Rail Safety & Standards Board

Research Programme

Engineering

Traction energy metrics

T618 - TRACTION ENERGY METRICS

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1 EXECUTIVE SUMMARY

The objective of this study was to answer the following questions:

- Which are the most appropriate metrics for traction energy consumption in the rail industry and how should one define benchmarks which can be used as a reference for energy use?
- What values of energy consumption, measured at the fuel filler or the pantograph / collector shoe, represent current good practice in the GB rail industry?
- How does the energy consumption of the GB rail industry compare with international good practice? Where there are differences, what are the reasons for them?
- How do the CO_2 emissions of different segments of the domestic GB rail industry compare with competing transport modes?

The study is restricted to passenger transport on the main-line network. It has not attempted to analyse underground rail, light rapid transport and other urban systems. Similarly it has been necessary to omit freight and parcels traffic due to the diversity of traffic types, routes and operators.

CHOICE OF METRICS

When making comparisons between different types of train, it is difficult to draw any useful conclusions from comparisons of the energy used *per passenger* because the results are affected more by the type of service and the load factor than by features of the vehicles. Comparisons between diesel trains and electric trains are further complicated by the assumptions that have to be made about the type of fuel used in power stations. It is therefore recommended that the industry uses the following figures:

◊ For comparisons between different types of electric train: kWh/seat-km

◊ For comparison between different types of diesel train: litres of fuel/seat-km

◊ For comparison between electric and diesel trains: grams of CO_2 /seat-km

Because of the different load factors on different transport modes, it is not possible to make reasonable comparisons on the basis of energy/seat and therefore, when making intermodal comparisons, the data should be expressed as follows:

◊ Grams of CO_2 /passenger-km.

ENERGY SOURCE

For electric traction the GB national energy mix has been used as a basis when considering the carbon intensity of grid electricity[1]. The current figure for converting

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[1] This approach is consistent with defra's policy for transport emissions as detailed in their *Passenger Transport Emissions Factors - Methodology paper*, June 2007.

generated electrical energy to CO_2 is 455 g/kWh but this is expected to reduce to around 320 g/kWh over about 15 years [2] [3].

GOOD PRACTICE

Limited international comparisons suggest that the energy consumption of GB electric trains is broadly comparable with that achieved by overseas administrations. Where there are differences, these can largely be attributed to the use of regenerative braking (in intensive urban areas), differences in loading gauge or restrictions on passengers travelling in certain areas of the train for safety reasons. On some networks, such as the Japanese Shinkansen, comparable energy use is significantly less than in GB, due to reduction in mass, aerodynamic drag and more efficient use of the train length.

For electric trains on regional or suburban services, current good practice is to use not more than 0.030 kWh/seat-km. For intercity trains the figure is 0.035 kWh/seat-km. It is suggested that, if the industry decides to set standards of energy consumption as maxima for new trains as has been done by the EU for road vehicles, the targets could be based on these figures.

A comparable figure for diesel-powered passenger trains might be that they should not consume more than 0.8 litres/100 seat-km. However, it must be recognised that many post-privatisation diesel trains exceed this figure, due in no small part by the desire to emulate the acceleration of their electric counterparts.

It is not the purpose of this paper to say exactly how energy savings might be achieved but, to achieve these targets, it will be necessary to give the same priority to energy saving as is given to safety or accessibility today.

INTERMODAL COMPARISONS

Trains are designed for an operating life of about 30 years. Since privatisation of the GB industry, a large number of new trains have been delivered and, at present, there are no trains on order significantly different to the present fleet in terms of energy use or emissions. Road vehicles, on the other hand, have a much shorter design life and there is a second-hand market that recycles high-mileage vehicles to low-mileage uses after 5 years. When looking at emissions with a time horizon of 2022, it is therefore reasonable to assume that trains will be much the same as today but that cars will show progress towards reduced EU emission standards. While companies are researching innovative technical solutions to reduce train energy use (hybrid drive systems, flywheels, super-capacitors, composite structures, etc.) it seems unlikely that these will have a significant impact on average energy use in this timescale.

The comparison of domestic rail with other transport modes confirms that electric trains are at least as efficient as other means of transport in terms of grams of CO_2/passenger-km. As electricity supply is "decarbonised" the benefit will increase so

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[2] DTI, *Our Energy Challenge - securing clean, affordable energy for the long-term*, January 2006

[3] George H.B. Verberg, President International Gas Union European Gas Market(s) and Regulation/Liberalisation, SGOA Autumn Conference, Bratislava, 3 November 2005

http://www.igu.org/knowledge/knowledge/presentations/2005bratislavasgoa_georgeverberg.pdf they become at least as good as double-deck diesel buses, despite their much higher average speed and passenger acceptability. On environmental grounds, there is a strong case for transferring passengers from road and air to electric railways meeting the energy targets discussed above.

The situation for diesel trains is less clear. Many newer and more powerful diesel trains produce significantly more CO_2/passenger-km than buses. As the efficiency of cars progressively increases, under the influence of EU legislation, the difference in emissions between cars and high-performance trains will narrow and it will be increasingly difficult to make an environmental case for transferring people onto diesel-powered railways.

There is a strong environmental case that further targeted electrification should be put back onto the industry's agenda as this is one of the best means of reducing CO_2 emissions[4]. There is also a case for redesigning some train services to minimise the number of empty seats transported.

Electric trains on the main London – Manchester and Scotland lines produce far lower CO_2 emissions than the jet planes used on competitive routes and there is a good environmental case for encouraging passengers to transfer to the train. (Note this does not necessarily apply to very high speed transport systems, even if they are electrically powered.) However in a comparison between slower turboprop airliners and high performance diesel trains the difference is not so marked and, for some cross-country routes, there may be little difference between the environmental impacts (in terms of CO_2 emissions) of these transport modes.

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[4] See also RSSB research report (T633) Study on further electrification of Britain's railway network

2 INTRODUCTION

The study has been designed, as part of a wider industry and Government agenda on sustainability and strategic planning, to identify ways to achieve energy efficiency savings in the rail industry. The work includes a benchmarking and metrics study, including consideration of alternative sources of energy supply and a comparison with other transport modes. The group has worked closely with other teams contributing to the development of a sustainable strategy for rail. In particular, we have collaborated with ATOC and their partners who have been undertaking a study into the energy consumption of rail vehicles in Britain.

In this part of the study, we have addressed four key questions:

- Which are the most appropriate metrics for the rail industry and how should one define benchmarks which can be used as a reference for energy consumption?
- What values of energy consumption measured at the fuel filler or the pantograph / collector shoe represent current good practice in the GB rail industry?
- How does the energy consumption of the GB rail industry compare with international good practice in terms of energy delivered at the pantograph or to the fuel tank? Where there are differences, what are the reasons for the differences?
- How do the CO_2 emissions of different segments of the domestic GB rail industry compare with competing transport modes?

In addressing the third of these questions we have had to take into account the original sources of energy used for electricity generation and the way in which these are likely to change over time.

Since this report was planned, the ATOC report on energy consumption[5] has been published. This includes up-to-date energy use data on several train services. As these data are based on more accurate and comprehensive measurements than heretofore available, the plan for this report has been changed to use the trains analysed by ATOC in preference to those originally proposed.

This report concentrates on passenger transport on the main line network. Some discussions have been held with freight hauliers and it has become clear that a comparative study of the relative performance of rail and other transport modes in these markets would require a report in its own right. The analysis is made complicated by the many different types of freight and parcels transported in a modern society and the diversity of load sizes and destinations.

Establishing benchmarks for the energy consumption and efficiency of existing electric and diesel passenger trains, against which proposals for new projects and future changes can be judged, is not straightforward. In the road vehicle industry a

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[5] Phillip Hinde and Christina Larsson, *The Energy Consumption of Rail Vehicles in Britain*. Published by ATOC, Bombardier Transportation and National Express Group, October 2006.

standardised test based on a simulation of urban and inter-urban driving is used to produce a combined fuel consumption and CO_2 emission footprint for a vehicle that, experience shows, is reasonably representative of that achieved by vehicles in service.

Rail vehicles are less easy to test and categorise than road vehicles for three main reasons:

- There is a wide variety of different vehicle types serving different market segments; apart from trains for bulk freight, containers and mail, the GB national network carries high-speed passenger trains, inter-urban multiple units, inner and outer suburban units, regional and rural services. Unlike for passenger road vehicles, assessing consumption when running to a standardised duty cycle is not a rational comparator and undertaking consumption tests on a test track is not easily achievable.
- Energy or fuel consumption can be measured per vehicle-km, per seat-km, per passenger-km or per tonne-km. If concentrating on the efficiency of the vehicle, it would be perverse to take account of train occupancy; however any comparison between transport modes (rail, air or road) cannot avoid taking into account the average loadings of the different transport systems.
- Road vehicle efficiency can be measured in terms of fuel use, but it is not self-evident what conversion factors should be used when comparing electric with diesel trains. The UK energy supply mix for electricity generation is dominated by coal, combined-cycle gas turbines and nuclear. Working out the carbon emissions from this supply mix allows a comparison between diesel and electric trains.

2.1 THE ELECTRICITY SUPPLY

Until about 2 years ago, the DTI assumed that electricity generation in the UK would become increasingly dependent on natural gas, mainly from Eastern Europe. The 2006 consultation on energy policy[6] suggested the following scenario for future energy mix, shown below. The second diagram[7] shows the anticipated geographical flows trade in natural gas would take.

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[6] DTI, *Our Energy Challenge - securing clean, affordable energy for the long-term*, January 2006

[7] Source BNG

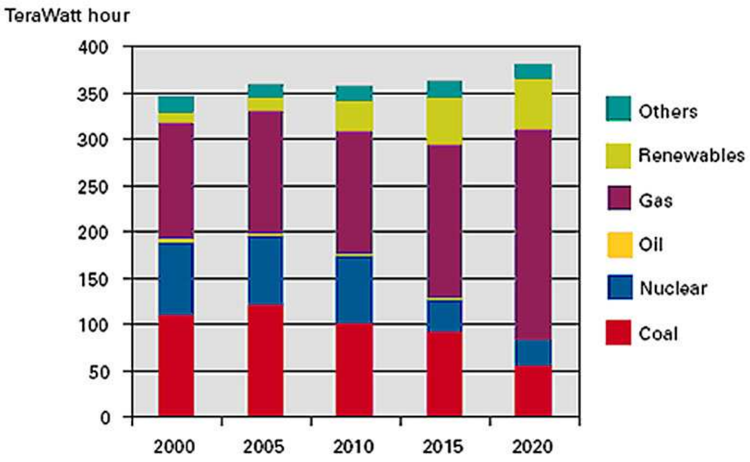

Figure 1 The mix of fuels for electricity generation

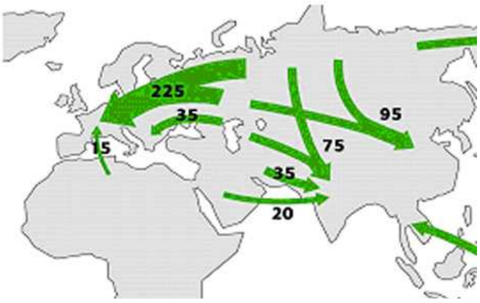

Figure 2: Future energy flows in Europe

With the recent turmoil in the energy markets, it now seems unlikely that any Government would accept with equanimity the possibility of such a large proportion of the UK's energy supplies being provided from a single source and it is likely that there will be a growth in the proportion provided from nuclear power and renewables. However it is not clear how any scenario that includes a continuing large role for carbon-based generation will be compatible with the stated objectives of achieving a 60% cut in greenhouse gas emissions and a third of energy produced from renewables by 2050.

Two scenarios have been considered: the existing fuel mix, and a lower carbon scenario, discussed below.

LOW CARBON ELECTRICITY?

It is sometimes argued that, because Network Rail currently purchases electricity from British Energy, a predominantly nuclear power generator, the electricity can be treated as "low carbon".

It is interesting to compare this line of argument with the debate in Norway over the possibility of building a high-speed line. Are Wormnes, Chief Editor of Samferdsel (Journal of Transport) published by the Norwegian Centre for Transport Research –

Institute of Transport Economics (TØI), argues in a recent issue that, even though most of Norway's electricity is generated from hydroelectricity, this does not mean that one can treat electricity for a new line as carbon-free. There is only a certain amount of electricity generated by hydro-power and, if it is not used for a high-speed line, it could be exported to Germany to replace the burning of lignite in conventional power stations. Operating a new line in Norway would thus result in an overall increase in European CO_2 emissions.

The opposite, and equally credible, way of looking at the situation is that, were the whole of the GB railway to be closed tomorrow, the nuclear stations would continue to operate at their normal power and some fossil fuelled power stations would be instructed to reduce load. Thus the avoidable energy use can be thought of as being entirely carbon based.

When looking at the whole GB rail network neither of these extreme ways of looking at energy consumption is appropriate. In this report, we have taken the view that, unless there is a unique supply to a railway completely isolated from the rest of the electricity supply (as used to be the case with the 16.7 Hz supplies in parts of Northern Europe), where a railway purchases electricity is purely a business decision and consequently does not materially affect the associated national carbon emissions in the short to medium term. For this reason, we have used the average carbon emissions for UK electricity based on the grid mix. This approach is consistent with defra's policy for transport as detailed in their Passenger Transport Emissions Factors - Methodology paper, dated June 2007.

