Are railways 'climate friendly'?

Moshe Givoni[a], Christian Brand[a] and Paul Watkiss[b]

[a] Transport Studies Unit, Oxford University Centre for the Environment, South Parks Road, Oxford, OX1 3QY, UK. Email: moshe.givoni@ouce.ox.ac.uk, Tel: +44 (0)1865 285068, Fax: +44 (0)1865 275885 (corresponding author)

[b] Paul Watkiss Associates, 18 Islip Road, Oxford, OX2 7SN, UK.

Note: this is a personal version, created by Christian Brand, of the text of the accepted journal article. It reflects all changes made in the peer review process, but does not incorporate any minor modifications made at the proof stage. The complete citation for the final journal article is:

- *Givoni, M., Brand, C., Watkiss, P., 2009. Are Railways 'Climate Friendly'?, Built Environment, 35 (1), 70-86(17).*
- *DOI: http://dx.doi.org/10.2148/benv.35.1.70*

Abstract
Rail is usually considered to be a 'green' mode of passenger transport, at least 'greener' than the car and plane in terms of its relative impact on climate change. It is therefore only natural that rail will play an increasing role in meeting demand for transport when the aim is to reduce environmental pollution associated with transport operation. Yet, referring to rail as 'green' has many limitations and can be misleading. In this context, the paper aims to examine the environmental impact from rail transport and to show how the above generalisation depends on many different factors. Attention is focused on comparing between different trains (e.g. diesel vs. electric, and in the latter examining how environmental impacts depend on the sources used to generate the electricity) and different modes (train vs. car and plane). The paper also examines the scope for improving the environmental performance of rail through technical and operational measures. The paper concludes with identifying how and where rail can play a role in achieving a more sustainable transport system.

Keywords: rail, environmental impacts, climate change, CO_2

1. Introduction

The goal to revitalise the railways is at the heart of EU transport policy. It aims mainly to shift the balance between transport modes, from private to public modes, and specifically from car and plane to rail. In 1996, the "Strategy for revitalising the community's railways" White Paper (CEC, 1996) emphasised that *"the European Commission believes that railways should play a much greater role in tackling the transport challenges facing the community"* (p. 6). One of these challenges is transport's impact on the environment. Rail is usually considered to be a 'green' mode of transport, at least 'greener' than cars and planes in terms of its relative impact on climate change. The view of rail as 'green' played an important factor in the role given to the railways in the 2001 Transport White Paper (CEC, 2001). The White Paper states that *"rail transport is literally the strategic sector, on which the success of the efforts to shift the balance [between the modes] will depend"* (p. 13).

Similar notion is apparent in UK transport policy, where increasingly the railways are seen as a key to achieving a sustainable transport system. The government therefore set a target to double the level of demand rail can accommodate in the long term (DfT, 2007a). In environmental terms, such a target can contribute to sustainability provided that this demand is not new demand for transport but demand shifted from other modes. In addition, it depends on the extent to which rail is better, from an environmental perspective, than other modes. This depends on the environmental performance of the railways, the extent to which rail operation impacts on the environment. Simply referring to rail as 'green' therefore has many limitations and can be misleading. In this context, the paper aims to examine and quantify the environmental impact from rail transport and to show the main factors contributing to it.

To analyse rail's impact on the environment we focus on rail's contribution to greenhouse gas (GHG) emissions and therefore climate change. Carbon dioxide (CO_2) is the main GHG with regard to the surface transport sector. Other GHG pollutants relevant to surface transport include nitrous oxide (N_2O) and methane (CH_4), both of which have higher impact values per mass of pollutant, but are emitted in much smaller quantities[1]. CO_2 is still the main GHG and the one for which data is usually readily available. We therefore use CO_2 emissions as the main indicator for climate change impacts. The paper further focuses on passenger rail; for an excellent analysis of freight transport and CO_2 see McKinnon (2007). Also, for reasons of data availability, we focus on Great Britain (GB[2]), but the discussion and main conclusions equally apply in the UK, Europe and elsewhere.

GHG emissions can be monetised, although the science surrounding this is still evolving. The Social Cost of Carbon (SCC) is a metric that has been used by government to do exactly that – put a (societal) price on CO_2/carbon emissions. Recently the UK adopted a slightly different metric, the Shadow Price of Carbon (SPC)[3], which values the expected increase or decrease in emissions of GHG emissions resulting from a proposed policy. Put simply, the SPC reflects the damage costs of climate change caused by each additional tonne of greenhouse gas emitted. For many different reasons there is no consensus on the SPC, but for the purpose of this paper, where the differences are more important than the levels as such, a representative figure is sufficient (for a recent review of the SCC, SPC and methodological approaches to estimate it see Watkiss et al. 2005; DEFRA, 2007a). The SPC figure used in UK policy guidance is £25.5 per tonne of CO_2 in 2007 (DEFRA, 2007a), or £93.5 per tonne of carbon[4]. Assuming a currency conversion rate of €1.40 per £ Sterling[5], this gives €35.70 per tonne of CO_2 (at 2007 prices) – very similar to the figure of €30 per tonne of CO_2 (at 2001 prices) typically used in European studies (e.g. Dings et al., 2003). The figure of €35.70 per tonne of

CO_2 is used throughout this paper to estimate the price of climate change impacts. For convenience, only Euro estimates are used throughout this paper.

Rail's impact on climate change varies greatly by context, operating conditions, geographical location, etc. For this paper we make a distinction between a number of cases. The most important, and the focus of the analysis, are: electric and diesel power trains; the energy sources used to generate the electricity to run electric trains; and the speed at which trains operate (Section 2). A comparison of rail with other modes of transport is presented in Section 3, followed by a review of options to reduce rail operation impact on the environment (Section 4). Summary of the findings together with conclusions are given in Section 5.

2. The carbon impact of rail operation

2.1 Impacts of different transport fuels: diesel vs. electric passenger trains

The comparison between diesel and electric trains in the UK is based on the well established fuel consumption method. This estimates the amount of CO_2 emissions by simply multiplying fuel consumption (in litres of fuel per vehicle-km, or per trip) and the CO_2 emissions per unit of fuel (e.g. CO_2 per litre of diesel or per kilowatt-hour (kWh) of electricity used). The figure for electric trains is based on the CO_2 content of the electricity, which is generated using a mix of primary fuels including coal, gas and nuclear (see section 2.2). In other words, the CO_2 emissions per unit of energy are then applied to the amount of fuel and electricity used in the operation of diesel and electric passenger trains in the UK to provide CO_2 emissions per vehicle-km of each type of train, the first basis for comparison. In the next stage, the amount of passenger transport demand (in passenger-km) carried by each type of train is considered for the comparison between diesel and electric trains, taking into account different passenger loadings (which in itself depend on route and operating conditions). The comparison of the derived aggregate figures is presented in Table 1.

