Factors Influencing the Energy Consumption of High Speed Rail and Comparisons with other Modes

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PhD degree of Imperial College London
I declare that the research presented is my own work and that the work of others is properly acknowledged and referenced.

Robert Watson
Abstract

High speed rail is increasingly viewed as an effective solution to the inter-city passenger transportation challenge of the 21st century due to its ability to significantly increase capacity and reduce journey times between city centres. The motivation behind this thesis is to try to establish whether high speed rail is an efficient mode of transport in terms of operational, traction energy consumption and associated carbon dioxide emissions, and to investigate scope for its improvement.

A computational model is developed and validated against existing data and simulations are carried out to estimate the energy consumption of a modern, European high speed train, labelled the HS2 reference train, running on the UK's proposed High Speed Two (HS2) line between London and Birmingham. Investigations are conducted to quantify the effects of different parameters on the operational energy consumption of the line according to a defined Key Performance Indicator.

Comparisons are made with the car and domestic air in terms of primary energy consumption, carbon dioxide emissions and journey time. Further simulations are conducted of a Class 390 'Pendolino' train running on the existing West Coast Main Line route between London and Birmingham and comparisons are made with the HS2 reference train, again with reference to the Key Performance Indicator and journey time.

In the final part of the thesis simulations are carried out of three different vehicle types running on the HS2 route, which could be considered as alternatives to the HS2 reference train. Analysis is undertaken to determine key areas of vehicle design which contribute to the minimizing of the operational energy consumption and carbon dioxide emissions of high speed rail.
Acknowledgements

I would like first of all to thank my supervisor Professor Rod Smith for his guidance and support throughout my time at Imperial. His enthusiasm is inspiring and I have learned a huge amount from him. I am hugely indebted to him for all the opportunities he gave me, including my congress visit to China and my research trip to Japan to name but a few.

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I would like to thank Rail Research UK (RRUK) for providing funding for my PhD research.

My thanks also go to my colleagues at the Future Railway Research Centre (FRRC) and the people who made my time at Imperial so special.