THE PRESENT ENERGY MIX

Generation of Electricity in the UK uses a variety of fuels: Gas 40%, Coal 33%, Nuclear 19%, Oil 1%, Hydro 1%, other fuels (including wind, biomass and landfill gas) 3.5% and imports 2.5%.[8] The last figure relates to electricity imported from France over the cross-channel dc interconnector which is predominantly generated by nuclear power. Over the years the proportion of the UK electricity generated by different fuels has changed, originally because of the "dash for gas" and, more recently, because the high cost of gas, which is indexed to the oil price, has encouraged generators to use more coal. The average figure for UK generating stations of the amount of CO_2 emitted per kWh sent out to the Grid is shown below for the last 8 years. (Note this does not include electricity imported through the interconnector from France, so it is not strictly comparable with the figures used later in this report.):[9]

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[8] DTI – Digest of UK Energy Statistics 2005, Chart 5.3

[9] Based on the National Atmospheric Emissions Inventory for 2003 and the UK Greenhouse Gas Inventory for 2003 developed by Netcen (2005), DEFRA 2005

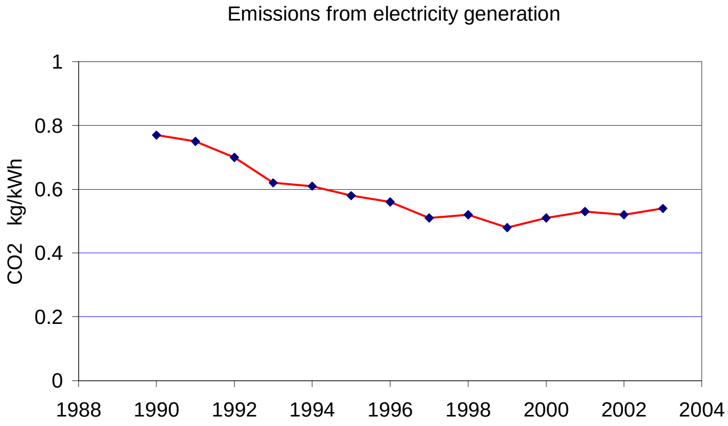

Figure 3 Emissions from electricity generation

Latest data show that the total carbon emitted by the generation of 1 GWh by different fuels is as follows:[10]

Coal 242.9 tonnes, Oil 166.0 tonnes, Gas 101.6 tonnes. Weighted average (including nuclear and renewables) is 124.1 tonnes/GWh.

There are 10^6 kWh in one GWh, thus, using the current energy mix, the carbon emitted in producing 1 kWh of electricity is 0.1241 kg. This is equivalent to 455 g of CO_2/kWh.[11] It should be noted that this figure is derived from a DTI publication and relates to emissions for each kWh at point of generation[12].

THE FUTURE

While the national energy debate continues, there is no clear picture of how future electricity supplies will be produced or how quickly the industry will be "decarbonised". We have therefore taken a hypothetical situation for 2022 (15 years time, when most post-privatisation rolling stock will still be in service) when, it is planned, CO_2 emissions per megawatt will be lower and the balance of fuels could be: Gas 55%, Coal 10%, Nuclear 25% and Renewables 5%. (If "clean coal" technology is developed, it is likely to produce comparable emissions to combined-cycle gas generation and could be used to reduce the dependency on imported gas. The balance between nuclear energy and renewables is irrelevant to the overall CO_2 emissions.) This energy mix would reduce the CO_2 output to about 320 g/kWh and calculations have been repeated for that value. (It should be noted that this represents a relatively modest improvement in grid electricity emissions performance in light of the aim to achieve a 60% reduction by 2050 as indicated earlier in Section 2.1).

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[10] Digest of UK Energy Statistics 2005, Table 5C

[11] The atomic weight of carbon is 12 and oxygen 16. one molecule of CO_2 is thus (12+16x2)/12 times heavier than an atom of carbon.

[12] Some other public domain figures give higher values of CO_2/kWh, as this relates to each kWh at point of use. However, which ever method is used the outcome is comparable.

2.2 UNITS AND METRICS FOR THE INDUSTRY

Assessing rail vehicles by the mass of CO_2 produced per passenger-km cannot avoid the fundamental question of how many passengers there are in a vehicle. The following graph, based on data provided by ATOC, shows the average load factor for 26 train operating companies (TOCs) in 2005/06.

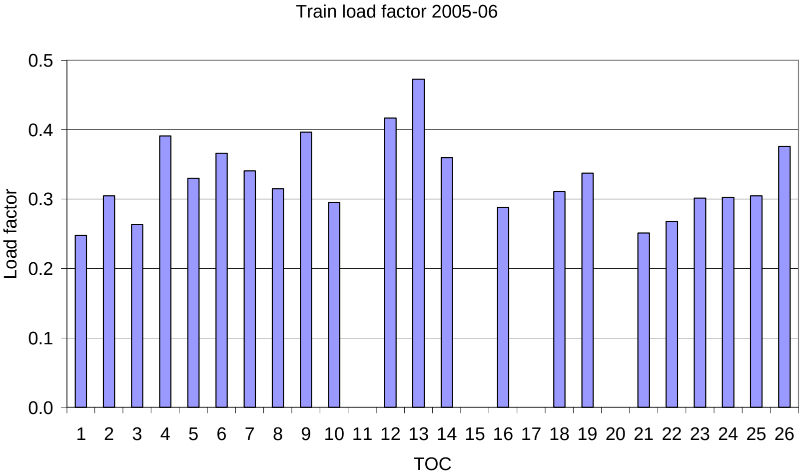

Figure 4: Comparison of GB Domestic Train Operating Company Load Factors

It can be seen that the GB domestic load factor varies by almost 2:1 from 25% to 47%. This is, to a large extent, determined by the type of service – TOCs serving a predominantly commuter market, where trains in one direction are heavily loaded for 3 hours in the morning and in the other direction for 3 hours in the evening, find it more difficult to maintain load factors than long-distance operators. It is clear from these data that using a metric such as kWh/passenger-km is dominated by how many passengers wish to travel or how well the TOC manages to vary the capacity of the service hour-by-hour to match the load, rather than by the efficiency of the rolling stock. (Note: there are gaps in the data where information was not available or where services carry a significant proportion of passengers travelling on non-standard rail tickets.)

Most of this report keeps data for electrically-powered vehicles and diesel-powered vehicles separate. Energy consumption of the former is measured in **kWh/seat-km** and of the latter in **litres/100 seat-km**. The former is readily understandable by anyone who pays an electricity bill and the latter is directly comparable with the road vehicle industry that measures car fuel consumption in litres/100 km.

When making comparisons between electrically-powered vehicles and diesel-powered vehicles the energy consumption of both has to be in the same units. Merely comparing the chemical energy in the fuel that is poured into a diesel tank with the electrical energy delivered to the pantograph would be unhelpful as the former has to be transformed into mechanical energy by a prime mover with an efficiency of 20 – 30% while the latter is already in a form that can be used with an efficiency of up to 85%. Some previous studies have attempted to convert all energy into tons or oil equivalent (toe) but this is open to challenge as efficiencies change with time.

From an environmental perspective, what is important is the amount of greenhouse gases produced by each transport mode. For that reason, we have not made any attempt to compare the energy use of different modes but have, instead, compared the CO_2 emitted either by the train itself or by the power stations feeding the line. It should be noted that this report uses measures of CO_2, not carbon. The conversion from one to the other is easy to make – a molecule of CO_2 has one carbon atom (atomic mass 12), and 2 oxygen atoms (atomic mass 16 each) so 1 kg of carbon is equivalent to (12 + 2 x 16)/12 kg of carbon dioxide. The units we have used for CO_2 emission are **grams/seat-km**. This is directly comparable with the data in the road vehicle industry which uses grams/km.

Because the average load factors of certain transport modes are higher than others, it has been necessary to use **grams of CO_2 /passenger-km** when making intermodal comparisons.

3 ENERGY CONSUMPTION OF GB TRAINS

3.1 METHODOLOGY

Some bodies publish aggregated figures for energy use by different transport modes in which the passengers carried and energy consumed by commuter stock and intercity trains are combined; in our view this is not particularly helpful as a management tool, but may be useful in considering broader energy issues. We have therefore analysed several different trains and have presented their energy consumption in terms of litres/seat-km or kWh/seat-km over typical routes. As agreed with the stakeholders,[13] this section of the study concentrates on the energy (kWh) measured at the pantograph or fuel (litres) delivered to the tank. It does not take account of losses in the supply system.

As discussed elsewhere in the project there are a number of factors that can influence energy use including: driving style, use of regenerative braking, number of signal checks, amount of coasting built into the timetable, and the energy used in stabling and station layovers. There are also at least three different methods of calculating energy use: by computer simulation, by measurement of fuel delivered to a depot or energy supplied from a substation, or by data from an on-board computer, which controls most trains built in the last 20 years. The last method is usually unable to distinguish between train heating energy and traction energy and measuring at the substation obviously includes system losses. Train simulation can assume "all out" running or can incorporate coasting and defensive driving techniques, which can make 20% difference to energy use.

As far as possible, we have tried to take as many different sets of data for each train service, compare them and form a view, based on the likely accuracy of each, of what is a reasonable compromise value for further analysis.

The trains analysed are:

Diesel trains:

- Class 170 Turbostar
- Class 180 Adelante
- Class 220/221 Voyager
- Class 222 Meridian
- Class 43 + Mk 3 coaches, HST

Electric trains:

- Class 357 Electrostar
- Class 373 Eurostar
- Class 390 Pendolino
- Class 458 Juniper
- Class 460 Juniper
- Class 90 + Mk 3 coaches
- Class 91 + Mk 4 coaches, IC225

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[13] Meeting at RSSB, 17 November 2006

3.2 DIESEL-POWERED PASSENGER TRAINS

CLASS 170 TURBOSTAR

The Class 170 Turbostar is either a 2-car or 3-car DMU, powered by respectively 2 and 3 MTU 315kW engines.

Figure 5 Class 170

The ATOC study looked at the fleet of 170 units and analysed the amount of fuel used by each unit during the test period. Main characteristics of the fleet and results of this study are shown below:

	Class 170 3-car	Class 170 2-car
Number of trainsets	8	4
Number of weekday diagrams	7	4
Tare mass	133.7 tonnes	91.4 tonnes
Number of seats	164	119
Total fuel consumption litres	245391	95820
Total kilometres run	179991	102214
Litres per vehicle kilometre	0.454	0.469
Litres per 100 seat-km	0.831	0.788

There are some differences between 2-car and 3-car units, as would be expected as they probably have different stopping patterns and run in different train formations. The 3-car version surprisingly has a lower average number of seats per vehicle, which affects the calculation. The average of the two sub-fleets is a fuel consumption of 0.81 litres/100 seat-km and this figure has been taken for subsequent analysis.

CLASS 180 ADELANTE

The Class 180 was made by Alstom and has 19 litre Cummins engines with Voith hydraulic transmissions. Main characteristics of the fleet are shown below:

Figure 6: Class 180 Adelante

	Class 180 Adelante
Tare mass	254.8
Number of seats	268
Litres per 100 seat-km	0.98

Fuel consumption was monitored during the first year's running on the Paddington to Cardiff and Swansea services.

CLASS 220/221 VOYAGER

Figure 7: Class 221 Voyager

There are two types of Voyager train, both have similar bodies. Class 220 is a non-tilting train with a lightweight inside-frame bogie. Class 221 is a tilting train with a more traditional bogie design using a hydraulic tilt system. Both trains use the 19 litre Cummins engine with an asynchronous electrical drive system.

	Class 220	Class 221 5-car
Tare mass	185.6	282.8
Number of seats	188	246
Litres per 100 seat-km	1.20	1.20

A simulation[14] using optimised coasting gives a fuel consumption of 2904 litres for a 1000 km journey, giving an average consumption of 1.18 litres/100 seat-km. For "all out" running, the simulation gives 3413 litres for 1000 km which is equivalent to 1.39 litres/100 seat-km.

ATOC data show energy consumption on cross country services as 7.22 kWh/vehicle-km which is equivalent to 7.22/10.32 x 5/246 = 1.42 litres/100 seat-km.[15] It is difficult to see why the consumption should be as high as this and so, on the basis of the simulations and the measured values, a figure of 1.20 has been used as representative of both classes.

CLASS 222 MERIDIAN (9-CAR)

Figure 8 Class 222

	Class 222 9-car
Number of seats	478
Total fuel consumption litres	854,989
Total kilometres run	182,488
Litres per 100 seat-km	0.98

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[14] Simulation by Alstom, the design authority for the asynchronous drive system

[15] The figures quoted were taken from the ATOC study (Ref 1) and are calculated from the energy consumption figures per vehicle kilometre and per passenger kilometre for all train companies across Britain during the financial year 2005-6. They have been produced by taking the total electricity consumption billed to train companies by Network Rail and the total volumes of diesel fuel supplied by wholesalers to train companies. These numbers were then divided by the vehicle kilometres reported to ATOC in connection with the national reliability monitoring programme, and by the total passenger kilometres recorded from Rail Settlement Plan, the system that records and attributes passenger revenues across the country.