Table 1: Comparison of CO_2 emissions from Diesel and Electric trains operation[1] in the UK (operation data for 2006/7)

Diesel trains			Electric trains	
gCO_2/litre	**2674**		**gCO_2/kWh**	**554 [2]**
Fuel use (million liters)	463.7		Electricity consumed (GWh)	2820
Vehicle-km (million)	893		Vehicle-km (million)	1444
Liters/vehicle km	0.519		kWh/vehicle-km	1.95
gCO_2/vehicle km	**1389**		**gCO_2/vehicle-km**	**1082**
Passenger-km (billion)	17.9		Passenger-km (billion)	28.93
Loading (passenger-km/vehicle-km)	20.045		Loading (passenger-km/vehicle-km)	20.035
Liter/passenger-km	0.026		kWh/passenger-km	0.097
gCO_2/passenger-km	**69**		**gCO_2/passenger-km**	**54**
UK average, weighted by passenger-km (gCO_2/passenger-km)				**60**

Source: ATOC (2007), DEFRA (2007b) and own calculations

Note: [1] operational data for ATOC 2006/2007 financial year (March 2006 to March 2007). [2] Based on the DEFRA GHG reporting guidelines value for 2006 (DEFRA, 2007b; Annex 3), assuming 1.5% for high voltage loss and 6% in the rail distribution system to give gCO_2 per kWh *rail end-use* as opposed to a 7.5% lower value for emissions per kWh of *supplied* electricity.

In terms of CO_2 emissions *per vehicle-km*, the operation of electric trains in the UK results in significantly less CO_2 emissions, about 22% less than diesel trains. The difference is a result of greater technical efficiency for electric trains, different operating conditions (electricity is mainly used on faster intercity routes, with fewer stops i.e. less energy used for acceleration – see also Figure 2 section 2.4) and, crucially, the CO_2 content of electricity. Given the expected continued decrease in the CO_2 content of UK electricity, the advantage of electric rail is set to increase (see section 2.2 for further analysis of these issues). Although an exact estimate cannot be derived from Table 1, it can be concluded that for a similar passenger load factor the use of electric trains will result in lower CO_2 emissions and therefore lower climate change impacts than the operation of diesel trains.

Table 1 also shows that in terms of carrying passengers on the routes operated by each type of train both are as efficient and achieve a very similar load factor (average number of passengers per train, calculated in passenger-km/vehicle-km). This suggests that the differences between the two types of trains in CO_2 emissions per passenger-km are the result of their operational/technological differences and not due to demand differences on the routes they operate. Based on the latest operational figures for the UK railways, one passenger-km transported by electric train will result in 54 gCO_2/passenger-km compared with 69 gCO_2/passenger-km when transported by diesel train; thus, electric train operation can be considered to be about 22% less costly to society in terms of climate impacts than diesel train operation.

During the 2006/7 financial year, UK passenger rail companies transported 46.8 billion passenger-km. Of these 38% and 62% were transported using diesel and electric power respectively[6]. Thus the UK average (weighted by the above shares of passenger-km) can be derived as 59.7 gCO_2/passenger-km – a figure that corresponds to the most recent figure of 60 gCO_2/passenger-km reported in DfT (2008). This is on the back of 33% electrification of the UK rail network (DfT, 2007b: table 6.1). This level of operation resulted in 2.7 million tonnes of CO_2, of which 1.2 and 1.5 million tonnes can be allocated to diesel and electric train operation respectively. The shadow price of these emissions can be estimated to be about €97 million (2007 prices), or a respective €44 million and €53 million associated with diesel and electric train operations.

The above exercise in comparing emissions from different energy sources begs the question: how much CO_2 would full electrification of the UK network save, and at what cost? In first order approximation, if the entire UK passenger rail network was electrified, about 0.2 million tonnes of CO_2 emissions could be saved each year, a 7% reduction in CO_2 emissions, or the equivalent of saving 6.6 million Euro per year in social damage costs (Table 2). The savings would occur every future year and, as the CO_2 content of electricity is expected to go down over the coming decade, the annual savings would increase over time. Taking the central estimates of the "with policies" projections of the 2007 Energy White Paper (DTI, 2007), annual savings would increase to about 0.25 million tonnes of CO_2 by 2020. With no further changes after 2020, the total emission savings over a period of 50 years (from 2006) is 12.0 million tonnes of CO_2. The net present value of these savings (as derived by discounting future savings over a 50 year period at the UK discount factor of 3.5% (HMT, 2007) and aggregate to present values) would be about €430 million.

Table 2: Potential reduction in annual CO_2 emissions from full electrification of the UK passenger rail network

	CO_2 emissions (million tonnes)	*Shadow price of emissions (million Euro at 2007 prices, 1.4 €/£ exchange rate)*
Current diesel and electric fleet	2.7	97
All diesel fleet	3.2	116
All electric fleet	2.5	90
Benefit from full electrification (2006)	**0.19**	**6.6**
Benefit from full electrification (2010; central estimate in the Energy White Paper, with policies)	**0.21**	**7.4**
Benefit from full electrification (2020; central estimate in the Energy White Paper, with policies)	**0.25**	**8.9**

The Railway Forum (2008) suggests the cost of electrification per single track km to be in the order of €770K to €910K. The national rail network is some 15,800 km long and offers a track length of about twice that value. Assuming 67% of this is served by diesel trains, and a mid range value for single track costs of €840K per km, full electrification of (0.67 * 2 * 15,800km =) 21,172km of track would cost around €17.8 billion. Thus, even when accounting for future years of CO_2 benefits, full electrification is not a very cost-effective solution on grounds of climate change mitigation alone – full rail electrification would cost around €14.8 billion (net present value, discount rate at 3.5% and spreading the capital cost over 10 years) while the cumulative benefits from the reduction in CO_2 emissions over a 50 year period associated with it would amount to 12 millions tonnes of CO_2 or only €190 million (over 50 years period, discounted at 3.5%). In other words the cost of reducing one tonne of CO_2 emission through rail electrification is about €1233, a relatively high value amongst the abatement options available.

The ATOC (2007) also provides the percentage change in key operational parameters and emissions factors in 2006/7 compared to the 1996/7 financial year. Overall, rail passenger transport has increased significantly over this period, with a 23% increase in vehicle-km (1.9 billion in 1995/6) and 56% increase in passenger-km (30 billion in 1995/6). Not only that more passengers were transported by trains, the train companies also markedly improved their load factors (by more than 25% for both diesel and electric trains), pointing to an improved efficiency of operation in both vehicle-km and environmental terms. Between the years 1995/6 and 2006/7 there was little change in the share of traffic transported by diesel and electric trains, thus some potential to further improve the environmental performance of passenger rail have been missed. In addition, the ATOC (2007) estimates show that in terms of train operation there was deterioration in diesel train emissions performance over time. In the year 1995/6, CO_2 emissions related to diesel train operation were 1322 gCO_2/vehicle-km, 5% lower than the current level. This is likely due to slow replacement of the diesel traction unit and locomotive fleets, more trains on less track and thus more congestion on the network, and heavier new rail stock (better equipped in terms of comfort and safety). CO_2 emissions related to electric train operation was 1201 gCO_2/vehicle-km in 1995/6, about 10% higher than the 2006 level. Hence from an operational and policy perspective electric trains have become more efficient in terms of CO_2 emissions. In gCO_2/passenger-km units, emissions from train operation in the UK in 2006/7 were 22% and 29% lower than in 1995/6 (diesel 89 and electric 76 gCO_2/passenger-km in 1995/6). This improved CO_2 performance is mainly the result of achieving higher load factors and the lower CO_2 intensity of the electricity used (see section 2.2).

