amount of life cycle CO_2 emissions from the construction and operation of HST is estimated to total 24–29 million-tonne CO_2 ($MtCO_2$) for 40 years, including 21–26 $MtCO_2$ related to the operation of the HST services on the route. The results show that overall CO_2 reduction is relatively small at about 100,000 tonnes of CO_2 per annum in 2033, which is less than 0.1% of the total UK domestic transport emissions in 2007 (Department for Transport 2010c). This is mainly because modal shift from air and road is relatively small on the London–Manchester route, and the UK electricity used to power rail transport relies heavily on non-renewable energy sources (Department of Trade and Industry 2007). If the UK electricity generation mix does not improve in the future, and continue to rely on coal and oil, additional 1.9 $MtCO_2$ will be generated by HST over 40 years. For the London–Manchester route, it is clear that energy efficiency improvements are important determinant of the environmental benefit from HST, although such improvements will result in environmental benefits for conventional rail as well (the main source of demand for the HST). At the same time, on this route, mode substitution from air and road has limited environmental benefits. Overall, the analysis suggests that for meeting the UK stringent carbon emission reduction targets, HST development does not offer much. In this context, it is important to reiterate that the main justification for the construction of HST in the UK is to increase rail capacity and avoid congestion on the rail network, and not environmental benefits.

An important question is to what extent the above conclusion can be generalized for the entire UK HST network, if all the lines depicted in Figure 1 are constructed and operated. Mode substitution to HST could be much greater if the analysis considered the wider network, including the Channel Tunnel link to the European HST network, in particular, from air. The London–Manchester air travel market is relatively small, 8.3 million passengers in 2010, compared to the whole London–Scotland air travel market, 11.2 million passengers in 2010. Yet, demand for rail (and even HST) between London and Scotland is lower than that between London and Manchester resulting in higher LC_CO_2 for HST and suggesting the environmental performance of HST on the sections from Manchester to Scotland will not be as good as indicated in the above analysis. The fact that current plans do not envisage direct HST services from the UK HST network to the European network (but a transfer via people-mover between Euston and St. Pancras stations in London (Department for Transport 2010c) and not a direct link to Heathrow airport (Department for Transport 2007) suggests that while the potential for mode substitution, especially from air, is greater, actual mode substitution will likely to remain modest. Furthermore, generation of new travel (by HST) is likely to take place. Thus, environmental benefits from completing the UK HST network are expected to be low. At the EU level, and considering the recent Transport White Paper (European Commission 2011) which advocates for completing the European HST network, partly on environmental grounds, the above analysis provides important guide as to whether such benefits can be expected and on what routes and in what circumstances. The same applies for other countries pursuing the expansion or development of HST. When, and where, HST can generate environmental benefits, it is crucial to account for the high cost of such benefits, given the cost of constructing and operating HST. There are likely to be many more cost effective ways to reduce emissions.

Rail emissions accounted for only 0.4% of the total UK domestic CO_2 emissions in 2007. The total CO_2 emission from car in the same year was 74.4 $MtCO_2$, from rail 2.2 $MtCO_2$ and from domestic flight 2.3 $MtCO_2$ (Department of Trade and Industry 2007). The UK Government ambitious CO_2 emission reduction target suggests mode substitution must play a role in achieving this, but the development of HST it appears might not contribute substantially in this respect.

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