One of the train operating companies has seven 9-car Class 222 units. Each unit is powered by a 560 kW Cummins 19-litre diesel engine under each car.[16] The ATOC study recorded a total fuel consumption of 854,989 litres for a total distance run of 182,488 km.

HST (IC125) – 200KM/H INTERCITY TRAIN

The HST was introduced around 1974 in two formations, 2 + 7 and 2 + 8 (i.e. 2 power cars and 7 or 8 passenger cars) and has been the workhorse of 200km/h services on diesel-powered routes for 25 years. There are two diesel engines, each rated at 1680 kW.

Figure 9 Class 43 HST

	2+7 formation	2+8 formation
Tare mass	447 tonnes	480.6 tonnes
Number of seats	541	617
Total fuel consumption litres	-	1,259,982
Total kilometres run		300,788
Litres per 100 seat-km (simulation)	0.88 / 0.79	0.89 / -
Litres per 100 seat-km (average value)	0.85	

A simulation of train performance[17] with a 2+7 formation on the ECML shows an "all-out" energy demand of 11.9MWh for 541 seats and 447 tonnes and an energy demand of 10.7MWh with 8% coasting. These equate to 0.88 and 0.79 litres/100 seat-km.

The ATOC study of a 2+8 train recorded a total fuel consumption during the measurement period of 1,259,982 litres during which time the fleet ran 300,788 km. This gives a fuel consumption of 1,259,982/(300,788 x 473) = 0.89 litre/100 seat-km. As an average for this study, a figure of 0.85 litre/100 seat-km has been taken.

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[16] Data from Porterbrook website

[17] Alstom Transport, January 2007

3.3 ELECTRICALLY-POWERED PASSENGER TRAINS

CLASS 357 ELECTROSTAR – 25KV EMU

Class 357 Electrostar 4-car EMUs were supplied by (what is now) Bombardier from 1999. They have 6 asynchronous motors, each rated 250kW.

Figure 10: Class 357 Electrostar

ATOC collected data from on-board recorders on a sub-fleet of 10 units as well as from the power supply for the whole fleet. The trains run on a 70 km route with a maximum speed of 120km/h (75 mph).

The data are shown below.

	10 sample units	Whole fleet
Number of trainsets	-	74
Number of weekday diagrams	-	69
Tare mass	-	157.6 tonnes
Number of seats	-	282
Total energy measured	870 MWh	6629 MWh
Total kilometres run	92,228	754,386
kWh per vehicle kilometre	2.36	2.2
kWh per seat kilometre	0.0335	0.0312

An appendix to the ATOC report is a study by AEA Technology Rail (now Delta Rail) which simulated the performance of 6 train services over the same route.[18] Nos 5 and 6 were off-peak semi-fast services running a commercial timetable with a 4-car train. The others ran to a simulated timetable:

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[18] AEAT report LRGS D9365 Issue 1. Class 357 Energy consumption modelling , 4 September 2006

Run	Traction kWh (m)	Traction kWh (e)	Aux kWh	Total kWh	kWh / veh-km	kWh / seat-km
Train 1 (All Stations)	517	598	92	690	2.48	0.035
Train 3 (Semi Fast)	472	546	87	633	2.28	0.032
Train 5 (S/F t.t.)	399	463	98	561	2.02	0.029
Train 2 (All Stations)	509	588	95	683	2.46	0.035
Train 2 (Semi Fast)	465	536	87	624	2.25	0.032
Train 6 (S/F t.t.)	391	452	99	551	1.98	0.028

Taking averages of the two sets of measured results and the six simulated figures gives average energy usage of 0.032 kWh/seat-km in both cases. (The standard deviation of all measurements is 0.0026). The results are consistent with the measured results.

CLASS 373 EUROSTAR EMU

Figure 11: Class 373 Eurostar

The Class 373 is currently used for European operations principally between London, Paris and Brussels with much of its operation at high speed. Available data from in-service operations indicate that a value of 0.055 kWh/seat km (excluding transmission losses) is an appropriate value for average energy consumption and this figure has therefore been used[19].

	Class 373 2 + 18-car
Tare mass	721 tonnes
Number of seats	750
kWh per seat kilometre (average value)	0.055

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[19] Data provided by Eurostar Group Ltd

CLASS 390 PENDOLINO EMU

The specification of the 250 km/h Pendolino trains[20] is that a 9-car train has a mass of 471 tonnes and a total of 439 seats (145 First Class, 294 Standard Class). The installed power is 5.1 MW at the rail or 6.7 MW at the overhead line.

Figure 12: Class 390 Pendolino

Alstom has analysed the energy use of 7 service patterns. The Euston-Stoke-Manchester service is typical for which the simulated figures are given in the table below.

During the last quarter of 2006 energy recorded by the on-board computer was analysed and this has given lower figures, as shown.

	Class 390 9-car	Class 390 11-car
Tare mass	460 tonnes	562 tonnes
Number of seats	439	591
KWh/seat-km (simulation train running to final 2008 profile and 225 km/h PUG2 profile)	0.050 / 0.055	0.046 / -
KWh/seat-km Measured figures (Euston – Manchester)	0.032	-
KWh/seat-km (average value)	0.040	0.035

It is interesting to consider why the measured figures are much lower than the calculated figure. Because the WCML upgrade is not complete, the trains are not running to their final schedule and there is considerable slack in the timetable, which allows drivers to coast when slowing for stations or reduced speed limits. (Many passengers from Euston to Lancaster have commented that a train can be 15 minutes late at Stafford and yet still arrive on time.) For safety reasons, drivers have been trained to use “defensive driving” techniques so they tend to brake early and at only about half the maximum brake rate. This means that most of the braking energy can be handled by the regenerative brake system (that puts energy back into the line).

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[20] Data from Virgin Trains on http://www.virgintrainsmediaroom.com

Data from ATOC shows that, in FY 2005/06, while the service was still constrained by the work on the track, the rate charged for electricity was 1.85 kWh/vehicle-km which gives 0.042 kWh/seat-km. Overall it seems reasonable to use a figure of 0.040 kWh/seat-km for a 9-car train and 0.035 kWh/seat for an 11-car train, recognising that it is likely to be higher than the current measured values when the 2008 timetable is introduced.

The data collected on the Pendolino trains show the importance of using regenerative braking in service. Figures from Alstom[21] show that the returned energy over a 24-hour period is between 16% and 18% of the energy drawn from the line. Energy measurements include all the electricity drawn from the overhead line, including during train preparation. The measured figure is higher than one would normally expect from an Intercity train but reflects the drivers' defensive driving, which maximises the regenerated energy, the route profile on West Coast and the high number of signal checks, due to engineering work on the WCML at the time the tests were undertaken.

IC225 – CLASS 91 LOCOMOTIVE + MK3 COACHES

The IC225 operates between London and Leeds / Edinburgh. It consists of a Class 91 locomotive, a rake of trailer cars and a driving van trailer (DVT). The simulated energy use of this train was published 13 years ago in the context of a discussion on future high speed lines.[22] This showed a total energy demand of 14.7 MWh for an "all-out" run from Kings Cross to Edinburgh with what were seen as the eventual speed limits.

Figure 13 Class 91 locomotive

	Class 91 (refurbished)
Number of seats	554
kWh per seat kilometre	0.038
kWh per seat kilometre (deducting 14% coasting)	0.032

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[21] e-mail from John Evans, 3 January 2007.

[22] Kemp, R. J. *The European High Speed Network*, Discussion Meeting at the Royal Society, *Passenger transport after 2000 AD* June 1993. (Reprinted in Passenger Transport after 2000 AD, edited Feilden, Wickens and Yates, ISBN 0 419 19470 3)

The seating capacity of the train, since refurbishment, is 554 passengers. A more recent simulation, using current speed limits, indicates a consumption of 12.7 MWh for a train running from Kings Cross to Edinburgh, a distance of 601 km.[23] This figure includes hotel services but does not include empty stock mileage or energy consumed in train preparation. Thus the average energy consumption is 12700/(601 x 554) = 0.038 kWh/seat-km. A similar calculation allowing 14% coasting has a consumption of 0.032 kWh/seat-km.

Data from the ATOC study reported that the average energy consumption of Intercity electric trains on the east coast main line (ECML) was 1.51 kWh/vehicle-km. This is based on the total energy billed to the TOC by Network Rail during FY 2005-06. On the assumption that there are 11 vehicles in a train (9 passenger cars, a locomotive and a driving trailer) that is 1.51 x 11 / 554 = 0.030 kWh/seat-km.

Intercity trains on ECML are a mixed fleet of diesel and electric trains. The former are HSTs which have two engines, each producing 1680 kW at the shaft. On the assumption that loco auxiliaries and "hotel loads" consume 300 kW and the efficiency of the traction chain (alternator, rectifier, motors, gearboxes) is 85%, the power at the rail is 0.85 x (1680 x 2 – 300) = 2.6 MW. Because most of the schedules, other than a few like *The Flying Scotsman*, are timetabled to be operable either by electric or diesel traction, the 4.4MW Class 91 locomotives are mainly being used at 60% of their nominal ratings.

On the basis of the above, a figure of 0.032 kWh/seat-km has been used in this study but it must be borne in mind that this is based on current timetables and would change if the IC225 trains were used at their full performance.

CLASS 458 JUNIPER – 750V EMU

A 4-car Class 458 unit has a mass of 164 tonnes and has 274 seats.

Figure 14: Class 458 Juniper

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[23] Simulation by M Lumley, Alstom, January 2007

	Class 458
Tare mass	164 tonnes
Number of seats	274
kWh per seat kilometre (resp without/with coasting)	0.036 / 0.024
kWh per seat kilometre (average value)	0.032

A 515 km simulation[24] full day diagram on the London suburban services showed that, with all-out running, a Class 458 consumed 4.63 MWh for traction, reducing to 2.87 MWh when coasting was used. The auxiliary load averages 60kW for either 515 minutes or 581 minutes in the two cases above. Hence the total energy consumption was simulated as 5145 and 3451 kWh respectively representing 0.036 and 0.024 kWh/seat-km.

Another simulation on the Waterloo-Reading stopping service worked out at 0.034 kWh/seat-km. Until regeneration is allowed, a figure of 0.032 has been used as typical of this class of train.

CLASS 460 JUNIPER – 750V EMU

Class 460 Juniper operates a non-stop service (up to 140 km/h) on the 750V dc line between London Victoria and Gatwick Airport using 8-car units.

Figure 15: Class 460 Juniper

	Class 460 8-car
Tare mass	317 tonnes
Number of seats	363
kWh per seat kilometre resp without/with coasting (result of simulation)	0.035 / 0.031
kWh per seat kilometre (average value)	0.032

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[24] Alstom Transport 2006

Simulations,[25] confirmed by test data, show that the 86 km round trip uses 1083 kWh all-out, including auxiliaries, dropping to 958 kWh with a 5% coasting allowance in the timetable. These are equivalent to 0.035 and 0.031 kWh/seat-km. ATOC data show an energy use of 1.90 kWh/vehicle-km which corresponds to 1.90 x 8/363 = 0.042 kWh/seat-km.

Why is the figure charged by Network Rail higher than the simulated figure that has been supported by tests on the vehicle? This appears to be because the NR figure is measured at the substation and the 750V system has higher losses, in comparison with 25 kV systems. (If the substation output is 780V and the voltage at the train is 650V, the efficiency is 0.83, which is the difference between these figures.)

This report is looking at the energy at the pantograph (or shoe) and so a figure of 0.032 kWh/seat-km will be used.

CONCLUSIONS

The following graph shows the fuel consumption of diesel trains considered above.

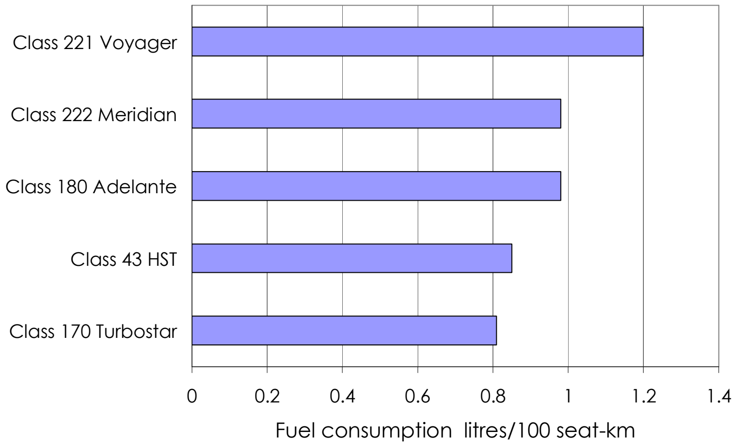

Figure 16: Fuel consumption of GB diesel trains

It can be seen that consumption increases roughly in line with the installed power. The difference between the Class 221 Voyager and the Class 222 Meridian is probably related to the route characteristics and the number of station stops and signal checks on the Cross Country service, in comparison with the relatively straightforward route on the Midland Main Line.

The graph below pulls together the data on electric trains. The analysis has covered a wide variety of rolling stock from 120 km/h suburban commuter vehicles to 300 km/h international trains. Surprisingly, the energy per seat-km is similar for many of the trains. The Class 390 Pendolino trains use regenerative braking and this reduces their energy demand in comparison to some other trains.