Finally I would like to thank my family and parents in particular, for all their love and support.
# Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>(SI) Unit</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>(BE(v&gt;20\text{km/h}))_R</td>
<td>-</td>
<td>Proportion of total braking energy at the wheel at speeds above 20 km/h regenerated</td>
</tr>
<tr>
<td>(F_B)_{ED}</td>
<td>N</td>
<td>Braking force provided by regenerative brakes</td>
</tr>
<tr>
<td>A</td>
<td>N</td>
<td>Davis equation resistance coefficient independent of velocity</td>
</tr>
<tr>
<td>a_B</td>
<td>ms(^2)</td>
<td>Braking deceleration rate</td>
</tr>
<tr>
<td>A_S</td>
<td>m(^2)</td>
<td>Seating area</td>
</tr>
<tr>
<td>A_{XS}</td>
<td>m(^2)</td>
<td>Cross-sectional area of train</td>
</tr>
<tr>
<td>B</td>
<td>Nsm(^{-1})</td>
<td>Davis equation resistance coefficient dependent on the first power of velocity</td>
</tr>
<tr>
<td>C</td>
<td>Ns(^2)m(^{-2})</td>
<td>Davis equation resistance coefficient dependent on velocity squared</td>
</tr>
<tr>
<td>c_D</td>
<td>-</td>
<td>Drag coefficient</td>
</tr>
<tr>
<td>E_{APS}</td>
<td>J</td>
<td>Energy consumption of auxiliary services (from the line)</td>
</tr>
<tr>
<td>E_B</td>
<td>J</td>
<td>Energy leaving the train at the wheel during braking</td>
</tr>
<tr>
<td>E_D</td>
<td>J</td>
<td>Component of energy consumption at the wheel to overcome the Davis equation resistance</td>
</tr>
<tr>
<td>E_D(A+Bv)</td>
<td>J</td>
<td>Component of energy consumption at the wheel to overcome the mechanical resistance</td>
</tr>
<tr>
<td>E_D(Cv(^2))</td>
<td>J</td>
<td>Component of energy consumption at the wheel to overcome the open-air aerodynamic resistance</td>
</tr>
<tr>
<td>E_D(TICv(^2))</td>
<td>J</td>
<td>Component of energy consumption at the wheel to overcome the total aerodynamic resistance (including the effect of tunnels)</td>
</tr>
<tr>
<td>E_G</td>
<td>J</td>
<td>Component of energy consumption at the wheel to overcome the gradient</td>
</tr>
<tr>
<td>E_I</td>
<td>J</td>
<td>Component of energy consumption at the wheel to overcome inertia (accelerate the vehicle mass)</td>
</tr>
<tr>
<td>E_L</td>
<td>J</td>
<td>Gross energy drawn from the line at the current collector</td>
</tr>
<tr>
<td>Symbol</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>------------</td>
<td>------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>$E_{\text{NET}}$</td>
<td>J</td>
<td>Net energy drawn from the line at the current collector (including braking regeneration)</td>
</tr>
<tr>
<td>$E_R$</td>
<td>J</td>
<td>Energy regenerated to the line at the current collector</td>
</tr>
<tr>
<td>$E_{\text{RB}}$</td>
<td>J</td>
<td>Energy leaving the train at the wheel during regenerative braking (for speeds greater than 20 km/h)</td>
</tr>
<tr>
<td>$E_{\text{RB}(D(A+Bv))}$</td>
<td>J</td>
<td>Component of energy leaving the train at the wheel during regenerative braking (for speeds greater than 20 km/h) to overcome the mechanical resistance</td>
</tr>
<tr>
<td>$E_{\text{RB}(D(Cv^2))}$</td>
<td>J</td>
<td>Component of energy leaving the train at the wheel during regenerative braking (for speeds greater than 20 km/h) to overcome the open-air aerodynamic resistance</td>
</tr>
<tr>
<td>$E_{\text{RB}(D(T^2Cv^2))}$</td>
<td>J</td>
<td>Component of energy leaving the train at the wheel during regenerative braking (for speeds greater than 20 km/h) to overcome the total aerodynamic resistance (including the effect of tunnels)</td>
</tr>
<tr>
<td>$E_{\text{RB}(D)}$</td>
<td>J</td>
<td>Component of energy leaving the train at the wheel during regenerative braking (for speeds greater than 20 km/h) to overcome the total Davis equation resistance (including the effect of tunnels)</td>
</tr>
<tr>
<td>$E_{\text{RB}(G)}$</td>
<td>J</td>
<td>Component of energy leaving the train at the wheel during regenerative braking (for speeds greater than 20 km/h) to overcome the gradient resistance</td>
</tr>
<tr>
<td>$E_{\text{RB}(I)}$</td>
<td>J</td>
<td>Component of energy leaving the train at the wheel during regenerative braking (for speeds greater than 20 km/h) to accelerate the vehicle mass (overcome inertia)</td>
</tr>
<tr>
<td>$E_W$</td>
<td>J</td>
<td>Energy consumption at the wheel</td>
</tr>
<tr>
<td>$F_B$</td>
<td>N</td>
<td>Braking force</td>
</tr>
<tr>
<td>$F_D$</td>
<td>N</td>
<td>Davis equation resistance force</td>
</tr>
<tr>
<td>$F_{D(Cv^2)}$</td>
<td>N</td>
<td>Aerodynamic component of the Davis equation resistance (in open-air)</td>
</tr>
<tr>
<td>$F_T$</td>
<td>N</td>
<td>Tractive force</td>
</tr>
<tr>
<td>g</td>
<td>ms$^{-2}$</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>LF</td>
<td>%</td>
<td>Passenger load factor</td>
</tr>
<tr>
<td>$L_{\text{TRAIN}}$</td>
<td>m</td>
<td>Length of train</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>M</strong></td>
<td>kg</td>
<td>Total mass of train (including passengers)</td>
</tr>
<tr>
<td><strong>M_P</strong></td>
<td>kg</td>
<td>Mass of passengers</td>
</tr>
<tr>
<td><strong>M_T</strong></td>
<td>kg</td>
<td>Tare mass of train (empty of passengers)</td>
</tr>
<tr>
<td><strong>N_S</strong></td>
<td>-</td>
<td>Number of seats on-board a train</td>
</tr>
<tr>
<td><strong>P_APS</strong></td>
<td>W</td>
<td>Auxiliary Power</td>
</tr>
<tr>
<td><strong>s_GCD</strong></td>
<td>m</td>
<td>Great circle distance</td>
</tr>
<tr>
<td><strong>t</strong></td>
<td>s</td>
<td>Time</td>
</tr>
<tr>
<td><strong>T_C</strong></td>
<td>K</td>
<td>Temperature of the cold reservoir</td>
</tr>
<tr>
<td><strong>T_H</strong></td>
<td>K</td>