There are obviously other important differences between diesel and electric trains in terms of their environmental impacts, in particular with regards to the scale and location of local and regional air pollution (e.g. sulphur dioxide, particulate matter, nitrogen oxides). A comparison of emissions factors for non-CO_2 pollutants can be found in AEA (2001). Electric trains have virtually zero impact on local air quality at point of use, i.e. alongside the rail network. This is particularly beneficial in highly populated urban areas, where exposure to high concentrations of particulate matter and ozone (a result of high nitrogen oxide levels and solar radiation) causes respiratory diseases, asthma and other negative health effects. However, pollution occurs at point of electricity generation, but this is usually away from densely populated areas resulting in relatively low impact when compared to urban areas.

2.2 How green are the electrons?

The extent to which electric trains can be regarded as being relatively more 'climate friendly' than other modes, and diesel trains in particular, depends on the mix of energy sources used to generate the electricity for railway operations. The five main primary fuels to generate electricity in the UK are hard coal, natural gas, nuclear, renewables (e.g. wind, hydro, wave) and oil. The CO_2 emissions resulting from generating one kWh electricity using these primary fuels is shown in Table 3. In very simple terms, the more renewable and nuclear energy used to generate electricity, the more 'climate friendly' UK rail operations would become.

Table 4 illustrates the amount of direct (end use) CO_2, and equivalent SPC, if each of the energy sources would have been the sole source to generate the electricity used in 2006/7 to drive the UK electric trains. Although this simple "what if" scenario ignores upstream and downstream lifecycle emissions as well as any capacity constraints, it illustrates that (a) there are clear environmental benefits from changing the electricity generation mix and moving away from reliance on fossil fuels, and that (b) there are also clear benefits from changing from one fossil fuel to another, e.g. relying even more on gas than coal[7].

Table 3: The carbon and CO_2 intensity of different primary energy sources (figures for the UK, in 2006)

Generation source	Coal	Oil	Gas	Nuclear	Renewable
$kgCO_2/kWh$	0.876	0.590	0.370	0.016	0

Sources: for coal, oil and gas: Department for Business Enterprise & Regulatory Reform (2007, Table 5C: Estimated carbon dioxide emissions from power stations in 2006). For Nuclear: Sustainable Development Commission (2006). For renewables the common assumption of zero emissions was adopted here.

Table 4: CO_2 emissions and SPC of emissions if UK electric passenger train services were generated by each of the energy sources (based on 2820 GWh electricity consumed in 2006/7)

Generation source	Coal	Oil	Gas	Nuclear	Renewable
Million tCO_2	2.47	1.66	1.04	0.05	0.00
Million Euro	74.14	49.94	31.33	1.36	0.00

Between 1995 and 2006 the share of natural gas in the UK electricity generation mix has increased by 18% while the share of coal and nuclear has decreased by 8% and 7% respectively. The UK Energy White Paper (DTI, 2007) projections for the years 2010 and 2020 include two scenarios, one where policies proposed in the Energy White Paper are assumed to be implemented and one where they are not. When compared to the 2006 generation mix, both scenarios assume substantial reductions in the share of coal and nuclear and a continued increase in the share of gas (Table 5). These changes over time in the generation mix would result in cleaner electricity to drive the UK electric trains fleet. Between 1995 and 2006, the CO_2 intensity of electricity used in UK railways decreased by 4.5%. When compared to 2006 the Energy White Paper projections suggest further improvements of 8-10% by 2010 and 11-25% by 2020 (Table 5). Due to the change in the electricity generation mix between 1995 and 2006 the 2006/7 output of the UK electric passenger trains was 0.07 million tonne CO_2 lower. If the UK had had the projected 2020 (with the White Paper polices) mix already in 2006, a further 0.4 million tonnes of CO_2 would have been saved.

Table 5: Historic and projected changes in the UK electricity generation mix and its effect on the CO_2 intensity of rail end-use electricity

	Generation mix (% share)						
	Coal	Oil	Gas	Nuclear	Renew-ables	other	**CO_2 intensity (gCO_2/kWh, rail end-use)[3]**
1995	46	3	18	26	2	6	**580**
2006	38	1	34	19	5	4	**554**
2010[1]	33	1	35	19	8	4	**511**
2010[2]	31	1	36	19	9	4	**499**
2020[1]	29	0	49	6	12	5	**491**
2020[2]	19	0	53	7	16	5	**415**

[1] Without Energy White Paper policy options, baseline projection
[2] With Energy White Paper policy options, central estimate
[3] CO_2 intensity is given for rail end-use, assuming a 1.5% loss in the high voltage system and a 6% loss in the rail distribution system (ATOC, 2007).
Source: DTI, 2007; ATOC, 2007 and own calculations

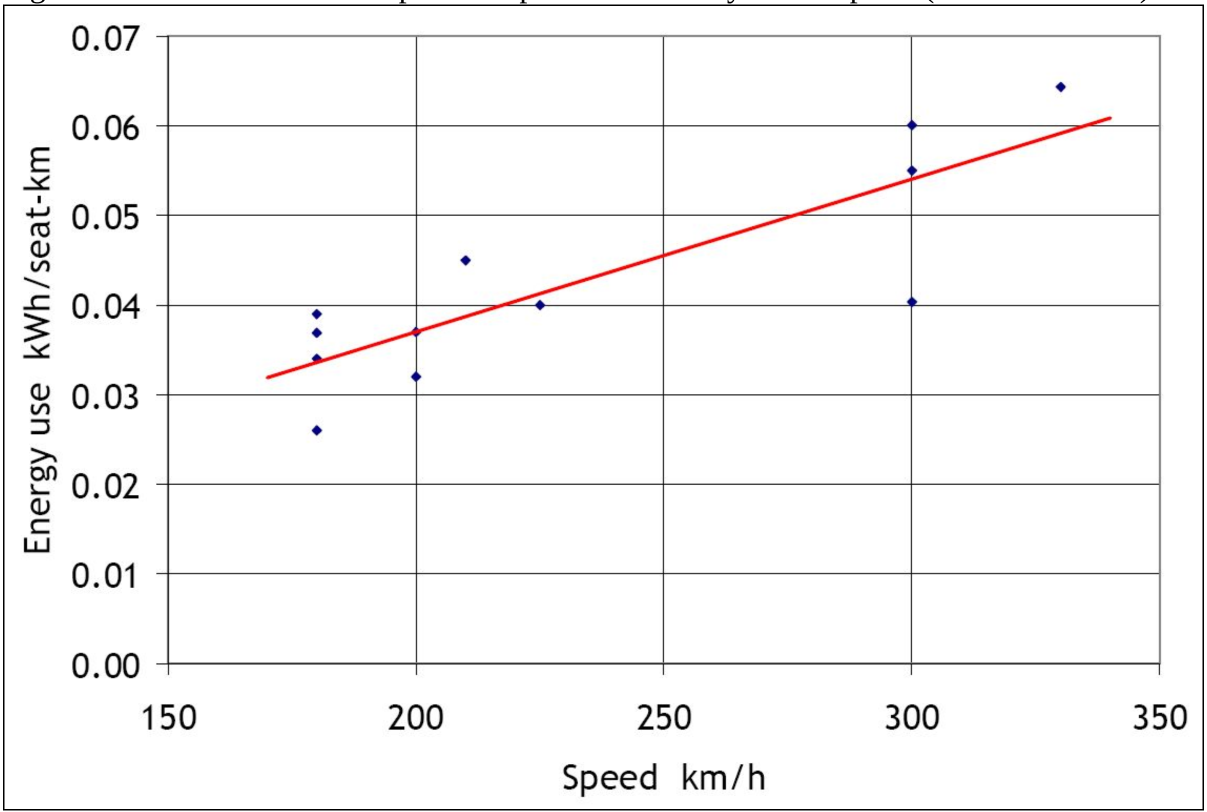
2.3 Average fuel consumption and the effect of speed