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[25] source Alstom Transport

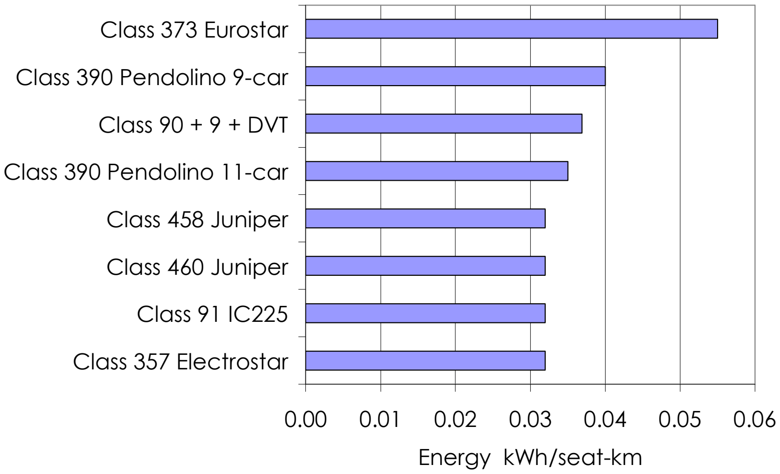

Figure 17: GB Electric trains energy/seat

It can be seen that many domestic trains use around 0.032 kWh/seat-km with the Pendolino taking about 25% more than this. The Class 91 uses much the same as the slower Class 357 Electrostar, probably because it is running a more relaxed timetable with fewer station stops. Whilst Class 373 Eurostar energy use is significantly higher it is unique within this group as it is a high speed train designed specifically for pan-European operations. This vehicle class is considered more fully in Section 4.4.

Not shown in this graph is the effect of regenerative brake, other than for Pendolino . If applied to the Classes 458 and 460, this would reduce the overall energy to below 0.03 kWh/seat-km.

3.4 COMPARISON OF DIESEL AND ELECTRIC TRAINS

For purposes of comparing electric with diesel traction or the rail system with other transport modes, it has been necessary to express all the figures to a common reference. Following discussions with RSSB and other stakeholders, it was decided to convert figures to use g/seat-km of CO_2 emissions. It is recognised that there are other greenhouse gases and other detrimental effects of energy use but CO_2 is the standard for other transport industries. (NB: this is the mass of CO_2, not mass of carbon, which is used in some environmental papers.)

For **diesel-powered trains**, the primary fuel has been taken as crude oil entering a UK refinery. A standard efficiency figure of 90% [26] has been used to take account of refinery and transport losses. There seems little point in analysing the oil extraction process and comparing, for example, the North Sea with Iranian production as these considerations apply equally to competing transport modes. Transport of diesel from the refinery to a

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[26] BP claim an energy efficiency in their refining business of 95.3% in 2005 (BP's 2005 sustainability reporting) which is comparable with an assessment by Zoran Milosevic and Wade Cowart of KBC Process Technology, Houston, Texas of 95% for a global average. From this must be subtracted energy used in the transport of oil products.

running depot is considered to be included in the above figure. We have used the conversion of 1 litre diesel/100km gives 26.5 g CO_2. (This is the conversion factor used by car manufacturers carrying out tests in accordance with EEC Directive 1999/100/EC.) Strictly speaking, the GB rail industry uses a high-sulphur gas oil which has a slightly different energy density but it was decided to use a common figure for all liquid fuel comparisons, in order to simplify calculations – the errors introduced are minor compared with other tolerances in the analysis.)

For **electrically-powered trains** calculations have taken into account the fuel used to generate the electricity. It has also been assumed that the electricity used by the railway has the same generation mix as the national average as described earlier in Chapter 2.1. We have used the figures calculated earlier of 455 g of CO_2 /kWh for 2007 and 320 g for 2022 (15 years time, which takes into account anticipated changes in emissions from the electricity supply industry). An efficiency of 0.9 from the power station output to the train pantograph / shoe gear has been assumed.

The following graph shows the calculated grams of CO_2 per seat-km for the GB trains studied above. Data for electric trains corresponding to the 2007 electricity generation mix are shown in green; those corresponding to an assumed 2022 generation mix are shown hatched. Data for diesel trains (Classes 43, 170, 180, 221 and 222) are shown with a blue bar. As the change in energy mix for electricity generation has no effect on diesel trains, the blue bar remains unchanged over the time span.

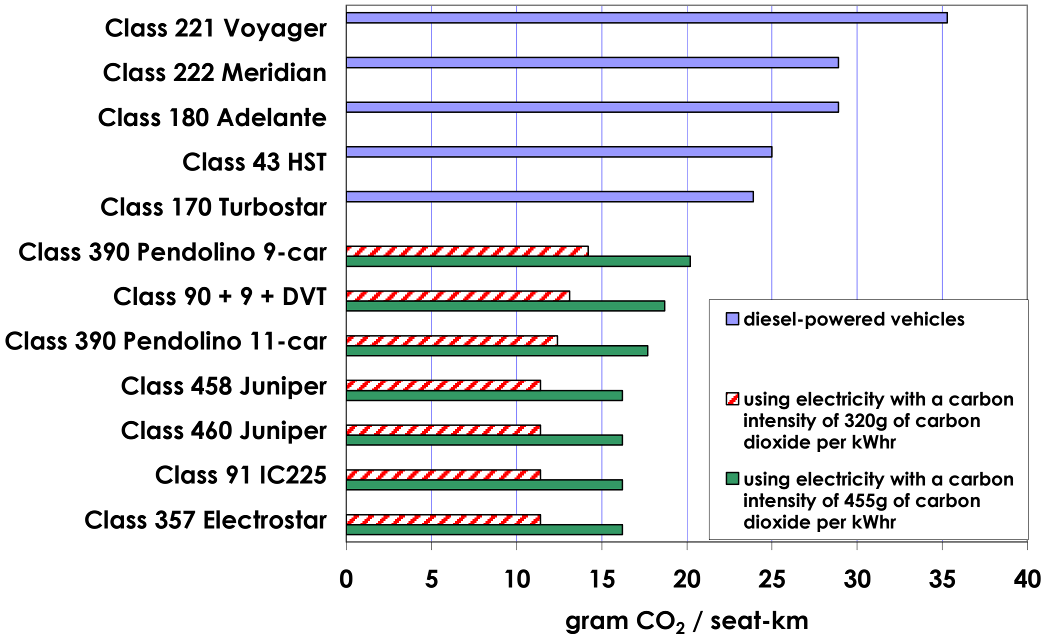

Figure 18: Grams of CO_2 per seat-km for GB Domestic trains

It can be seen that diesel trains create significantly more CO_2 than do electric trains. (They also produce more local pollution in terms of SO_2, oxides of nitrogen and particulates, but that is not the purpose of this report.) With the assumed 2022 fuel mix all the electric trains are better than any diesel train.[27]

Consideration was given to projecting efficiency improvements for diesel trains over the duration of the study, as has been done with passenger cars. However this was rejected because it was not felt to be likely during the timescale under consideration. Trains are designed for an operating life of c. 30 years. Since the privatisation of the rail industry, a large number of new trains has been delivered and, at present, there are no trains on order significantly different to the present fleet in terms of energy use or emissions. With the exception of the HST, GB has a relatively young fleet of diesel passenger trains, most of which will still be in service in 2022. While companies are researching innovative technical solutions to reduce train energy use (hybrid drive systems, flywheels, super-capacitors, composite structures, etc.) it seems unlikely that these will have a significant impact on average energy use in this timescale.

Road vehicles, on the other hand, have a much shorter design life and there is a thriving second-hand market that recycles high-mileage vehicles to low-mileage uses after 5 years or less. When looking at emissions with a time horizon of 2022, it is therefore reasonable to assume that trains will be much the same as today but that cars will show progress towards reduced EU emission standards.

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[27] Note that this calculation uses the UK average CO_2 emissions per kWh as described in chapter 2.1 .

4 INTERNATIONAL COMPARISONS

4.1 METHODOLOGY

There are many hundreds of railways around the world but only a proportion are comparable with the GB main line railway. Factors that have to be taken into account include the relative proportions of freight and passenger traffic, route characteristics and the length of traffic flows. Most American networks are primarily freight lines with passenger trains representing a small proportion of traffic. Some passenger trains are designed for very long distances with facilities (such as sleeping and dining cars) for that service. At the other end of the scale, many lines in less densely populated countries operate over very tortuous routes at much lower speeds than in the UK and passengers on some rail systems are prepared to tolerate levels of crowding and ambient temperature that would be considered unacceptable in the UK.

Against this background we have selected a number of rolling stock examples as comparators of relevant current practice. In some of the projects examined, energy consumption is lower than in comparable British projects. Where this is the case, the reasons have been analysed. In some cases these relate to the smaller GB loading gauge (which could be enlarged, but at a high price) or to specific safety features of the trains being considered. It is not an objective of this report to make recommendations about whether safety regulations represent good or bad value for money (or energy) but, clearly, there is a balance to be struck between the desire for safety, the desire for a low environmental footprint and the desire to make the transport system inclusive.

4.2 SHINKANSEN 700

The Japanese Shinkansen high-speed trains are well-known for paying attention to energy efficiency. Taniguchi[28] claims an energy consumption of 0.03 kWh/passenger-km for the Shinkansen services. However it is not clear from the English summary whether this is really per passenger-km or per seat-km. Other figures from Takagi[29] give 14.7 kWh/seat for the total energy usage of the Shinkansen Series 700 trains running between Tokyo and Osaka, a distance of 500 km. This represents 0.029 kWh/seat-km for a train with an operational speed of 300 km/h, which supports Taniguchi's figure as being "per seat".

	Shinkansen 700
Number of seats	1323
kWh per seat kilometre	0.029

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[28] Mamoru Taniguchi, High Speed Rail in Japan: a review and evaluation of the Shinkansen train; UCTC Working Report No. 103, California High Speed Rail Project

[29] Ryo Takagi, University of Birmingham School of Engineering; Development of Low-Energy-Consumption Trains in Japan; 26/11/2005

Figure 19: Shinkansen 700

Why does this train use less than 70% of the energy of some British intercity trains discussed earlier, despite travelling faster? Part of the reason is that the Shinkansen railcars have a width of 3.4 metres, as opposed to 2.8 metres in the UK, which allows 2 + 3 seating throughout the standard class coaches. A 400 metre trainset holds 1323 passengers, compared with 524 passengers for the IC225, in a little more than twice the length. Passenger capacity is also improved by having proportionately less space taken up with areas from which passengers are excluded for safety reasons.

Apart from size, the long nose of the train (which would be prohibited on Network Rail due to the unprotected overhang at switches and because it would foul platform edges) has been designed to minimise drag, as has the fairing of the pantograph and the design of the below-floor area. However, much of the impetus for improving aerodynamics came from the need to reduce trackside noise and pressure pulses on tunnel entry. Reducing drag has been a long objective of the Shinkansen programme. A Japanese report[30] describes how traction energy was reduced from 42.0 to 33.3 and 29.8 kWh/km for series 0, 100 and 300 Shinkansen trains by attention to the design.

4.3 SCANDINAVIAN EMU TRAINS

Evert Andersson and Piotr Lukaszewicz have analysed the energy consumption of five types of train in use in Scandinavia.[31] Details of these (taken from their report) are given below. In addition the Arlanda Express, exported from the UK, has been included.

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[30] Takafumi Nagatomo et al., Preliminary investigation into lifecycle assessment of Shinkansen vehicles, Railway Technical Research Institute, Kokubunji-Shi, Tokyo 185, Japan.

[31] Evert Andersson & Piotr Lukaszewicz, *Energy consumption and related air pollution for Scandinavian electric passenger trains*. Report KTH/AVE 2006:46, Royal Institute of Technology, Stockholm, Sweden (39 pages)

HIGH-SPEED TRAIN X 2000

The Swedish high-speed train X2000 is used for premium long-distance services between major cities in southern and central Sweden, a market sector roughly equivalent to "intercity" in the UK but serving smaller conurbations. X2000 trains provide services on the lines Stockholm - Göteborg (455 km), Stockholm - Malmö - København (661 km), Stockholm - Sundsvall (402 km) and Göteborg - Malmö (306 km). Speeds are usually 180 - 200 km/h on these lines, although short sections have lower restrictions.

REGINA REGIONAL TRAINS

The services called "Tåg i Mälardalen" (TiM) are connecting cities around lake Mälaren, including Stockholm, Västerås, Eskilstuna, Örebro, Uppsala and others. The nearest GB equivalents are "regional services". This is a fast regional service on intermediate distances (100-200 km), with scheduled stops at a distance of about 25 km on average. The maximum permissible speed is 200 km/h on about 60 % of the lines, otherwise 120-160 km/h.

ØRESUNDSTOGET (OTU)

Øresundstoget - also called the Øresund Train Units (OTU) - run fast regional services over the Øresund link (including the bridge) between Sweden and Denmark. The Øresund region includes the Danish capital København, and the Swedish third city Malmö, as well as a number of medium-sized other cities. Scheduled stopping distances are about 18 km in Sweden and 5 km in Denmark. Maximum speed is usually 140 - 180 km/h, but parts of some lines are more restricted.