<td>Temperature of the hot reservoir</td>
</tr>
<tr>
<td><strong>t_DWELL</strong></td>
<td>s</td>
<td>Station dwell time</td>
</tr>
<tr>
<td><strong>Tf</strong></td>
<td>-</td>
<td>Aerodynamic tunnel factor</td>
</tr>
<tr>
<td><strong>t_J</strong></td>
<td>s</td>
<td>Journey time</td>
</tr>
<tr>
<td><strong>v</strong></td>
<td>ms(^{-1})</td>
<td>Velocity</td>
</tr>
<tr>
<td><strong>v_MAX</strong></td>
<td>ms(^{-1})</td>
<td>Maximum operational speed of the train</td>
</tr>
<tr>
<td><strong>V_S</strong></td>
<td>m(^3)</td>
<td>Seating volume</td>
</tr>
<tr>
<td><strong>x</strong></td>
<td>m</td>
<td>Displacement</td>
</tr>
<tr>
<td><strong>α</strong></td>
<td>degrees</td>
<td>Gradient of the line relative to the horizontal</td>
</tr>
<tr>
<td><strong>ε</strong></td>
<td>%</td>
<td>Effect on the KPI energy consumption of applying a certain per seat parameter to the HS2 reference train in the HS2 baseline simulations</td>
</tr>
<tr>
<td><strong>ε_APS/S</strong></td>
<td>%</td>
<td>Effect on the KPI energy consumption of applying the auxiliary energy consumption per seat of a particular train to the HS2 reference train in the HS2 baseline simulations</td>
</tr>
<tr>
<td><strong>ε_APS/SA</strong></td>
<td>%</td>
<td>Effect on the KPI energy consumption of applying the auxiliary energy consumption per unit seating area of a particular train to the HS2 reference train in the HS2 baseline simulations</td>
</tr>
<tr>
<td><strong>ε_D/S</strong></td>
<td>%</td>
<td>Effect on the KPI energy consumption of applying the Davis equation resistance per seat of a particular train to the HS2 reference train in the HS2 baseline simulations</td>
</tr>
<tr>
<td><strong>ε_D/SA</strong></td>
<td>%</td>
<td>Effect on the KPI energy consumption of applying the Davis equation resistance per unit seating area of a particular train to the</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_{M/S}$</td>
<td>Effect on the KPI energy consumption of applying the mass per seat of a particular train to the HS2 reference train in the HS2 baseline simulations</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_{M/SA}$</td>
<td>Effect on the KPI energy consumption of applying the mass per unit seating area of a particular train to the HS2 reference train in the HS2 baseline simulations</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_{R/S}$</td>
<td>Effect on the KPI energy consumption of applying the energy regenerated per seat by a particular train to the HS2 reference train in the HS2 baseline simulations</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_{R/SA}$</td>
<td>Effect on the KPI energy consumption of applying the energy regenerated per unit seating area by a particular train to the HS2 reference train in the HS2 baseline simulations</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_{SD}$</td>
<td>Effect on the KPI energy consumption of applying the seat density of a particular train to the HS2 reference train in the HS2 baseline simulations</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_{SINUOSITY}$</td>
<td>Effect on the KPI energy consumption of applying the route sinuosity of the West Coast Main Line (WCML) to the HS2 baseline simulations</td>
<td></td>
</tr>
<tr>
<td>$\eta_{APS}$</td>
<td>Auxiliary power system efficiency</td>
<td></td>
</tr>
<tr>
<td>$\eta_{DRIVE}$</td>
<td>Efficiency of the drive system</td>
<td></td>
</tr>
<tr>
<td>$\eta_{L-W}$</td>
<td>Line-to-wheel efficiency</td>
<td></td>
</tr>
<tr>
<td>$\eta_{R}$</td>
<td>Efficiency of regeneration from wheel to line</td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of air</td>
<td></td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Rotational inertia mass factor</td>
<td></td>
</tr>
</tbody>
</table>
# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGR</td>
<td>Advanced Gas-cooled Reactor</td>
</tr>
<tr>
<td>APS</td>
<td>Auxiliary Power System</td>
</tr>
<tr>
<td>ATO</td>
<td>Automatic Train Operation</td>
</tr>
<tr>
<td>ATOC</td>
<td>Association of Train Operating Companies</td>
</tr>
<tr>
<td>CCGT</td>
<td>Combined Cycle Gas Turbine</td>
</tr>
<tr>
<td>DECC</td>
<td>Department of Energy and Climate Change</td>
</tr>
<tr>
<td>DEFRA</td>
<td>Department for Environment, Food and Rural Affairs</td>
</tr>
<tr>
<td>DfT</td>
<td>Department for Transport</td>
</tr>
<tr>
<td>EMU</td>
<td>Electric Multiple Unit</td>
</tr>
<tr>
<td>ERA</td>
<td>European Railway Agency</td>
</tr>
<tr>
<td>ERTMS</td>
<td>European Rail Traffic Management System</td>
</tr>
<tr>
<td>FRRC</td>
<td>Future Railway Research Centre</td>
</tr>
<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>HS2</td>
<td>High Speed 2</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>KPI</td>
<td>Key Performance Indicator</td>
</tr>
<tr>
<td>LGV</td>
<td>Lignes à Grande Vitesse</td>
</tr>
<tr>
<td>LHV</td>
<td>Lower Heating Value</td>
</tr>
<tr>
<td>L-W</td>
<td>Line-to-Wheel</td>
</tr>
<tr>
<td>NEDC</td>
<td>New European Driving Cycle</td>
</tr>
<tr>
<td>SMMT</td>
<td>Society of Motor Manufacturers and Traders</td>
</tr>
<tr>
<td>TGV</td>
<td>Train à Grande Vitesse</td>
</tr>
<tr>
<td>TR</td>
<td>Transrapid</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>TRL</td>
<td>Transport Research Laboratory</td>
</tr>
<tr>
<td>TSI</td>
<td>Technical Specification of Interoperability</td>
</tr>
<tr>
<td>UIC</td>
<td>Union Internationale desChemins de fer (International Union of Railways)</td>
</tr>
<tr>
<td>WCML</td>
<td>West Coast Main Line</td>
</tr>
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Chapter 1: Introduction