Average fuel consumption is expected to increase with speed. At higher operating speeds (>100km/h), the laws of physics would suggest a non-linear increase mainly due to disproportionally higher aerodynamic drag. However, the relationship between operating speed and energy consumption is not straight forward and data which show energy consumption for a specific train and route at different (average) operating speed and station spacings were not found. Nevertheless, some conclusions about the relationship between speed and energy consumption can be drawn, and these also highlight operational characteristics which will affect average speed and environmental impact.

RSSB (2007b) plot specific energy consumption data (in kWh/seat-km) for various single-deck European trains against their *maximum* speed (Figure 1). This confirms the expected positive correlation between speed and energy consumption. However, the figure also shows that trains with very different maximum operating speed might have similar energy use. This is probably the result of aerodynamic design and larger distances between stations for trains designed to operate at high speeds. The higher the designed maximum speed of a train is the more emphasis will be put on making it aerodynamic, lowering its drag and consequently energy use when at cruising speed. Thus a train designed for 250 km/h cruise will most likely not consume double or four times the energy as a train designed to cruise at 125 km/h, but for each train to get to this speed the energy required is probably more proportional to the speed.

It is difficult to conclude from Figure 1 the role variations in a) operational speed (determined by infrastructure speed limits and other operational constraints, rather than by vehicle capability), b) geographical characteristics of the route (flat vs. mountainous) and c) the spacing of intermediate stops along the route, have in determining energy consumption. The spacing of intermediate stops along the route is probably the one factor affecting energy consumption that operators have most control over. Here a trade-off between exploiting commercial opportunities, picking more passengers by stopping at more stations, and fuel and energy savings must be struck. However, increasing the number of stops also has commercial penalties as more stops increase travel time for passengers not using them making railways a less attractive option comparative to other modes.

Figure 1: Effect of maximum speed on specific electricity consumption (in kWh/seat-km)



Source: RSSB (2007b)

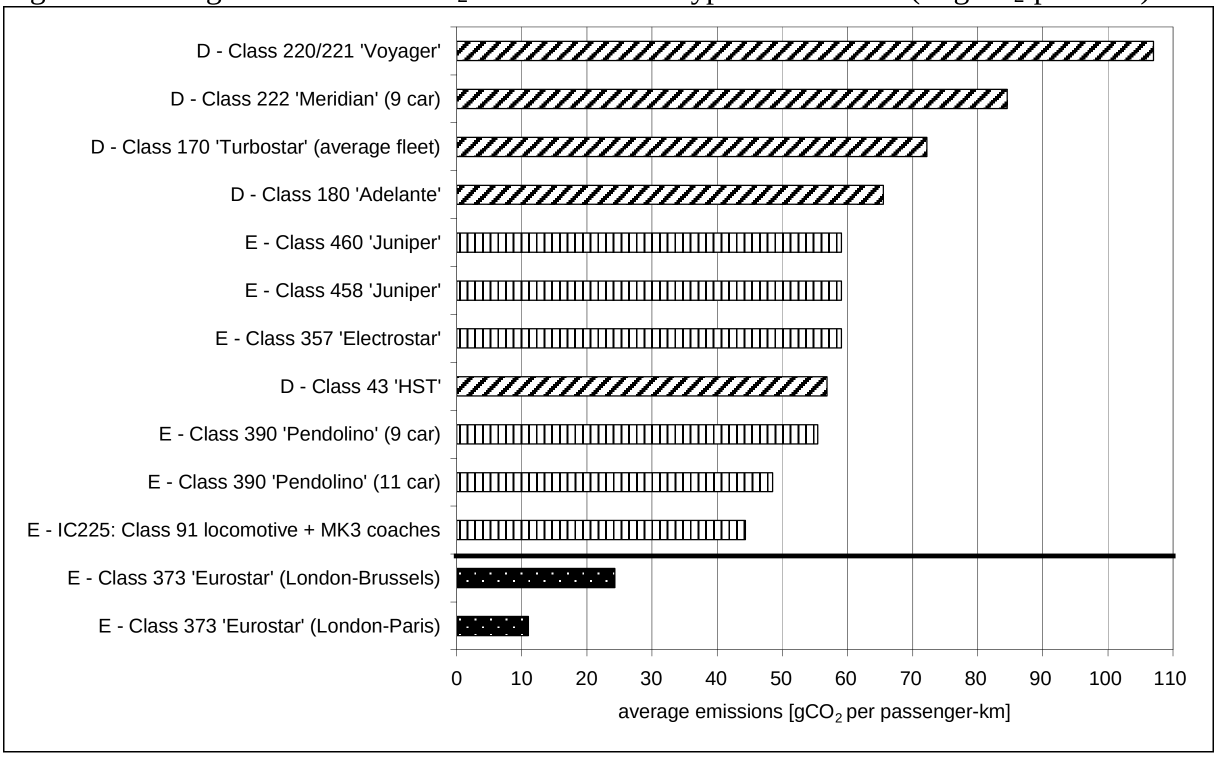
The reason the number of stops are so important in determining energy use and therefore emissions, especially for high-speed trains, is the energy required to achieve high speed. Therefore, the provision of four stations on the line connecting London with the Channel Tunnel (known as the Channel Tunnel Rail Link, or nowadays as 'High-Speed 1') - London St. Pancras, London Stratford, Ebbesfleet and Ashford – will not only affect travel time on the route but also the environmental performance of Eurostar. This problem is overcome by having some trains stopping at only some or none of the intermediate stations.

2.4 Summary - the CO_2 impact of different trains

A comparison of gCO_2/passenger-km for different typical UK trains (Figure 2) illustrates how marked the differences in CO_2 emissions from rail transport are, depending on the type of train, operating conditions and the services it provides. It is clear (from section 2.1 and Figure 2) that electric trains have an advantage over diesel trains, certainly at the current mix of sources used to generate electricity in the UK. As the share of fossil fuels in the electricity generation mix decreases so increases the advantage of electric trains over diesel trains. In addition, electric train operations are less harmful than diesel trains in terms of local and regional air pollution and associated impacts on human health and ecosystems, as the pollution is more likely to occur away from centres of population.