FLYTOGET

Flytoget - officially designated as Type 71 - is a Norwegian dedicated high-speed airport shuttle train to and from the Gardermoen airport, serving Oslo city (49 km) and the line to Asker on the other side of Oslo city (25 km away). This is directly equivalent to Gatwick Express or the Stansted Express trains in the UK. Almost half the trains are non-stop between Oslo and Gardermoen. These trains cover the distance of 49 km in 19 minutes. Maximum speed is 210 km/h on the new line between Oslo and Gardermoen, of which a considerable part is laid in tunnels. Speeds between Oslo and Asker are lower. Between Oslo and Asker there are 4 intermediate stops. Many trains also stop at Lillestrøm between Oslo and Gardermoen.

SIGNATUR

Signatur - officially designated Type 73 - is a long-distance train serving the electrified main lines in southern and middle Norway. The trains are mainly serving the main lines Oslo - Trondheim (553 km), Oslo - Bergen (489 km) and Oslo - Kristiansand - Stavanger (587 km). Generally these lines run in mountainous regions, they have partly considerable gradients and many curves, although parts of the lines are straighter. Maximum speed is 210 km/h, but Signatur operations are - despite the tilting carbody and its increased speed in curves - more typically run at speeds between 100 and 160 km/h due to frequent curves. The nearest GB comparator, in terms of passenger use, is probably the Virgin Voyager service between Aberdeen and Birmingham, but that is diesel-hauled, not electric.

Photos of the trains are shown below:

Figure 20: X2000

Figure 21: Regina

Figure 22: Øresundstoget

Figure 23: Flytoget

Figure 24: Signatur

Figure 25: Arlandabanan

One might expect the energy consumption of Scandinavian trains to be at the higher end of the spectrum because of the low population density (hence short trains), mountainous terrain with many lakes (twisting routes) and extreme winter conditions (high auxiliary loads). It must be easier to run an efficient service between, say, London and Bristol than between Oslo and Bergen.

In the tests, energy measurements were generally made from the on-train computer systems. There are considerable seasonal variations in train energy consumption, due to the heating load. Swedish examples indicate some 10-15 % higher energy consumption for propulsion and comfort during January and February than the annual average. Due to this, and due to the limited number of energy measurements, the authors estimate possible errors in some measurements of 10-15%.

Train type	Formation	Mass	Seats	Speed	Energy/ train-km	Energy/ seat-km
		tonne		km/h	kWh	kWh
X2000	P+5T+DT	366	320	200	11.7	0.037
Regina 2-car	M+M	120	167	200	5.9	0.035
Regina 3-car	M+T+M	165	272	200	8.3	0.031
Øresundstoget	M+T+M	157	237	180	6.1	0.026
Flytoget	M+M+M	168	168	210	7.5	0.045
Signatur	2M+T+M	233	227	210	8.2	0.036

ARLANDABANAN

The calculations for the Arlanda Express train were separate from the above measurements.[32] Each 4-car unit has 256 seats and a mass of 220 tonne fully laden; the round trip is 80 km, and is timed to take 55 minutes; the service is roughly equivalent to Heathrow Express or Gatwick Express in the UK. Net energy consumption is 795 kWh (in summer) which is equivalent to 795/(80 x 256) = 0.039 kWh/seat-km

4.4 ENERGY CONSUMPTION OF HIGH-SPEED TRAINS

In most countries high speed trains, such as TGV, Shinkansen or ICE, operate over segregated tracks at speeds of more than 250 km/h and have a different stopping pattern to conventional trains. It is therefore inappropriate to make a direct comparison between the two categories. The figure below compares two groups of high speed trains (European and Japanese), capable of operating at over 250 km/h sorted within each group in order of maximum speed.[33]

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[32] Data provided by Alstom Transport

[33] Data on TGVs and ICE from SNCF. Data on Shinkansen Series 0 – 300 . Nagatomo, T, Miyauchi, T and Tsuchiya, H. *Preliminary investigation for life cycle assessment of Shinkansen vehicles*, Railway Technical Research Institute, Japan Data on other trains from earlier sections of this report.

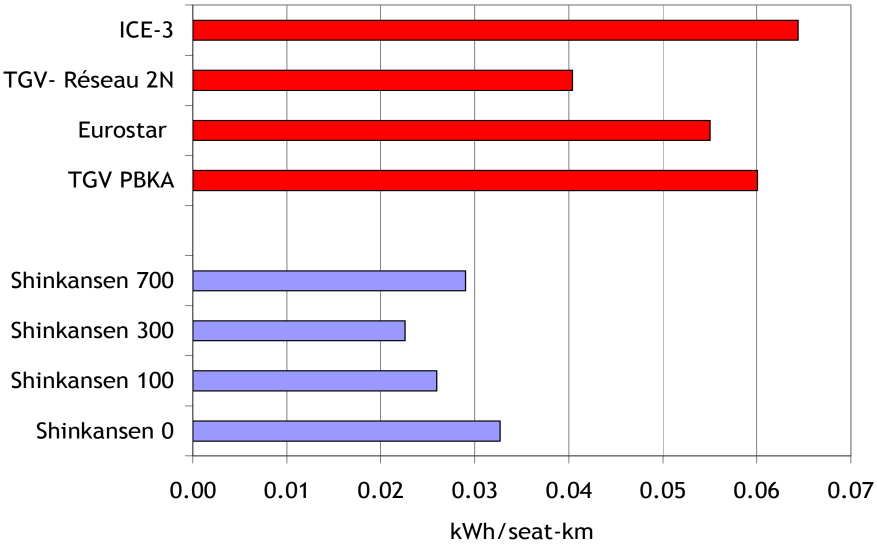

Figure 26 : Comparison of high speed trains

The above graph can only give an approximate picture of energy use as the available data does not distinguish between factors such as variations in journey speed, geographical route profiles, spacing of intermediate station stops, and there is no standardisation of the make-up margin built into timetables. Also different administrations have differing requirements relating to seat pitch, catering and so on which affects the number of seats per unit length of the train. They are arranged in 2 groups, European and Japanese, with the more recently built trains above the earlier trains. In general the more recent trains have a higher maximum speed but this is not definitive as the operating speed is often determined by infrastructure limits, rather than the capability of the vehicles.

It can be seen that the European high speed trains are fairly similar in terms of their energy consumption. Within tolerances of the analysis, Eurostar is comparable with TGV PBKA, which is to be expected as they are both second-generation single-deck TGVs. Within this group the TGV Réseau -2N is clearly superior for routes where the loading gauge can accommodate taller double-deck trains. This design achieves 50% more seats in the same train length with minimal increase in energy use. The Japanese high speed trains are significantly more energy-efficient, mainly due to their lower mass and higher seating capacity allowed by a lower crash load specification and larger loading gauge.

4.5 EFFECT OF SPEED

It is interesting to compare the effects of increasing the operational speed on energy consumption. The following graph shows data energy consumption data for various single-deck European trains (Øresundstoget, Regina, Arlandabanan, Class 90, X 2000, Class 91, Class 390, Flytoget, Eurostar, TGV PBKA, and ICE-3) plotted against maximum speed. The data were filtered to remove Shinkansen trains as the effects of greater efficiency, described in the above section, swamped the effect of speed.

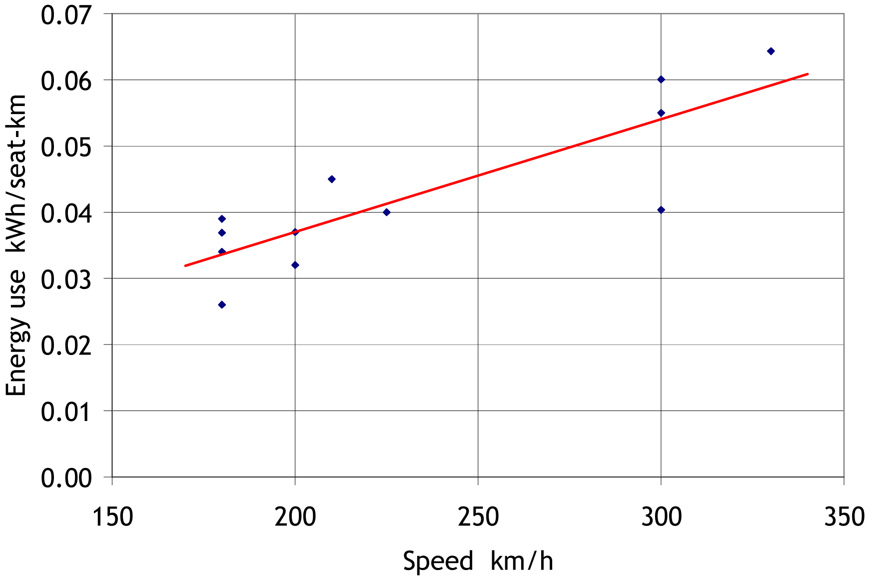

Figure 27: Effect of speed

4.6 EFFICIENCY OF TRAIN DESIGN

Several authors have emphasised the importance to energy efficiency of maximising the number of passengers per unit train length and minimising the mass per unit length. Ryo Takagi, in the report referred to above, calculated the mass per unit length of European and Japanese trains and Lagneau[34] also compared mass per seat and seats per unit length of high-speed trains. Data from these studies are combined in the table below.

The following graph shows overall train mass per unit length (tonnes/metre). It is seen that, over 40 years, the mass has been in the range 2.4 to 1.8 tonnes/metre and, where concerted efforts have been made, a fall of 25% has been achieved relative to previous vehicles of the same type. The average of all trains considered is just over 2 tonnes/metre and the Class 390 Pendolino is 6% worse than the average but 30% worse than the best in class – the Shinkansen 700.

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[34] Henri Lagneau, Guy Murry & Jürg Zehnder, *Les structure des véhicules*, Revue Générale des Chemins de Fer. No 7-8, July – August 1991

Train type	Cars	Seats	Tare Mass t	Length m	Mass/ Length t/m	Seats/ metre	Mass/ seat t/seat	Max Speed km/h
Shinkansen 0 (1964)	16	1285	967	400	2.42	3.21	0.75	220
Shinkansen 100 (1980)	16	1285	927	400	2.32	3.21	0.72	220
Shinkansen 200 (1985)	12	885	714	300	2.38	2.95	0.81	240
Shinkansen 300 (1991)	16	1321	740	400	1.85	3.30	0.56	270
Shinkansen 700 (1998)	16	1323	634	400	1.59	3.31	0.48	270
TGV-PSE (1981)	10	384	380	200	1.90	1.92	0.99	270
TGV-A (1989)	12	485	440	237	1.86	2.05	0.91	300
TGV PBKA (1990)	10	485	385	200	1.93	2.43	0.79	300
Class 373 Eurostar (1993)	20	750	723	394	1.84	1.91	0.96	300
TGV- Réseau 2N (1994)	10	545	384	200	1.92	2.73	0.70	300
Class 390 Pendolino (2003)	9	439	460	215	2.14	2.04	1.05	225
ICE (1991)	15	693	854	384	2.22	1.80	1.23	280
ICE-3 (2000)	8	415	409	200	2.05	2.08	0.99	300
ETR 450 (1998)	8	368	368	208	1.77	1.77	1.00	280

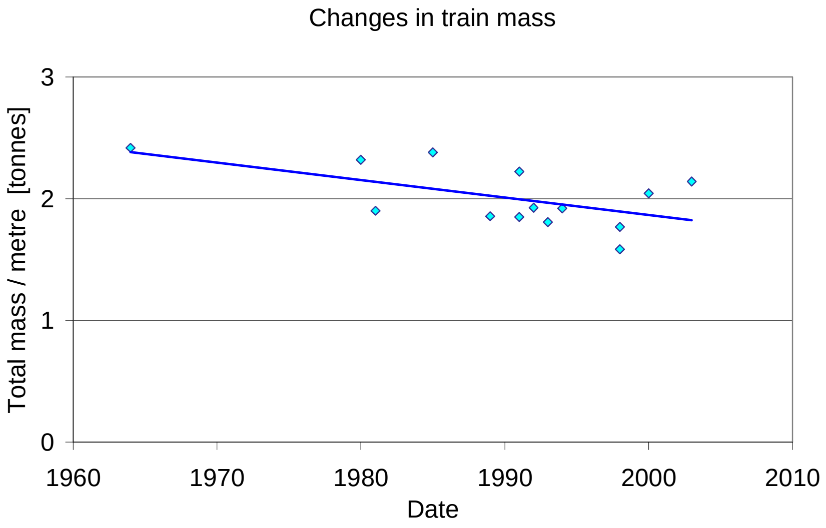

Figure 28: Changes in high-speed train mass over time

5 INTER-MODAL ANALYSIS

5.1 METHODOLOGY

Two different techniques can be used to compare the environmental impact of two or more different transport systems. The first calculates an average figure for fuel consumption based on a mixture of routes. The advantage of this method is that it gives a single authoritative figure. The disadvantage is that mixing the results for unspecified services with very different characteristics makes the final figure of limited value and the results are always open to challenge.

The second method, which has greater granularity, is to analyse specific journeys, that are broadly representative of how competing transport systems might be used, and to calculate the energy used by different modes in each case. For example, one might consider two people travelling together from Luton to Livingston by train, air or road and look at the total primary energy used for the trip. Other examples might be a single person commuting from Bristol to Swindon by train or car or a family of four going on holiday from Wolverhampton to Exeter. The advantage of this method is that by looking at specific cases it is easier to make accurate comparisons. The disadvantages are that results can be quoted out of context or special interest groups can find a figure that supports a particular case forgetting the details of the scenario to which it relates. This has happened with previous work at Lancaster University when figures for a 350 km/h line have been widely quoted as though applicable to all rail travel.