The background of the thesis is given before an overview of the issues of energy and climate change and their relation to transport. The approach of the thesis is described before the aims are set out. The structure is then summarized on a chapter by chapter basis.

1.1. Background

In January 2009 the then Labour UK government set up a company called High Speed Two (HS2) Ltd. to consider the case for the construction of a new high speed rail network between London and the North. At current rates of growth passenger demand on the existing West Coast Main Line (WCML) between London and Birmingham is set to reach capacity by the 2020s. The idea behind the building of a new line to transport passengers at high speed between the UK's biggest cities was that it would create much needed capacity, which could then open up the existing line to more freight services. The company had one year to produce a report weighing up the case for such a network for the then Secretary of State for Transport (the Rt. Hon. the Lord Andrew Adonis). The report (1) was made public in March 2010 and the government endorsed its findings that a new line should be built.

After coming to power in May 2010, the Conservative / Liberal Democrat coalition government continued to support HS2 Ltd. and its work, and after a public consultation lasting 6 months between February and July 2011, the government gave the go-ahead for the project and the start of the engineering, design and environmental work for the 1st phase London to Birmingham route, estimated to eventually cost around £17 billion. A hybrid bill is set to be put to Parliament before the next election in 2015 to authorise the construction of the 1st phase, estimated to be completed by 2026. Figure 1-1 illustrates how a potential high speed rail network in the UK may eventually look:
In June 2009, HS2 Ltd. approached the Future Railway Research Centre (FRRC) at Imperial College London to conduct calculations to estimate the operational energy consumption of the future London to Birmingham phase of the network and to carry out parametric studies to investigate the effect of various factors, such as maximum operational speed and station stops. The author developed a computational model to do this and the results of the work the FRRC carried out for HS2 Ltd. were included in their final report to the government at the end of 2009 and can be seen in (3). The author has since expanded on the work which was carried out for HS2 Ltd. to create this thesis.
1.2. Energy, CO₂ and Transport

1.2.1. The Energy Problem

The world's population has undergone a period of very sharp growth since the start of the industrial age in the 18th century, as Figure 1-2 illustrates. At the same time, the global average Gross Domestic Product (GDP) per capita has grown in a similar manner, as seen in Figure 1-3. Figure 1-4 shows the clear link between GDP and energy consumption per capita.

Figure 1-2: World population through history - reproduced from (4)
Figure 1-3: World GDP per capita through history - reproduced from (5)
Figure 1-4: Relationship between power consumption and GDP per capita (6)

The vast majority of energy use today is derived from fossil fuels, a finite resource with global reserves of perhaps as little as a few decades at current rates of usage and growth. There exists three potential strategies to solving, or at least delaying, the looming energy crisis:

i. Reverse population growth,

ii. Reduce people’s energy use,

iii. Develop new energy production technologies.
Population reversal and energy restriction measures are highly controversial and may prove difficult to implement despite their potential effectiveness in tackling the looming energy crisis. The development of new energy producing technologies, the 3rd strategy listed above, therefore becomes a must.