Figure 2 also demonstrates how important route characteristics are in determining emission levels. It appears that these characteristics (especially the number of stops on the route and the distance between them) are more important than the speed at which these trains are running at in determining emission levels. Figure 2 suggests that the faster trains are responsible for lower CO_2 emission levels per passenger-km. For example, maximum speeds of the Class 357 Electrostar, Class 390 Pendolino and Class 373 Eurostar trains are 161, 225 and 300 kph respectively. Class 43 HST (diesel) has a maximum speed of 201 kph. Thus, although the faster Eurostar trains use more electricity per seat-km (in the region of 0.05 kWh/seat-km), the combination of higher load factors, fewer stops en-route, aerodynamic design and, crucially, the much lower CO_2 content of the electricity supplied on *non-UK route segments* (France, Belgium) yields significantly lower average emissions per passenger-km then other trains[8]. Surprisingly, the most polluting (diesel) train in Figure 2 is probably the newest train, entered service after 2000. Its high level of emission can probably be associated with the nature of routes it is operating on ("CrossCountry" services), its relatively high weight and level of comfort provided for passengers (e.g. air conditioning system, which is not present on all UK trains). The Class 222 (Meridian) is a derivative of the Voyager trains but has significantly lower emissions. This can be associated in part to Class 222 comprising 9 'cars' compared with the 4 or 5 for Voyager trains; highlighting that capacity is another element which can significantly influence environmental performance.

Figure 2: Average emissions of CO_2 for a number of typical UK trains (in gCO_2/pass-km)



Legend/notes:

1. 'D' stands for diesel traction, also indicated by diagonal pattern; 'E' for electric traction, indicated by vertical pattern. 'Eurostar' figures indicated by black pattern with white dots.

2. The analysis assumes passenger load factors of 0.4 for UK intercity trains ('Adelante', 'HST', 'Pendolino', 'IC225') and 0.3 for other UK trains ('Voyager', 'Meridian', 'Turbostar', 'Electrostar', 'Juniper').
3. Class 373 'Eurostar' emissions values taken directly from Eurostar (2008).

Source: RSSB (2007b), DfT (2007a), Eurostar (2008) and own calculations

3. Comparing the carbon intensity of rail with other modes of transport

It is the environmental performance of the railways, in comparison to other motorized modes, that is making modal shift (to rail) such a priority in current transport policy. This section aims to assess the potential benefits of such modal shift by comparing CO_2 emissions from aircraft and car to those from rail operation. The different characteristics of aircraft and car journeys means that if mode substitution takes place different types of trains services (and routes) will replace each mode. Aircraft journeys will most likely be substituted by High-Speed Trains (HST) while car journeys more likely by conventional passenger trains (although variations in these are also expected, depending mainly on the route distance). Bus services, especially in the UK, are used more for travel within cities and as such do not usually compete directly with train services. Therefore, the analysis below focuses on comparing between aircraft and HST and between private car and conventional intercity and regional trains.

Mainly for lack of data and complexity reasons, comparison of the environmental impact from the operation of different modes of transport is done in average and not marginal units. The latter, however, would add value to the debate as it better accounts for variations in load factors across different parts of the network and different times of the day and therefore better reflects changes in environmental pollution when demand fluctuate. The marginal additional emission from one passenger on a train or plane operating below capacity is negligible, while it will be very high at reaching capacity and an increase in demand will require additional service, i.e. the operator puts on an additional train or plane (Rietveld, 2002). Compared to car and air transport, rail transport operators, for various reasons, are not as flexible in adjusting capacity to fluctuating levels of demand (across the network and the day), and this means the gap between average and marginal emission levels is higher in rail transport. Riteveld (2002) provide empirical examples for this in the case of the Dutch Railways. He shows that peak passengers are more polluting than off-peak passengers when marginal units are used while the opposite is the case when using average units.

It is not only the units of measurement which are debated. There is still a debate, especially amongst specialists, as to the most appropriate methodology for calculating energy consumption/emission from different modes and the appropriateness of different assumptions and therefore any conclusions made in regard to the advantage of one mode over the other is often contested (see for example Russell, 2007).

A comparison of CO_2 emissions from aircraft and HST for the London (Heathrow airport) to Paris (Gare Du Nord railway station) route shows that HST operation results in lower CO_2 emission levels (Givoni, 2007). Although CO_2 emissions from aircraft operation are sensitive to assumptions about the flight they are at least five times greater than the emissions from the HST. Furthermore, although airlines are better than the HST companies in filling up their seats, they achieve higher load factors, HST operation results in much lower CO_2 emissions per passenger (Table 6). This difference in the load factors between the modes suggests that in marginal, rather than the average, CO_2 emission terms the advantage of the HST over the aircraft is even greater.

A more detailed and up to date analysis of return trips from London to Paris which compares HST (Eurostar) service against air transport (Eurostar, 2008) leads to similar conclusions. The analysis uses route specific load factors to assess the emission per passenger carried as well as the emissions per passenger-km. On the analysed route, emissions from aircraft range from 110 to 172 kg CO_2 per passenger trip (depending on airport, airline and aircraft). The average for Heathrow to Paris CDG (return) was estimated at 122 kg CO_2 per passenger trip. This compares to 17 kg CO_2 per passenger trip (return) for the HST, assuming the average electricity generation mix in each country (UK, France). In terms of gCO_2 per passenger-km, aircraft operation result in 151 to 237 gCO_2 per passenger-km (depending on airport, airline and aircraft) for a return trip to Paris, and the current average (Heathrow to CDG return) is 168 gCO_2 per passenger-km. This compares to 17 gCO_2 per passenger km for the HST using the average UK mix. These figures compare well with government derived figures reported in DfT (2007b) and DfT (2008).

Table 6: Comparison of CO_2 emissions from aircraft and High-Speed Train operation on the London-Paris route

Aircraft (flight from Heathrow to CDG)					
Model	Flight time	Climb rate$^{(1)}$	Descent rate$^{(1)}$	$kgCO_2$/seat	$kgCO_2$/passenger$^{(2)}$
A320	70 min.	2500	1850	42.5	60.7
B737	70 min.	2500	1850	53.5	76.4
A320	70 min.	1600	1250	52.0	74.3
A320	70 min.	3000	2800	39.7	56.7
A320	60 min.	2500	1850	40.0	57.1
A320	85 min.	2500	1850	46.3	66.2
High-Speed Train (journey from Heathrow$^{(3)}$ to Paris), electric traction					
	Distance			gCO_2/seat	gCO_2/passenger$^{(2)}$
HST	525 km			7.2 $^{(4)}$	14.4

[1] meters/minute
[2] Load factors assumed: 70% for aircraft and 50% for HST (it is expected that at current market conditions this is higher and comparable to the airlines' load factors).
[3] The research investigated the potential benefits from airline and railway integration at Heathrow airport, which is why the airport, and not the city centre railway station, is the origin
[4] This figure is based on the electricity use and CO_2 intensity assumed by Givoni (2007) and therefore not consistent with the estimates in section 2 above.
Source: Givoni (2007).