In consultation with stakeholders,[35] it was suggested that some analysis should be undertaken of journeys that start in the suburbs of one city and end in the centre of another – a typical business trip. However it has been difficult to identify journeys where one mode is not intrinsically favoured over another. For example, Reigate to Edinburgh favours air, Stevenage to Edinburgh favours rail and Luton to Edinburgh favours air or road; the decision on which to choose risks predetermining the outcome. For long trips (London to Manchester or further) the contribution to energy use by travel to a train station or airport is small and so it has been decided to consider only point-to-point energy use, rather than actual journeys.

It was also agreed that air should be considered as a competitor on London-Manchester or greater distances but could be ignored for shorter trips, such as London-Birmingham.

JOURNEY TIME

It is sometimes argued that it is inappropriate to compare the energy consumption of a 125 mph train with that of a car operating on roads restricted to 70 mph[36] and that the speed of the train should be reduced to a number that is closer to the competition, with a consequent reduction in energy use. We are not convinced by this argument as what is

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[35] Meeting at RSSB, 17 November 2006

[36] See, for example, Railwatch December 2004

important to passengers is the end-to-end journey time, including travel to a station, parking, buying a ticket, etc.

Using the National Rail Enquiries and the RAC Route Planner websites, we have compared end-to-end timings for a number or journeys. To give one example, Slough to Edinburgh is shown to take between 6h 36m and 7h 38m by rail, to which has to be added 30 to 45 minutes getting to and from the stations making the total trip 7 to 8½ hours. The road travel time is shown as 7h 4m to which might be added an hour for breaks, adding up to much the same overall time. There are obviously particular trips – including many into central London – where the train is faster than the competition but we have seen no evidence justifying a modification of the energy demand of different transport modes as a function of their maximum speeds.

COMPARABILITY

If a study compares two similar vehicles, for example, a Virgin Voyager with a First Great Western Adelante, a Ford Mondeo with a Vauxhall Vectra or a Boeing 737 with an Airbus 321, it would be possible to simulate their performance and/or test them over a typical route. Although the absolute energy consumption may not be representative of the situation in service, differences of 2 or 3% between calculated values would be significant to the way the different vehicles performed. However a study comparing different transport modes could have larger intrinsic error bands. For example, the raw data might show that the energy use of a railway starting in a city centre is 5% greater than of a coach service starting at an out-of-town terminus but the energy cost of getting to the out-of-town terminus could add 10% to the average passenger which would reverse the statistic. On all modes considered there are variations depending on exactly how a service is operated, what slack is left in the timetable, etc. For example, a report on energy efficient flying techniques[37] lists a dozen technical factors, such as rate of climb, position of centre of gravity, and cruise altitude that can affect energy consumption – and that is before considering air traffic delays, security restrictions or the weather!

Because of these factors, the consumption figures used in this study are unlikely to be more accurate than ±10%. It is entirely possible that the figures for one mode will be +10% while those for another -10%. Thus any difference less than 20% between modes could be the result of a real difference or merely the way data has been gathered.

5.2 PASSENGER CARS

The European Community's strategy is to reduce average carbon dioxide emissions from new passenger cars to 120g/km by 2010, compared to the 1998 estimated average level of 186g/km. The strategy includes voluntary agreements with the European, Japanese and Korean automobile manufacturers to reduce average carbon dioxide emissions from new passenger cars to 140g/km by 2008. Assuming the life of existing

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[37] Airbus; *Getting to grips with fuel economy*, Issue 3 - July 2004

vehicles is around 10 years, we can expect the average for the vehicle fleet to approach these values by about 2020. The fuel consumption of newly registered 2-wheel drive petrol vehicles is shown in the following graph:[38]

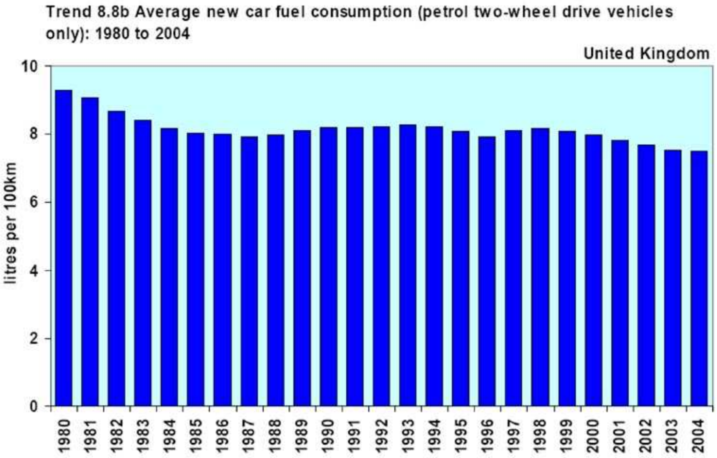

Figure 29: Trend in new car fuel consumption

However there are two problems in using national statistics to provide a comparator for rail vehicle energy use. The most obvious problem is that the EU statistics and the DfT data on emissions of new cars do not include diesels, SUVs[39] and some hybrid vehicles. Thus the graph above may not be representative of the vehicles in use. Non-inclusion of diesel cars will tend to over-estimate road fuel use while non-inclusion of SUVs will under-estimate it.

The second is that the fleet consists of larger and smaller vehicles. The former are most likely to be used by higher socio-economic groups who predominate in the rail market, particularly business travellers. These groups have also been shown to travel a higher annual mileage than lower socio-economic groups, so larger cars are likely to be driven a greater distance than smaller cars. The fact that the average emission of *each* car in use in 2005 was x g/km of CO_2 does not mean that the average of *all* emissions divided by the total km run was also x g/km. And using the average value will understate the additional emissions of transferring from rail to road transport.

As part of the research we have carried out two surveys of vehicles used by people who park at train stations on the basis that, if passengers do not take the train, these are the vehicles that are likely to be used. (This argument is not particularly reliable as drivers may have two vehicles, a small one for driving to the station and a large one for long trips. Alternatively rail users may have a thirsty "old banger" they use to drive a few miles to the station while other family members use an efficient modern diesel and, were they to make the trip by car, they would take the more efficient car. Also, as many cars do not have badge detail of their engine size or fuel type, there is necessarily some

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[38] Transport Trends 2005, Office for National Statistics and Department for Transport

[39] Sports Utility Vehicles (SUVs) a generic term for off-road 4x4 vehicles used as passenger cars.

guesswork as to their fuel consumption. However, we have not been able to devise a more appropriate method of assessing car fuel consumption without getting involved in time-consuming passenger surveys.)

Bearing in mind these possible problems, two studies were undertaken. The first, by Phillip Hinde of ATOC, was a survey of 135 cars at Etchingham at 15:00 on Friday 1 December 2006. The second, undertaken by Robin Harrison and Robert Foxon, students at Lancaster University, surveyed 110 cars at Preston Station on the afternoon of Wednesday 13 December 2006. These data are shown in Appendix A. The average fuel efficiency of the vehicles in the first study was 8.0 litres/100 km and, for the second study, 6.5 litres/100 km was calculated. Bearing in mind the relative accuracy of the two studies and the data from Transport Trends, it seems reasonable to take an average fuel consumption of passenger vehicles of 7.0 litres/100 km (40 mpg). On the assumption that, on average, cars have 5 seats, this is 1.4 litres/100seat-km.

5.3 BUSES

The original intention was to analyse buses that ran on routes parallel to particular train services but it was not possible to obtain data. However fuel consumption figures have been obtained for a number of services operated by Stagecoach in the Lancaster area and four of these have been used as comparators.

The first is a traditional double-deck urban bus, the Dennis Trident. Most of the 12 in this sub fleet are about 15 years old and have 87 seats with 5 standing places, a total of 92 passengers. The fuel consumption is 0.50 litre/km (5.63 mpg) or 0.54 litre/100 place-km.

Figure 30: Trident

A more modern comparator is the MAN single deck bus used, inter alia, on the route from Heysham to Lancaster University. There are 19 vehicles in this sub-fleet and the average fuel consumption is 0.385 litre/km (7.34mpg). The buses have 42 seats and 28 standing places, alternatively used for wheelchairs or buggies, so per passenger place the consumption is also 0.55 litre/100 place-km.

Figure 31: MAN

The Volvo B10 coach is used for longer distance routes and has less standing space but more seats. Seating capacity is 51 and the fuel consumption is 0.38 litre/km (7.37 mpg) which gives 0.75 litre/ 100 seat-km

Figure 32: Volvo B10

As a comparator for intercity travel, we have adopted the double-deck Stagecoach Megabus. These new coaches are described as the biggest and most modern of their kind in Britain[40] featuring air-conditioning, toilets, comfortable seats and good legroom. They can carry up to 91 passengers. The fuel consumption is 0.577 litre/km (4.9 mpg) or 0.63 litre/ 100 seat-km.

Figure 33: Megabus

5.4 AIRLINES

Most of the flights leaving UK airports are not in competition with the rail industry so a comparison of emissions is not relevant. For the main domestic routes from London to Glasgow, Edinburgh or Manchester, a plane from the Airbus 320 family is typical:

Figure 34: Airbus

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[40] http://www.megabus.com/

The main comparators that have been used in this paper are the Bombardier Q400, as used by flybe for routes like Manchester to Exeter, and the ATR 72. Both are very relevant as comparators for Cross-Country services.

Figure 35: Bombardier Q400

Figure 36: ATR 72-500 turboprop

SOURCES OF DATA

Most airline operators publish environmental reports detailing the amount of fuel used in providing their services. As an example, the graph below shows CO_2 emissions per passenger kilometre declared by Lufthansa for the period 1995 to 2005.[41] It should be noted that this relates to all Lufthansa flights, including intercontinental flights.

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[41] Lufthansa sustainability report 2006

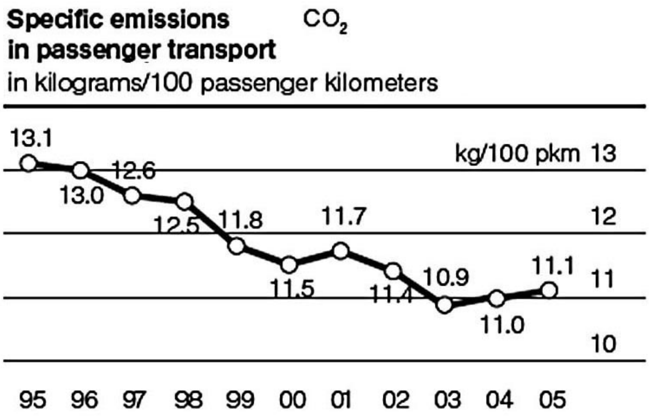

Figure 37: Emissions data from Lufthansa

CO_2 emissions in recent years are 11kg/100 pass-km (or 110 g/pass-km). Another European airline, Finnair, declares CO_2 emissions of 1.030 kg/RTK for 2004 (where RTK = revenue tonne kilometre).[42] If we make the assumption that the average mass of a passenger plus baggage is 100kg, that represents 100g CO_2/pass-km, about 10% lower than Lufthansa. Unfortunately they do not give seat occupancy to allow a conversion to CO_2/seat-km.

The Japanese airline ANA provides the following information:[43]

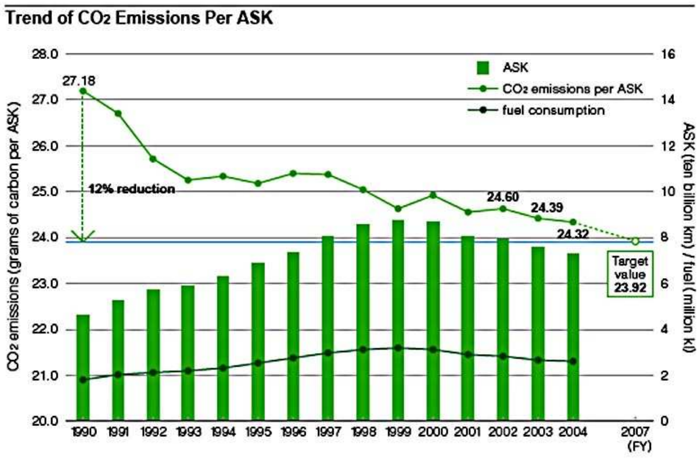

Figure 38: Emissions data from Finnair

This shows that the CO_2 emission is 24.3g carbon /seat-km or, using the ratio in an earlier footnote, 89g CO_2/seat-km.

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[42] Finnair environmental report 2004

[43] All Nippon Airlines, Approach to the Environment for Contribution to a Sustainable Society 2005

Aircraft CO_2 emissions per passenger-km are predicted to fall in future. Boeing claim that, with a typical utilisation of 70 percent, their new 7E7 "Dreamliner" will require only 2.4 litres of kerosene per 100 passenger kilometres, compared with a mid-sized car consuming 6.4 litres over the same distance.[44] [This is equivalent to 1.7 litres fuel/100 seat-km, 62g CO_2/pass-km, or 43g of CO_2/seat-km.] Airbus claim "less than 3 litres /100 pass-km" for the A380[45] However, these figures are for an intercontinental distance, not London to Manchester and exclude taxiing etc. which are included in the Lufthansa and Finnair figures. In absolute terms, emissions will rise as the annual number of pass-km is increasing faster than the improvement in CO_2/pass-km.