An additional element to the need to replace existing fossil fuel energy sources with alternative supplies is the Climate Change issue. It is generally accepted amongst the scientific community that man-made emissions of carbon dioxide and other greenhouse gases into the atmosphere has contributed to the rise in average temperatures. Whilst there are other factors which may influence the temperature of the Earth, for example solar activity, the basic theory of Climate Change is founded upon the work undertaken by Tyndall in 1856 which showed that certain gases, like CO$_2$, trap infra-red light (and therefore heat), the same wavelength of light as that which is reflected from the Earth's surface. Arrhenius in 1896 later showed that too much CO$_2$ in the Earth's atmosphere could lead to dangerously large increases in the average temperature of the Earth, 5 or 6 degrees Celsius for a doubling in the atmospheric CO$_2$ concentration (7).

Increases in the CO$_2$ concentration in the atmosphere are undoubtedly occurring; fundamental chemistry and measurements prove this. Present day attempts to match the Climate Change theory with observations have, however, been clouded in controversy due to the political nature of the issue and the fact that records of direct measurements only go back two or three centuries, too short a period to determine for sure whether the Earth's warming is not simply due to climactic cycles. Despite the furore surrounding it the main finding in (8) from 1998, the so-called 'hockey stick' graph (shown in Figure 1-5 below) created from a collection of data from direct measurements of the past couple of centuries and other indirect sources such as tree rings and ice cores, remains accepted amongst the vast majority of the scientific community today; the temperature of the Earth in the last part of the 20th century was the highest it has been for the entire millennium previously.
THE HOCKEY STICK: THE ORIGINAL AND LATER VERSIONS

The 2001 IPCC version: "Variations of the Earth's surface temperature over the past 1000 years"
The error bars (in grey) show the 95 per cent confidence range.

Figure 1-5: The original 'hockey stick' graph and the reconstructed version, as suggested by the US National Academy of Science in its 2006 report (9)
The case for the development of new energy production technologies is compelling. The challenge to replace fossil-fuel based energy production is, however, formidable. Renewable sources of energy like solar, wave and wind, whilst limitless in supply, have two major drawbacks: there may not be the power available and the supply is intermittent. Due to the difficulty in storing large quantities of energy, renewable sources are likely to only provide for a small proportion of the energy requirement. Nuclear fission can also be part of the solution, but nothing more because of its limited supply and the danger of the proliferation of fissile material. Nuclear fusion has potential to become a viable, clean and abundant energy source. As of yet however, 'breakeven', the point at which more energy is produced than is consumed, has not been reached. Whether or not such an energy source is eventually discovered, it is clear that improvements in the energy efficiency of technology in all industries, including transport, are required if the world's social and economic development is to continue.

1.2.2. Transportation and High Speed Rail

As of 2001, transportation accounted for approximately 25% of total global energy consumption, when measured at the point of use (10). The link between the level of transportation and wealth is well illustrated in Figure 1-6 below. From Figure 1-7, it is seen that trains generally appear below the Gabrielli / von Kármán line¹, whereas cars and planes are plotted above it.

As seen from Figure 1-2 earlier, the global population is growing at an unprecedented rate. Concurrently, global urbanisation is occurring to such an extent that, according to the UN, urban dwellers outnumbered rural ones for the first time in history in 2008 (11). With efficient transportation a key driver of social and economic development, the construction of high density, high capacity, inter-city passenger transport networks is becoming a priority for countries across the world.

High speed rail is increasingly viewed by business and governments as an effective solution to the inter-city passenger transportation challenge of the 21st century due to its ability to:

¹ The Gabrielli / von Kármán diagram plots the specific resistance and maximum operational speed of different types of vehicle.
• Significantly increase transport system capacity and connectivity between city centres; and
• Significantly reduce journey-times between city centres.

The motivation behind this thesis is to try to establish whether the development of high speed rail is an efficient means with which to do this in terms of operational, traction energy consumption and associated carbon dioxide emissions, and to investigate its scope for improvement in these respects.

![Figure 1-6: The link between income and propensity to travel (12)](image-url)
1.3. Research Aims

The main aims of the thesis are as follows:

- Establish the key factors which influence the operational energy consumption of a journey by high speed rail.

- Evaluate the performance, in terms of operational energy consumption and CO₂ emissions, of high speed rail in comparison with its competitor modes of road, domestic air and existing rail.