The environmental advantage of rail over aircraft is also apparent when considering the UK domestic air services. ATOC (2007b), based on data from the National Atmospheric Emissions Inventory (NAEI) and Transport Statistics Great Britain (TSGB), shows that in 2005 air travel within GB amounted to 9.9 billion passenger-km or 15.2 billion seat-km (accounting for 65% load factor achieved in that year). This level of operation translated to 227 gCO_2/passenger-km and 147 gCO_2/seat-km. CO_2 emission from train operation was 60 gCO_2/passenger-km in 2006/7 (weighted average of diesel and electric train operation, see section 2). Surprisingly, the performance of the aircraft fleet in 2005 was worse than in 1995 when gCO_2/passenger-km was 204. This is probably the result of a significant increase in demand (from 5.9 to 9.9 billion passenger-km, partly as a consequence of market changes like deregulation and the spread of low-cost airlines) which led to the introduction of jet aircraft on domestic routes, replacing and complementing the turbo-prop aircraft which can be more fuel efficient (RSSB, 2007b).

Similar sources of data, including data from the National Travel Survey (NTS), are used by ATOC (2007) to show the CO_2 emission levels associated with car and taxi transport in GB (Table 7). Due to differences in seating capacity between the modes, only comparison in gCO_2/passenger-km can be made. In 2005, car travel resulted in 104 gCO_2/passenger-km, substantially higher than the level for rail (69 for diesel trains, 54 for electric, and 60 weighted average of the two). The average occupancy rate of cars has been relatively constant over time at about 1.6 persons per car. The 10% reduction in specific car emissions between 1995 and 2005 can therefore be associated almost entirely with improved fuel economy, which has been offset by a move towards larger and heavier vehicles (CfIT, 2007). This is similar to the trend of improved efficiency in electric train operation, which can be associated with technological development, reported above (as noted CO_2 emissions related to diesel train operation deteriorated in the last 10 years). In terms of CO_2 emissions per passenger-km, cars could be much more efficient – the relatively low occupancy rate of 40% (assuming capacity of 4) could certainly be improved. If instead of 1.64 people per car 2 people would use it the gCO_2/passenger-km would have fallen to 85, and as low as 68 and 57 if occupancy rate was 2.5 and 3 people respectively. This suggests that from a technological perspective, and considering average emissions as opposed to marginal emissions, cars are not necessarily inferior to trains in terms of CO_2 emissions. Indeed, a better approach to compare between cars and trains would be to exclude taxi travel (very short distance in nature) and include only long-distance inter-city car journeys where car fuel efficiency is much better and load factor tend to be higher than the average (for most short distance car journeys rail is not a substitute), but such data were not available. Such data would have probably revealed a much smaller gap between the modes in terms of gCO_2/passenger-km then the one found here. The implications of this for the difference between the modes in terms of marginal emission are hard to draw. Both car and rail transport operate at relatively low load factors suggesting marginal emission is close to Zero. However, on the one hand cars have lower capacity and will be filled up quicker than trains (requiring addition of new vehicles as demand increase leading to increased emission). On the other hand, load factor is relatively equal across all car journeys while it is not for rail transport (e.g. high during peak journeys to city centre and low during off-peak journeys or peak journeys away from the city centre) suggesting as demand grows additional trains will be required since new demand will most likely be for when load factor is already high. This emphasizes the difficulties in using marginal units as well as the limitations of using average units.

Table 7: CO_2 emissions from car and taxi travel in Great Britain

	1995	2005
Vehicle-km (billion)	351.1	397.2
gCO_2/vehicle-km	**191.5**	**170.5**
Passenger-km (billion)	588	651.1
gCO_2/passenger-km	**114.3**	**104**
Occupancy rate	1.67	1.64

Source: ATOC (2007).

4. Potential for reducing the environmental impacts of rail operation

The options for reducing the relative environmental impacts of rail can be broken down into technological and operational measures[9]. Technological measures improve the environmental performance per vehicle-km; for instance improved energy efficiency of a powertrain, lower carbon intensity of power generation or alternative fuels with lower lifecycle carbon content. Operational measures reduce the number of vehicle-km driven for a certain demand level (passenger-km); for example making better use of available seating capacity (improved load factor), or reducing empty running of trains for fuelling, berthing and maintenance activities. This section briefly introduces the options and, where available, their potentials to reduce emissions.

4.1 Technical options that reduce CO_2 emissions per vehicle-km driven
For electric traction, the rail industry is pursuing energy savings through the introduction and further roll-out of regenerative braking, i.e. using the electric motors as generators that convert kinetic energy released while braking back into electrical energy. Electric trains which have already been equipped with such a system have shown energy savings of up to 20% (ATOC, 2007a). This measure should improve the energy efficiency of electric rail in the short to medium term. In addition, as discussed in section 2, emission reductions are expected from reducing the carbon intensity of the electricity used. The UK government projections of a reduction in the carbon content of electricity of between 18% and 30% between 2006 and 2020 is in addition to any technical and operational improvements implemented by operators, e.g. regenerative braking and increased passenger loads.

For diesel trains, lowering the carbon content of rail diesel can be done by blending normal rail diesel with lower carbon fuels (e.g. first generation biodiesel from rapeseed oil). Diesel trains can easily run on low (5% or 20%) to medium (50%) level blends of biodiesel and conventional diesel. Some diesel engines can even take 100% biodiesel without much modification. First generation biodiesel is available now and is said to save around 60% carbon when compared to conventional diesel (Woods and Bauen, 2003) but it has been criticised for not being low carbon at all since upstream fuel lifecycle carbon impacts and land use effects, in particular when in direct competition with food crops, are considered to be substantial (see for example Fargione et al., 2008).

Re-engining of the existing fleet (i.e. replacing old with new engines) is another technical option to reduce emissions, but require high capital investments. Re-engining of the UK diesel High Speed Trains (Class 43, maximum speed of 201 kph) has the potential to reduce fuel consumption by as much as 15% (FirstGroup, 2007). Furthermore, modern hybrid-electric drivetrains such as diesel-electric trains with on board energy storage (batteries, fly-wheels and super-capacitors that store electricity at various degrees of efficiency) can save fuel and thus CO_2 by about 10% (RSSB, 2007a). Also, fuel additives designed to increase engine fuel efficiency can save fuel. Trials with Platinum Plus by Clean Diesel Technologies, Inc. have shown fuel efficiency improvements of 4-12%, depending on driving patterns and load conditions (ibid). In the longer term (post 2025), hydrogen fuel cell drivetrains could play a major role. Woods and Bauen (2003) estimated that hydrogen produced from renewable sources (e.g. wind) can save up to 90% of CO_2 when compared to diesel. Fuel cells are efficient in converting hydrogen into electrical energy, which then power electric drivetrains.