The following graph shows fuel consumption for an Airbus 321/100 with single class seating.[46] It should be noted that these figures are for the sector itself and are understood not to include non-revenue mileage.

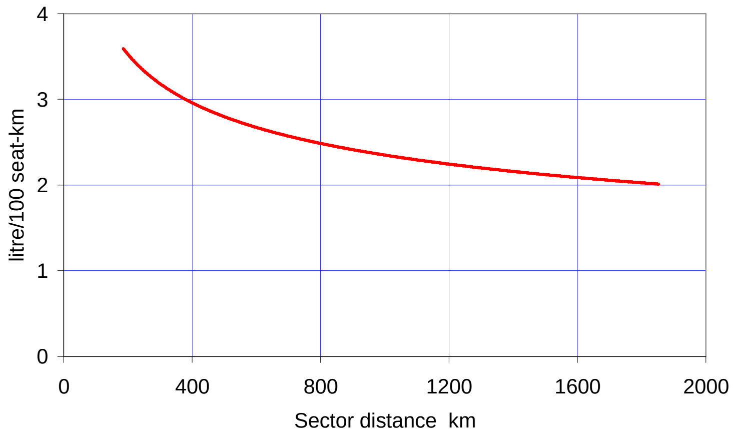

Figure 39: Airbus fuel 321/100 consumption

Smaller aircraft tend to be less efficient than larger planes. Turboprop aircraft, with a cruise speed of about 650 km/h and a maximum altitude of 7,500 metres can be more fuel efficient than jet equivalents of a similar size on short sectors. The following graph shows the fuel use of two different planes, the Bombardier Q 400 and ATR 72.[47] [48]

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[44] http://www.flug-revue.rotor.com/FRheft/FRHeft04/FRH0406/FR0406g.htm

[45] Rainer von Wrede, Airbus Director Environmental Affairs, *Energie et transport aérien*, 13 décembre 2005

[46] based on data from Airbus, reproduced in *The European High Speed Network*, Discussion Meeting at the Royal Society, "Passenger transport after 2000 AD" June 1993. ISBN 0 419 19470 3)

[47] data from e-mail from Gianfranco Barone, ATR Product Marketing Director, 31712 Blagnac, France.

[48] data from Florentina Viscotchi of. Bombardier Aerospace, Dorval, Québec, Canada

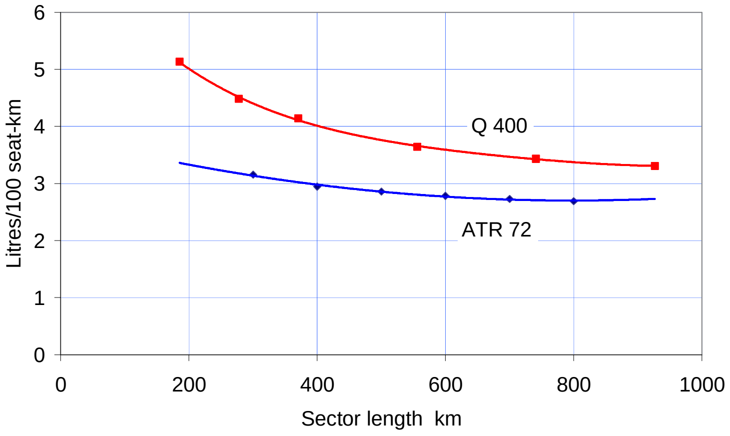

Figure 40: Turboprop fuel consumption

CHOICE OF COMPARATORS

On the basis of the above, the following three services have been selected as comparators for the rail industry:

Service	Plane	Sector km	litre/100 seat-km
Heathrow to Manchester	Airbus	300	3.2
Heathrow to Edinburgh	Airbus	600	2.6
Cardiff to Newcastle-on-Tyne	ATL	400	2.9

5.5 RADIATIVE FORCING

The term “radiative forcing” is used in the IPCC Assessments to denote “an externally imposed perturbation in the radiative energy budget of the Earth’s climate system”.[49] Such a perturbation can be brought about by changes in the concentrations of CO_2, water vapour, aerosols, etc. or other changes that affect the radiative energy absorbed by the surface, such as changes in surface reflectivity.

The earth’s atmosphere can be thought of as being in two main layers. Up to about 10 km above the surface of the earth is the troposphere. This layer contains 80% by mass of the atmosphere; it has low concentrations of ozone and high concentrations of

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[49] Intergovernmental Panel on Climate Change – Working Group I: The Scientific Basis Climate Change 2001, Section 6.1

water vapour. The atmospheric temperature drops until at the top of the troposphere it is around -55°C. All the world's weather systems are in the troposphere.

Above the troposphere is the stratosphere which extends out to around 50 km from the earth's surface. This is stable, has a high level of ozone and little water vapour. The interface between the two is known as the tropopause. In tropical latitudes, the tropopause is typically 16 km above the earth's surface while in the artic regions it can be as low as 9 km.

It is acknowledged that the issue of radiative forcing factors for aviation is the subject of ongoing consideration, and opinions vary with regard to the use of multipliers to take account of indirect effects associated with aviation emissions at altitude. Consequently, to ensure transparency we have clearly indicated the main sources of third party information and opinion relating to this aspect.

AIRCRAFT EMISSIONS[50]

During flight, aircraft engines emit carbon dioxide, oxides of nitrogen, oxides of sulphur, water vapour, hydrocarbons and particles. These emissions alter the chemical composition of the atmosphere in a variety of ways, both directly and indirectly. The unique feature of these emissions is that the majority of them occur far above the Earth's surface. Intercontinental subsonic aircraft generally cruise at an altitude of 9-13 km, close to or in the tropopause.

The impact of aircraft emissions can be very different depending whether they are in the upper troposphere or the lower stratosphere. Both the abundance of trace gases and the dominant chemical composition and associated chemical reaction are very different in the two regions. In particular water vapour content is relatively high in the troposphere and low in the stratosphere whereas ozone levels are much higher in the stratosphere. Stratospheric ozone absorbs radiation from the sun. This leads to a heating profile in the stratosphere that determines its character, and also protects life at the surface from the harmful effects of the UV radiation.

According to IPCC, in 1992 aviation was responsible for 2% of carbon dioxide emissions due to the total burning of fossil fuel and 13% of that associated with transport. However, the total greenhouse impact was more important than this would suggest. Since the vast majority of the flights were subsonic and therefore in the 9-13 km height range, the emissions of oxides of nitrogen led, on average, to an increase in ozone as well as a decrease in methane. Relative to carbon dioxide, the radiative forcing factors were estimated to be +1.3 for ozone and -0.8 for methane. The factor +1.1 was given for contrails. The impacts of water vapour, and sulphate and soot particles were given as small and positive. The total radiative forcing was calculated to be about 2.7 times that of the carbon dioxide alone.

Since the IPCC work in 1999, there has been further research under the EU FP5 TRADEOFF programme which generally supports IPCC figures. As in the IPCC report, the new TRADEOFF estimate does not include the contribution from aviation-induced

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[50] This section is based on: Royal Commission on Environmental Pollution; *The Environmental Effects of Civil Aircraft in Flight*, November 2002

cirrus clouds. However the new work suggests that radiative forcing from aviation-induced cirrus clouds is much larger than the IPCC estimate which would increase the factor of 2.7 quoted above. [51]

RADIATIVE FORCING OF DOMESTIC FLIGHTS

For intercontinental air travel, most of the fuel burn is at high altitude and so it is reasonable to use a radiative forcing factor of 2.7 or higher (i.e. 2.7 g of CO_2 at sea level has the same effect as 1 g produced by an aeroplane, along with the other products of combustion). However, this is not necessarily true of domestic flights where much of the fuel burn is at take-off and the cruise altitude is usually below the tropopause. For turboprop flights, with a service ceiling of around 7.5 km, all the operation would be below the tropopause.

For the rest of this paper, we have used a radiative forcing factor of 2.0 for turbojet aircraft. This is probably pessimistic if cirrus cloud formation is ignored but might be optimistic if the effect is included as the FP5 research suggests. For turboprop aircraft a factor of 1.3 is used but the justification for this number is not strong.

5.6 LOAD FACTOR

GB DOMESTIC RAIL

In making intermodal comparisons, it is necessary to make assumptions about the load factor in different vehicles. An earlier section of this report indicated a variation of 25% to 48% for various TOCs with a median of 31%. Over the years, there has been a reduction in the length of the average journey on main lines. The following graph[52] shows this reduction for 5 rail lines.

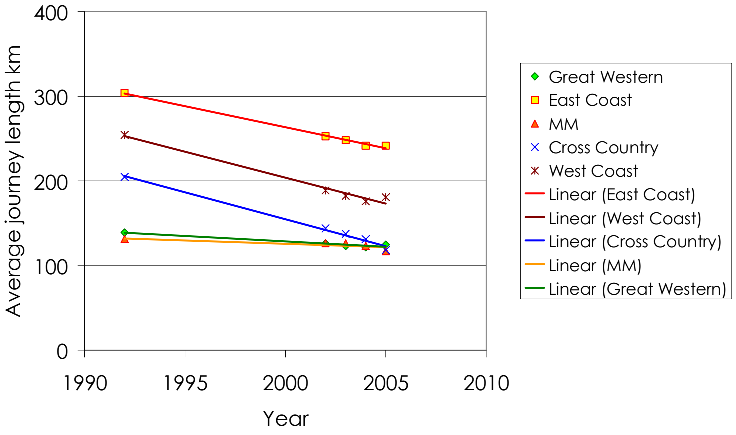

Figure 41: Average journey length

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[51] Gebrüder Borntraeger, *Aviation radiative forcing in 2000: An update on IPCC (1999)*, Meteorologische Zeitschrift, Vol. 14, No. 4, 555-561, August 2005.
[52] Data from Roger Ford, Modern Railways

The effect is that trains are full in one part of the journey and less full over other sectors. As example, on early-evening Euston–Glasgow services, it is normal for a train to be standing room only for the first 100km of the journey and almost empty for the last 100km. For this reason it seems unlikely that average domestic load factor will improve significantly.

CARS

Occupancy of road vehicles is calculated from surveys. For England and Wales, there has been a slight fall in the average number of occupants per car stage, from 1.62 in 1992/1994 to 1.59 in 2004.[53] The highest occupancy rates in 2004 were for holidays/day trips and education (both 2.1). The lowest rates were for business travel and commuting (both 1.2). Assuming 5 seats in the average car, that is 32% load factor.

The Scottish Household Survey (SHS)[54] asks adults about their journeys on the day before the interview. In 2004, 60% of journeys which were made as the driver of a car were made unaccompanied, 27% were made with one passenger, 9% with two passengers, 4% with three passengers, and 1% with four or more passengers. As a result, the average number of people per car journey was 1.61, an average load factor of 32.2%, making the same assumption on seating capacity.

However, considering the above statistics, it is valid to ask whether a parent driving a child 10km to school and then returning home represents 30 pass-km or 10 pass-km, as the parent is, in effect, part of the transport system, not a traveller. There is a further problem in that people travelling in groups have a propensity to travel in a car and people travelling alone often prefer the train. Using average values of occupancy when considering car travellers transferring to the train or vice-versa could incur inaccuracies.

DOMESTIC AIRLINES

Aircraft load factors fluctuate around 70%. For 2003/04, British Airways reported an average load factor of 67.6%.[55] In July 2004 BMI recorded an average load factor of 74% and, for the year ended 31 December 2005, overall passenger load factor was 71%.[56] EasyJet announced a load factor for November 2006 of 80.5%. The figure for the 12 months to November was 84.5%.[57] However the ticket pricing policy of some low-cost airlines that sell surplus tickets at very low prices must raise the question of whether some of the higher load factors represent a valid comparison with other modes. For this report, an average of 70% has been used.

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[53] DfT Transport Statistics bulletin table 6.2 and 6.3

[54] Scottish Executive website

[55] BA Social and Environmental Report 2003/04

[56] BMI press release, April 2006

[57] EasyJet press release 7 Dec 2006

BUSES

National data an buses shows average occupancy of 9 passengers.[58] Data from Manchester[59] and Merseyside[60] PTEs has confirmed this figure. However the average figure, which includes routes round remote housing estates that have no similarity with those used by train passengers, is not an appropriate metric for this study. As an alternative, data on departures from Victoria Coach Station[61] are: domestic departures 184, international departures 12, total number of passengers 7,930 which implies an average load of 40 passengers/coach. Therefore, for this report we have assumed a load factor of 60% for point-to-point coach services.

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[58] *Hansard* 20 Jul 2005 : Column 1798W

[59] The GMTU website http://www.gmtu.gov.uk/reports/default.htm quotes 72m bus miles for 2005 (115.8m km). The Local Transport Plan http://www.gmltp.co.uk/ gives 1,050m pass-km for 2005, thus 1050/ 115.8 = 9.06 pass/bus. (Data via Peter Black, GMPTE)

[60] J Barrett, A Scott & H Vallack; *The Ecological Footprint of Passenger Transport in Merseyside*. Provided via Karen Booth, Merseytravel

[61] Transport for London, *London Travel Report 2006*, http://www.tfl.gov.uk/tfl/pdfdocs/ltr/London-Travel-Report-2006-final.pdf

6 COMPARISON BETWEEN MODES OF TRANSPORT

6.1 LIMITATIONS OF THIS COMPARISON

Results presented in previous sections of this report were based on hard data calculating the energy and fuel consumption for different groups of vehicles on the basis of kWh/seat-km or litres/100 seat-km. It is not appropriate to use these measures when comparing different domestic transport modes as they have very different load factors. In general, services that operate a fully reserved, point-to-point service have a higher average load factor than those that operate a "turn up and walk on" service with multiple stops. In this section, we have assumed the following load factors: urban bus 20%, intercity coach 60%, intercity rail 40%, all other trains 30% (including commuter services), domestic airlines 70%, cars 30%.