- Identify areas of vehicle design which contribute towards the minimizing of the operational energy consumption and CO₂ emissions of high speed rail.
1.4. Approach

In any study of energy consumption, it is vital to state clearly where the measurement is being taken from. Due to efficiency losses in the system, the energy consumption at the wheel of a high speed train is less than that at the current collector. Similarly, the power collected at the line is less than the power required from the power station. In addition energy is not only consumed in train operation, but also during construction and maintenance, and there is the non-traction aspect to consider. In this thesis the analysis is restricted to the operational traction energy requirement at the train's current collector. For comparisons with the car and domestic air, primary energy consumption is considered. Associated CO₂ emissions are restricted to direct emissions only, not indirect emissions from fuel transportation and refining, for example.

No two high speed rail systems are the same. The rolling stock and route features such as gradient, the density of stops and the maximum operational speed can all vary considerably from line to line. In addition, high speed rail systems throughout the world are powered by a wide variety of sources. For example, 78% of French electricity generation is by nuclear power, compared to a global average of 15% (14). The results from any investigation into the energy consumption and CO₂ emissions of high speed rail are unique to the scenario used.

In the thesis presented here the UK's HS2 route is used to realize the research aims. The UK case is a prime candidate with which to carry out such an analysis for the following reasons:

- The debate as to whether the high speed network, labelled High Speed Two (HS2), should be built at all is fierce with energy and the environment central issues for both sides of the argument.
The UK, like many developed countries in the world, is currently very reliant on fossil fuels for power generation and has plans to de-carbonise it in the future in accordance with European and global agreements. The CO₂ emissions of the electrically powered HS2 line would therefore be representative of the performance of high speed rail in this respect with the competing modes across the globe. Such a study using the French case of power generation for example, the vast majority of which is nuclear based, would clearly not suffice.

An existing line, the West Coast Main Line (WCML), already connects London, Birmingham and Manchester, three of the four cities which will be connected by the HS2 network. It has recently (in the last decade) been upgraded to increase capacity and to allow 200 km/h travel across much of the route. A comparison of the energy consumption and CO₂ emissions of HS2 and the WCML would therefore provide a useful insight into how high speed rail performs against existing, conventional intercity rail.

1.5. Summary of Thesis

The thesis is summarized as follows:

In Chapter 2 a literature review is undertaken to understand the energy flow in high speed rail systems. Train and route-based factors which influence the energy consumption of a journey are then reviewed before a summary of existing work comparing the energy consumption and CO₂ emissions of high speed rail with other modes. Gaps in current knowledge are identified.
A train energy simulator which was developed to carry out the investigations is described in Chapter 3. Train and route data (for the London to Birmingham section) provided by HS2 Ltd. as well as a control strategy are input into the simulator to estimate the operational energy consumption of a train running on the line, measured at the point of consumption, the train's current collector. Validation of the model is discussed before the results of two so-called baseline simulations (one for each direction) are used to carry out an initial analysis into the factors which affect the energy consumption. In order to do this, a Key Performance Indicator (KPI) is defined, the kWh/pass-km, where the distance unit refers to the great circle distance between the end points and not the route length.

In Chapter 4 those factors which affect both the energy consumption and the journey time are investigated: the number of intermediate stops and the line speed profile. An analysis is then conducted to calculate their effect based on a constant journey time, along with the effect of shorter dwell times at stations.

In Chapter 5 the energy consumption of the HS2 reference train is compared with data collected for its competing modes: road and domestic air, using the KPI defined earlier in the thesis. Comparisons are made with reference to the respective journey times of the modes and are also made in terms of CO₂ emissions. Train and route data for the WCML between London and Birmingham are then input into the simulator to estimate the energy consumption of the existing line and comparisons are made with the proposed HS2 line. Analysis is then carried out to quantify the contributing factors towards the energy difference observed between the WCML and HS2.

For the final investigation of the thesis in Chapter 6, the focus switches to comparing the energy consumption of the HS2 reference train with that of other high speed vehicles using an analysis methodology similar to the WCML comparison. The first type of vehicle studied is the Transrapid maglev, before moving on to the Japanese Shinkansen, generally regarded as the most energy-efficient type of high speed rolling stock in the world. A final comparison is made with the double-decker TGV Duplex. The aim of this last phase of the thesis is to attempt to quantify by how much the energy consumption of the HS2 line could be reduced (if at all) by the use of different rolling stock and to identify key areas of vehicle design which minimize the energy consumption of high speed rail.
Chapter 7 reviews the thesis, summarizes the main findings and discusses implications of energy-reducing measures identified. The contributions which this thesis makes to knowledge are stated before recommendations of further work.
References


2. Ibid.


7. Ibid. 4.


13. Ibid.
Chapter 2: High Speed Rail, the Energy Flow and Comparisons with Other Modes

The definition of high speed rail is discussed and a history of its development is given. The conversion of primary energy stored in the fuel in power stations to kinetic energy of the train is explained. Factors which influence the energy consumption of a journey are then reviewed. Information on CO₂ emissions associated with electricity consumption in the UK is then presented, together with a summary of those from other modes. Previous research into the operational energy and CO₂ performance of high speed rail in comparison with other modes is detailed along with data collected for various types of high speed rolling stock. Areas warranting further study are considered in the final discussion.