Other technical options for the medium term include weight reduction per seat, intelligent engine control and distributed power trains, and aerodynamic drag reduction. However, this may be partly offset by the need to incorporate features such as power doors and air conditioning. Indeed, new trains may also have to operate in a more carbon intensive way e.g.: higher acceleration, deceleration and top speeds, in order to deliver greater capacity on the network (DfT, 2008).

4.2 Operational measures that reduce vehicle-km driven per unit of passenger demand

It is widely recognised by the industry that there is significant scope for operational measures to save fuel (and operating costs) and thus carbon. The rail industry is running trials of on-train energy metering to manage energy consumption, recognising that measurement, monitoring and feedback are important tools in improving operational energy efficiency. Further "quick wins" include reducing stabling loads (i.e. ensuring trains are wholly or partly shut down when not in traffic so heating/lighting is not fully 'on' – a mixture of operational steps and improved technology for auto switch-off) and running shorter trains off-peak. In a new work undertaken to look at emissions from the rail sector, DfT (2008) reports that reducing stabling loads has the potential to save 2-3% of CO_2 by 2020. Energy efficient lighting, revised thermostat settings and improved control technology can save about 1-2% of CO_2 across the fleet (DfT, 2008). Other operational measures such as selected engine running (i.e. switching off one or more engines on a diesel multiple unit train), reduced engine idling (whereby engines are automatically shut down after a pre-determined period of idling, e.g. in stations) and maximising the use of external supply rather than using the train engines to provide power (e.g. for heating, lightening) when trains are not in service can save CO_2 of around 2-7% (DfT, 2008; RSSB, 2007a). Equally, traffic management systems linked to on-board driving advice units on trains could help avoid most unnecessary stops at signals in the future (CER, 2004). Higher capacity trains, i.e. adding rolling stock to an existing train, is expected to have a lower carbon impact compared to running additional trains at higher frequency due to the reduced weight and aerodynamic drag impact (note the differences between the Voyager and Meridian trains mentioned in section 2.4).

On the behavioural side, training drivers in more energy efficient driving techniques can save fuel and CO_2 in the region of 10% as in the case of the German Railways "EnergieSparen" project (CER, 2004). The DfT (2008) puts the potential savings in the UK at a more conservative rate of 3-5%. All in all, improved fleet management and driver technique measures could reduce rail emissions in 2020 by 10 - 14% below what they would otherwise be (ibid).

5. Summary and conclusions

In the UK, and similarly in Europe, rail has an important role to play in achieving a more sustainable transport system and reducing transport's contribution to climate change. However, while transport policy makes a general reference to rail transport in terms of being relatively 'green', there are many different types of 'green', many different types of rail and different operating conditions that determine how 'green' or 'climate friendly' rail really is.

There are good environmental reasons to promote a mode shift to rail, but the level of environmental benefits depends on the type of train that substitutes the car or the plane. The levels of CO_2 emissions from the most polluting trains, however, are not much better than the levels of aircraft emissions on some routes. Yet they are still much better than the level of emission of the domestic fleet in GB. In this context, to make rail more attractive for air passengers, especially those using a domestic flight to connect to international flights, the rail network must include stops at the main airports (Givoni and Banister, 2006). At the current average load factors, passenger rail transport in GB provides an environmentally beneficial alternative to car transport, but these benefits can be further improved if the utilisation of the available seating capacity on the rail network will be improved.

Electrification of the entire rail network in the UK would certainly reduce CO_2 emission from rail. However, strictly from a carbon cost abatement perspective, it appears that electrification of the UK rail network is not economically justified (section 2.1). If local and regional air pollution effects and noise were included in the analysis, this conclusion may well change. Strategic electrification can be economically justified and three options should be considered. First, run fewer diesel services under existing electrified sections. Second, electrification of small part of the network to connect between stretches of the network that are already electrified (for example on routes between Liverpool-Manchester, Manchester-Leeds and Leeds-York). Third, consider strategic electrification of additional routes and especially that of main rail corridors (e.g. the Great Western Mainline – London to Bristol). In general, countries in which large parts of the network are not electrified are therefore advised to take measures to reduce emissions from diesel trains, electrify where the carbon content of electricity is low (e.g. France, Norway) and invest the money in carbon abatement options in other transport sectors and the wider economy.

The analysis presented above demonstrated the limitations in regarding rail transport simply as relatively 'green' or 'climate friendly' and in using this generalisation to promote the development of the rail network. At the same time the analysis highlights the potential for rail transport to contribute towards reducing the climate change impact of transport and emphasizes that there are potentials in the order of 10-15% to reduce CO_2 emission from rail operation. It is worth keeping in mind, however, that overall rail is a growing industry and therefore *absolute* reductions in carbon emissions from rail operation will be difficult to achieve, unless the main sources of its energy become themselves much less carbon intensive.

Parts of the UK rail network, especially routes into London, are already operating at or close to full capacity, and therefore to relieve congestion and meet new demand, additional capacity is required and this inevitably increases emission. Furthermore, making rail more attractive to travellers might require new trains to operate in a more carbon intensive way e.g. higher acceleration, deceleration and top speeds, in order to deliver greater capacity on the network (DfT, 2008). Finally, large scale increase in demand for rail will increase demand for electricity, and this might only be met by electricity from carbon intensive generation plants (coal without carbon capture and storage, or gas). On the other hand, one could this as an opportunity for green electricity to provide this increase in demand - policy must make sure this opportunity is not lost.

In 1960, 40 billion passenger-km were carried on the rail network in GB, but this declined to 35 billion in 1980. Since then, rail transport increased markedly and in 2006 55 billion passenger-km were transported on the network. This appears as an important step forward towards a more sustainable transport system. However, while in 1960 the share of rail in passenger-km transport was 15%, it declined to 7% in 1980 and remained at 7% in 2006 (DfT, 2007b). While demand for rail is increasing over time demand for other modes is increasing as well. Thus, the increase in demand for rail is mainly from new demand and not demand shifted from other modes, and this is not 'climate friendly'.

Related to the issues raised above is the question of whether a new HST line (from London to the North, HS2 - see Hall, this issue) is desirable from an environmental perspective. There is no straight forward answer. If the effect of such line would be a shift in demand from car and plane (for this the line must include a stop at Heathrow airport – see Givoni and Banister, 2006) and even conventional rail (see Figure 2) then HST is desirable from an environmental perspective. But if, as experience show is the often the case, a new HST mainly result in new demand for travel generated then the answer is no.

In conclusion, as such rail transport, certainly in the GB, cannot be considered 'green', but it is most likely greener than other modes of transport it competes with and it can certainly be even 'greener'. Thus the main challenges for making the railways truly climate friendly are in shifting demand from car and plane to rail, rather than generating new demand; increasing the load factors rail operators achieve, thus making better use of available infrastructure capacity; and in implementing operational and technological measures to improve energy efficiency of rail operation. We are on the right track – but more can and needs to be done.

References:

AEA (2001) Rail and road emissions model, Final Report to the Strategic Rail Authority. AEA Technology, Harwell, UK.