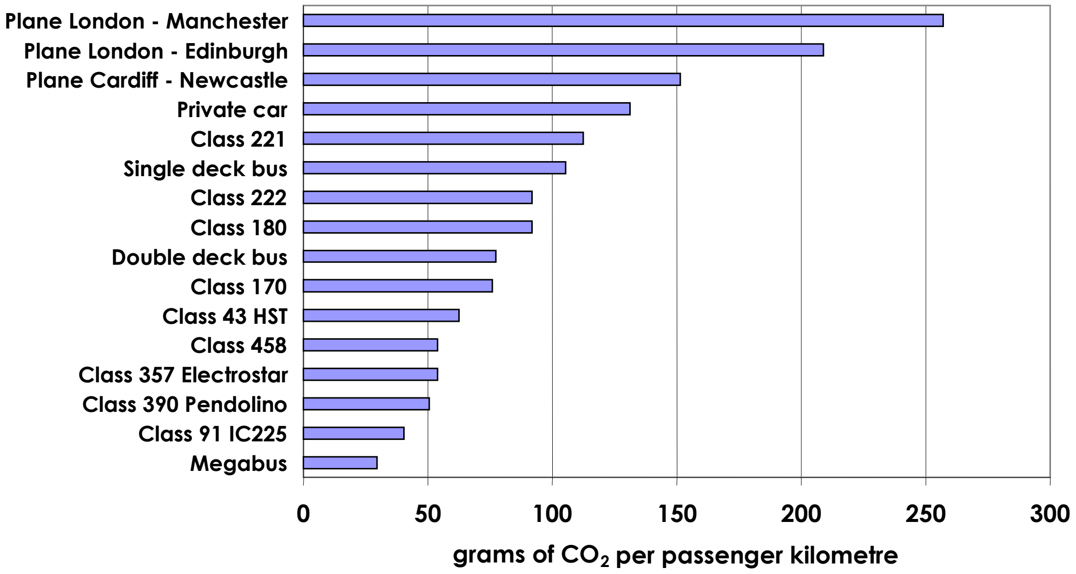
This section also compares domestic transport modes across a wide range of speed and styles of passenger accommodation. Urban buses may have an average speed of 10 km/h and stop every 500 metres; domestic airlines fly almost 10 times faster with 500 times the distance between stops. The data in the following section is not intended to be an authoritative league table of transport modes but provides broad comparative data of CO_2 emissions, which can be a surrogate for energy consumption.

We have considered only the relative CO_2 emissions of the different domestic transport modes. This is valid with the present and assumed future GB energy mix and with existing technologies. However a completely new technology, such as a hydrogen-fuelled bus with a dedicated supply of hydrogen produced directly from nuclear power without going through the public electricity supply, could be considered to have zero CO_2 emissions, but may have very large energy demands. In such a case, it would be appropriate to also compare other factors such as total energy use, not just CO_2 emissions, as has been done here.

The Class 373 Eurostar train has been omitted from this section because the assumptions used for domestic trains cannot reasonably be applied to Eurostar pan-European services as they are operationally and commercially very different.

6.2 COMPARISONS OF CO_2 EMISSIONS OF DIFFERENT MODES

The following diagram shows indicative CO_2 emissions per passenger on the load-factor assumptions above. Road, air and diesel-powered rail vehicle emissions have been increased to take account of refinery losses and electric powered vehicles take into account losses from power generation through to the train. The bar length represents the emissions based on current electricity generation mix.



Notes: Data assumes the following load factors: urban bus 20%, intercity coach 60%, intercity rail 40%, all other trains 30%, domestic airlines 70%, and cars 30%. Road, air and diesel-powered rail vehicles emissions have been increased to take account of refinery losses and electric powered vehicles take into account losses in the grid. The aviation figures include a factor for radiative forcing.

Figure 42: Domestic intermodal comparison of CO_2 emissions

This analysis shows that the least polluting means of transport are electric trains (almost of whatever speed), and Megabus type intercity buses. The difference between them is small in comparison with the likely errors in load factor. The worst are planes, private cars and diesel-powered trains in that order.

During the 1990s, the European Commission secured voluntary agreements with European, Japanese and Korean car manufacturers to reduce new car CO_2 emissions to 140g/km by 2009, a cut of 25% on 1995 levels.[62] The 140g/km target is unlikely to be met and the EC now proposes to make this mandatory. It is likely that, because of compulsion, by 2022 the UK average will be close to the target. The bar represents car emissions today, as discussed in §5.2, however by 2022 (again with a 30% load factor) the bar would be indicating around 100g of carbon dioxide per passenger kilometre.

Significantly, this puts 2022 combined car emissions below a single deck bus and recent high-performance diesel trains. In addition it should also be noted that the bar lengths for electrically powered rail vehicles would indicate a reduction of around 30% by 2022 based on the assumed decarbonisation of grid electricity as discussed in §2.1.

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[62] DfT consultation "Reducing new car CO_2 emissions: what should succeed the Voluntary Agreements", published: 13 September 2006

7 CONCLUSIONS AND RECOMMENDATIONS

As an *aide mémoire*, the objective of the study is to answer the following questions:

- Which are the most appropriate metrics for the rail industry and how should one define benchmarks which can be used as a reference for energy consumption?
- What values of energy consumption, measured at the fuel filler or pantograph / collector shoe, represent current good practice in the UK rail industry?
- How does the energy consumption of the GB rail industry compare with international good practice in terms of energy delivered at the pantograph or to the fuel tank? Where there are differences, what are the reasons for the differences?
- How does the energy consumption of different segments of the domestic GB rail industry compare with competing transport modes?

These are addressed in the following sections.

7.1 CHOICE OF METRICS

This report has argued that, when making comparisons between different electric trains or different diesel trains, it is difficult to draw any useful conclusions from comparisons of the energy used per passenger because the results vary widely and are affected by the type of service rather than by features of the vehicles. It is therefore recommended that the industry uses the following figures for passenger trains:

kWh/seat-km or **litres of fuel/seat-km**

For comparisons between diesel and electric trains it is recommended to use:

grams of CO_2 / seat-km

When making intermodal comparisons, for CO_2 only - not energy efficiency in terms of KWh or primary fuel per unit of utility, it is necessary to refer all data to common units. It is recommended that these should be:

grams of CO_2 / passenger-km

There is no justification in claiming that the rail industry uses "green" electricity just because of the company with which Network Rail contracts to buy energy.

The current figure for converting electrical energy to CO_2 is 455 g/kWh but, as the EU Large Combustion Plant Directive[63] starts to bite and Governments aim to reduce global

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[63] The LCPD (2001/80/EC) does not refer to CO_2 emissions, per se, but places obligations on countries to reduce SOx, NOx and dust which is likely to cause the older coal-fired power stations to close. This will have the effect of switching more generation to combined-cycle gas plants and other systems that have lower CO_2 emissions.

warming gases from power stations, this is expected to reduce to around 320 g/kWh over about 15 years.

7.2 ENERGY CONSUMPTION GOOD PRACTICE

ELECTRIC TRAINS

For domestic electric trains other than intercity services, current good practice is represented by an energy consumption of not more than 0.030 kWh/seat-km. For domestic intercity trains current good practice is not more than 0.035 kWh/seat-km. It is suggested that the industry should set targets for new domestic trains at an agreed percentage below these figures. To meet the targets, it will be necessary to give the same priority to energy consumption as to safety or accessibility. To achieve these targets will require equipment designs and operating regimes that maximise the amount of regenerated energy during braking and that minimise the mass of the train per passenger seat.

On most trains, but particularly Intercity, first class accommodation uses much more space per passenger than standard class. Operators may need to review the relative proportions of first and standard class accommodation and the proportion of train length given to catering or other non-passenger uses to meet the above targets.

DIESEL TRAINS

The study has shown that diesel trains are responsible for more CO_2 emissions per seat-km than are electric trains. Thirty years ago, when the HST was introduced, most electricity generation was by coal-fired power stations and there was little to choose in CO_2 emissions between diesel and electric trains – not that anyone was particularly concerned. Over the last decade the "dash for gas" has reduced the amount of CO_2 from the electricity supply industry and, as electricity generation continues to move from coal to combined cycle gas generation, renewables, co-generation and nuclear power, the difference is expected to become more marked.

Future good practice on diesel-powered passenger railways is that a train should not have a fuel consumption greater than 0.8 litres/100 seat-km. This would represent a shift towards a more energy efficient approach than recent practice. Many post-privatisation diesel trains exceed this figure by around 20% and a review of the design objectives for diesel passenger trains is therefore needed. It is not environmentally sustainable to design diesel trains with the same performance envelope as electric trains.

FUTURE DEVELOPMENTS

It is recommended that further targeted electrification should be put back onto the industry's agenda. The electrification of short lengths of track, such as Doncaster to Hull, Manchester to Leyland, Liverpool to Preston and Preston to Blackpool would remove the need for running diesel trains under the wire which would reduce the industry's CO_2 emissions and would provide shorter-term benefits. In addition, from a CO_2 emissions perspective electric trains are also well place to exploit the advantages of low carbon grid electricity. The importance of this is graphically illustrated by recent independent research by Paul Watkiss associates and AEA technology covering pan-European rail and air intermodal comparisons for Eurostar which takes account of the carbon intensity of grid electricity in other countries. This work has calculated that CO_2 emissions of around 11 to 35 grams of CO_2 per passenger kilometre can be achieved (with a load factor of around 45% to 67%) for high speed services when low carbon electricity is available. It is also noteworthy that the low carbon electricity is substantially derived from existing established low CO_2 emissions generation technologies deployed currently elsewhere in Europe[64].

7.3 INTERNATIONAL RAIL COMPARISONS

GB has a lower proportion of electrified lines than most other EU states and it has been difficult to find appropriate comparators for diesel trains. For electric trains there are many comparators available. The energy performance of electric trains on the British network is neither exemplary nor very poor. It is typical of Scandinavian railways but less good than much European practice. Some of the most energy-efficient railways internationally are in the Far East, and the Japanese Shinkansen system is an example of an energy efficient high speed intercity railway.

Partly the indifferent energy performance is because British intercity trains are shorter than those in most other European countries and operate within a more constrained loading gauge. The data in Chapter 4 show that the Pendolino has a greater mass per seat and fewer seats per linear metre than contemporary vehicles in other countries. Also a greater proportion of the train length is not available for passenger accommodation.

It is recommended that the industry should investigate how the constraints of the GB rail infrastructure could be eased to allow larger trains that would permit more passengers to be accommodated in the same structural mass and the energy consumption to be reduced. As an example, increasing the gap between a train and the coping stones on curved platforms could allow a greater vehicle length (and reduced mass/unit length). Changing the rules on the layout of track circuits in junction areas could permit trains to have longer noses, with a consequential reduction in drag.

A review of safety regulations that restrict the carrying of passengers in particular areas of trains is overdue. It is recommended that, when reviewing whether risk has been reduced to ALARP, the value of carbon proposed by the Stern Review[65] should be treated as an allowable factor.

7.4 DOMESTIC INTERMODAL COMPARISONS

The comparison with other transport modes on domestic routes confirms that electric trains, of the speed band considered in this report, are significantly more CO_2-efficient

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[64] Data supplied by Eurostar Group Ltd

[65] *The economics of climate change* ISBN: 0-521-70080-9, Cambridge University Press, January 2007

than other means of powered transport. As the electricity supply is progressively "decarbonised" the benefit will increase so they become at least as good as motorway coaches, despite their much higher average speed and passenger acceptability. On environmental grounds, there is a strong case for transferring passengers from road and air to electric railways meeting the energy targets discussed earlier.

The situation for diesel trains is less clear. Many newer and more powerful diesel trains produce far more CO_2 than some buses. As the efficiency of cars increases, under the influence of progressive EU legislation, the difference in emissions between cars and trains, such as the recent Class 221 or 222, will narrow and it will be difficult to make an environmental case for transferring people onto diesel-powered railways. There is, however an environmental case for transferring passengers from airlines onto rail – other than in exceptional circumstances where the rail service is very lightly loaded or follows a more tortuous route that the equivalent air route.

Electric trains on the main London – Manchester and Scotland lines produce far lower CO_2 emissions per passenger than the aircraft used on competitive routes and there is a good environmental case for encouraging passengers to transfer to the train. (Note this does not necessarily apply to very high speed transport systems, even if they are electrically powered.[66]) However in a comparison between slower turboprop airliners and current high performance diesel trains the difference is not so marked and, for routes such as Plymouth to Newcastle-on-Tyne, further study may demonstrate that there is little difference between these transport modes.

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[66] Kemp R J & Smith R A, *Technical issues raised by the proposal to introduce a 500 km/h magnetically-levitated transport system in the UK*. Report to the Department for Transport, October 2006

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