2.1 High Speed Rail

2.1.1 How Fast is ‘High Speed’?

The concept of ‘high speed’ is relative and has changed over time. Whilst 30 mph trains were considered very fast back in the 1830s, such maximum speeds would be considered totally inadequate in today’s developed world.

According to the UIC today, there is no single standard definition of ‘high speed rail’ due to the complex reality of the infrastructure, rolling stock and operations which make up railway systems. Some trains run at restricted speeds on conventional lines, even though they are capable of much higher speeds, whilst some lines carry trains, which have a maximum speed much below the speed for which the line was designed. In other cases, newly built high-speed trains may be running on rail designed to withstand high speeds, but still be limited to lower speeds due to nearby built-up areas or tunnels. Finally, due to the UIC’s wish ‘to take into account those railways which are making laudable efforts to provide high speed despite a basis of old infrastructure and technology which is far removed from that employed by the railways of Western Europe’, systems which are viewed as a step towards a future genuinely high speed service may already be considered ‘high speed’ (1).
In the European Union however, so-called ‘high speed’ lines comprise those which are specially built for speeds greater than or equal to 250 km/h and those existing lines which have been upgraded for 200 km/h travel. Where those lines have special features as a result of topographical, relief or town-planning constraints, high speed lines may have lower speed limits (2).

2.1.2 The Development of High Speed Rail

By defining ‘high speed’ railways as those which have rail services operating today at speeds of 250 km/h or above, the majority of high speed rail development over the past few decades has occurred in only a few countries, principally Japan, the European countries France, Germany and Spain and, most recently, China.

Japan

The first railway specifically built for rail travel at high speeds, the Tokaido Shinkansen, opened in Japan in 1964 in time for the Olympic Games that year. The line stretched some 515 km and connected Japan’s two most populous cities, Tokyo and Osaka. The new Shinkansen 0 series trains operated at 210 km/h, which at the time was far ahead of other rail operators, leading to a cut in the journey time from Tokyo to Osaka from 6 ½ hours on the old existing line to just 4 hours, further reducing to 3 hours 10 minutes by 1965 (3).

Since then high speed lines have been constructed along the length of Japan, such that, according to UIC figures, as of today there are over 2,000 km of such lines (4). The maximum operating speed of the Shinkansen sets has also gradually increased since the days of the Series 0, with the Series 300 introduced in 1992, with its lightweight aluminium alloy body and more streamlined nose, attaining speeds of 270 km/h (5). Maximum operating speeds have since been pushed to 300 km/h with the 2007 introduction of the N700 onto the Shinkansen network. Figures 2-1 and 2-2 below illustrate the development of the Shinkansen train sets since 1964:
France, Germany and Spain

France was the next country to build a high speed rail system, completing its first, largely dedicated, Ligne à Grande Vitesse (LGV) between Paris and Lyon, the Sud-Est, in 1981, with the high-speed Train à Grande Vitesse (TGV) vehicles operating with a maximum speed of 270 km/h. Speeds on the network, which has developed from this original line, have since increased to 300 km/h and, according to UIC figures, France now has over 1,800 km of high speed lines. In addition, the high speed TGV trains run over a further 7,000 km of conventional track (8).

The West German government decided in 1969 to upgrade and extend its intercity rail network, principally to reduce bottlenecks on the most heavily used route: Hamburg to Munich. In 1991 new sections from Hannover to Würzburg and from Mannheim to Stuttgart were opened on which Inter-City Express (ICE) trains operated with a maximum speed of 280 km/h. Since the fall of the Berlin Wall, three more major high speed lines have been built: Hannover to Berlin, Cologne to Frankfurt and Hamburg to Berlin and there are now over 1,200 km of high-speed lines in Germany (9).