ATOC (2007) Energy and Emissions Statement - 2006/7, Report by the Association of Train Operating Companies. London, UK.

CEC, Commission of the European Communities (1996) White Paper – a strategy to revitalise the community's railways. Commission of the European Communities, COM(96)421final, July.

CEC, Commission of the European Communities (2001) White Paper - European transport policy for 2010: time to decide. Commission of the European Communities, COM(2001)370, Brussels, September, [http://europa.eu.int/comm/off/white/ index_en.htm (15/2/2002)].

CER (2004) Railways and the Environment: Building on the railways' environmental strengths. Community of European Railway and Infrastructure Companies (CER), Brussels, Belgium.

CfIT (2007) Transport and Climate Change: Advice to Government. Commission for Integrated Transport, London.

DEFRA (2007a) The Social Cost Of Carbon And The Shadow Price Of Carbon: What They Are, And How To Use Them In Economic Appraisal In The UK. Defra, London. Available at http://www.defra.gov.uk/environment/climatechange/research/carboncost/pdf/background.pdf, last accessed on 15/07/08.

DEFRA (2007b) Guidelines to Defra's GHG conversion factors for company reporting, Annexes updated June 2007. TSO, London.

Department for Business Enterprise & Regulatory Reform, DBERR (2007) *Digest of United Kingdom energy statistics (DUKES) 2007*, National Statistics, TSO, London

DfT (2007a), Delivering a sustainable Railway, White Paper CM 7176 and supporting documents. Department for Transport, July. Available at http://www.dft.gov.uk/about/strategy/whitepapers/whitepapercm7176/.

DfT (2007b) Transport Statistics Great Britain: 2007 edition. Department for Transport, TSO, London.

DfT (2008) Carbon Pathways Analysis: Informing Development of a Carbon Reduction Strategy for the Transport Sector. Department for Transport, TSO, London, July.

Dings J. M. W., Wit R. C. N., Leurs B. A., Davidson M. D., and W. Fransen (2003), External costs of aviation, Federal Environmental Agency (Umweltbundesamt), Berlin, June.

DTI (2007) Energy White Paper – Meeting The Energy Challenge, Department for Trade and Industry. The Stationary Office, London. Available at http://www.berr.gov.uk/files/file39387.pdf

Eurostar (2008) *Greener than flying*, based on research conducted for Eurostar by an independent consortium of Paul Watkiss Associates and AEA Technology Environment. Eurostar Group Ltd., available at http://www.eurostar.com/UK/uk/leisure/about_eurostar/environment/greener_than_flying.jsp

Fargione, J., Hill,, J., Tilman, D., Polasky, S. and Hawthorne, P. (2008) Land Clearing and the Biofuel Carbon Debt, *Science*, **319**, 1235-1238.

FirstGroup (2007) Climate Change Strategy 2007. FirstGroup plc, Aberdeen. Available at http://www.firstgroup.com/assets/pdfs/csr/csr_report_2007/FirstClimateChange.pdf

Givoni M. (2007) Environmental benefits from mode substitution - comparison of the environmental impact from aircraft and high-speed train operation. *International Journal of Sustainable Transport*, 1(4): 209-230.

Givoni M. and Banister D. (2006) Airline and railway integration. *Transport Policy*, 13, pp. 386-397.

Hall, P (2008) …..this issue

HMT (2007) The Green Book: Appraisal and Evaluation in Central Government. HM Treasury, TSO, London.

McKinnon, A. (2007) CO_2 Emissions from Freight Transport in the UK, Report prepared for the Climate Change Working Group of the Commission for Integrated Transport. Heriot-Watt University, Edinburgh.

Rietveld P. (2002) Why railway passengers are more polluting in the peak than in the off-peak; environmental effects of capacity management by railway companies under conditions of fluctuating demand, *Transportation Research Part D*, **7**(**5**), pp. 347-356.

RSSB (2007a) *Improving the Efficiency of Traction Energy Use*. Enotrac and Interfleet Technology for the Rail Safety and Standards Board, June. Available at http://www.rssb.co.uk/Proj_popup.asp?TNumber=618

RSSB, Rail Safety and Standards Board (2007b) *Traction energy metrics*. Lancaster University and Interfleet Technology for the Rail Safety and Standards Board, December. (Available at http://www.rssb.co.uk/Proj_popup.asp?TNumber=618)

Russell J. (2007) Measuring the impact of transport modes: are the railways really greener than flying?, Focus (CILT's Focus magazine), 10(4), pp. 28-33.

Sustainable Development Commission (2006) The role of nuclear power in a low carbon economy, SDC position paper, March.

The Railway Forum (2008) *Electrification*. Available at http://www.railwayforum.com/electrification.php, last accessed 15/07/2008.

Watkiss, P., D. Anthoff, T. E. Downing, C. Hepburn, C. Hope, A. Hunt and R. S. J. Tol (2005). The Social Costs of Carbon (SCC) Review – Methodological Approaches for Using SCC Estimates in Policy Assessment, AEA Technology Environment.

Woods, J. and Bauen, A. (2003) *Technology Status Review and Carbon Abatement Potential of Renewable Transport Fuels in the UK*, Imperial College Centre for Energy Policy and Technology for the Department for Trade and Industry, London.

[1] Aviation is similar and different at the same time – similar in that CO2 is the main culprit, and different in that non-CO_2 GHG play a much more significant role in climate change impacts than for surface transport.

[2] While the paper makes a general reference to the UK, the data presented are for Great Britain (England, Scotland and Wales and excluding Northern Ireland).

[3] The SPC is different from the previously used social cost of carbon (SCC) in that it takes more account of uncertainty and is based on a stabilisation trajectory. Values are usually accompanied with a GHG stabilisation figure, e.g. 450ppm or 550ppm (ppm: parts per million).

[4] The atomic mass of carbon dioxide and carbon are 44 and 12 respectively. 1 kg of carbon combines with 2.667 kg of oxygen to produce 3.667 kg of carbon dioxide. This assumes complete combustion, which is realistic as any pollutant from incomplete combustion – mainly carbon monoxide – eventually react to form CO_2.

[5] This was relevant for the time the analysis took place. As noted, for this research the differences between estimates are more important then the absolute level so using the correct exchange rate is less important.

[6] Freight is different in that 90-95% of UK tonne-km moved on the rail network are hauled by diesel locomotives, with the remainder by electric traction (McKinnon, 2007; DfT, 2008).

[7] What has happened in the UK recently is the opposite; gas prices have soared while coal prices have increased at a relatively lower rate. As a result, more coal has been used in generating UK electricity, thus the CO_2 content has increased over the last couple of years (DEFRA, 2007b; DTI, 2007). This is not expected to become the trend in the near future.

[8] The differences between the London-Paris and London-Brussels routes are probably due to the longer share of the route (in the former) where non-UK electricity is used plus a higher load factor.

[9] Demand measures that reduce the need to travel (i.e. reduce passenger-km) or shift demand from peak to off-peak (i.e. tariff structure that account for peak and off-peak travel) are not covered here, but nevertheless play a significant role with respect to CO_2 emission reductions.