The first high speed line in Spain opened in 1992 and stretched 471 km between Madrid and Seville, cutting journey times by 60% from 6 ½ to just over 2 ½ hours, with trains operating at speeds of up to 270 km/h. Due to the success of the first line, further high-speed lines have been built between Madrid and Barcelona, Madrid and Valladolid and from Cordoba to Malaga, which branches off the Madrid to Seville line, with maximum operating speeds of up to 300 km/h. In 2009 there were almost 1,600 km of high speed lines (10).
China

The pace of development of high speed rail in China over the past few years has been nothing short of incredible. In the few years since construction began in the 2000s, as of 2010, over 3,000 km of existing lines had been upgraded to 200-250 km/h operation and over 2,000 km of new railway line have been built for maximum operating speeds of up to 350 km/h, the fastest in the world (11). This feat is all the more remarkable when it is considered, for example, that almost a third of the 1,068 km Wuhan to Guangzhou line has been built over karst topography. The eagerly awaited Beijing to Shanghai line opened in 2011, with plans to eventually push the maximum operating speed to 380 km/h, which would make it the fastest operating line in the world, cutting journey times by rail from 10 to just 4 hours (12). Such speed up plans have been put on hold since the Wenzhou crash in July 2011, but the rate of construction of high speed rail lines appears to have remained relatively unscathed. By the end of 2012, China is set to have over 10,000 km of high speed lines, with a further 15,000 km planned to make up the final network (13).

Globally

According to the UIC’s definition of high speed, as of the end of 2010, there were almost 15,000 km of high speed railway across the world. As can be seen from Figure 2-3, this figure is set to increase to over 40,000 km by 2024.

From inspection of these figures one can, quite understandably, come to the conclusion that high-speed rail has a very bright future ahead of it. Whilst this may be true, there is also a small region of this graph which exposes high speed rail’s weakness in terms of global growth. The rise from just below 15,000 km to over 25,000 km from the end of 2010 to the end of 2012 is almost entirely due to the rate of development in China, as seen from Figure 2-4. During 2014 there is virtually no growth of high speed rail globally, because no major lines are planned for completion in China that year. In other words, without China the graph would look very different.
Elsewhere, there are plans for high speed rail development in Turkey, the Middle-East, South America, India, the UK as well as in the U.S., where in February 2011, the Obama administration announced a 6-year, $53 billion plan to build a national and intercity passenger rail network (14). Whether such ambitious plans will be realized in a time of severe global economic austerity remains to be seen.

Figure 2-3: The development of the global high speed rail network - reproduced from (15)

Figure 2-4: The development of the Chinese high speed rail network - data from (16)

Figure 2-5 below shows how the maximum operating speed record for high speed lines globally has increased over the years from 160 km/h pre-Shinkansen to 270 km/h in the late 1970s / early 1980s, and to 350 km/h today.

Figure 2-5: The evolution of maximum speed on rails (17)
2.2 The Energy Flow

Modern high speed rail systems are generally powered from national electricity grids. The flow of energy from primary energy contained in the fuel at the power station to energy consumed at the wheels of an electrically-powered train can be split into 3 broad stages as illustrated in Figure 2-6, each of which is associated with an energy loss:

![Energy flow diagram](image)

*Figure 2-6: Energy flow from the fuel at the power station to the wheels of an electric train*

2.2.1 Primary Energy in the Fuel to Electrical Energy for Transmission

The primary energy contained in the fuel can come from a variety of sources. In 2008, 77% of the electricity generated in the UK came from 2 main sources: gas and coal, with nuclear next on 13%, as Figure 2-7 shows:
Where we get our electricity from 2008

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>1%</td>
</tr>
<tr>
<td>Other</td>
<td>2%</td>
</tr>
<tr>
<td>Renewables</td>
<td>6%</td>
</tr>
<tr>
<td>Nuclear</td>
<td>13%</td>
</tr>
<tr>
<td>Coal</td>
<td>32%</td>
</tr>
<tr>
<td>Gas</td>
<td>45%</td>
</tr>
</tbody>
</table>

*Figure 2-7: The UK’s electricity mix in 2008 (18)*

**Fossil Fuel and Nuclear Energy**

The energy loss from converting the fuel energy into electrical energy for transmission from the power station depends on the source and power station design. For the fossil fuels, such as coal, oil and gas, the primary fuel energy is in the form of chemical energy, which is released as heat during combustion. For nuclear fuels, the primary fuel energy is in the form of heat released when the nuclei of fissile isotopes, like Uranium-235 and Plutonium-239, split when bombarded by free neutrons (when the nuclei split, neutrons are also released, thereby creating a self-sustaining chain reaction, which is controlled inside the nuclear reactor). For both fossil fuel and nuclear power stations the thermal energy released is used to heat steam to drive turbines to generate electricity. The amount of thermal energy which can be converted to useful work is limited, however, by the Carnot efficiency, which is the maximum theoretical efficiency of a closed loop heat engine given the temperatures of the hot and cold reservoirs, as Equation 2-1 shows:

\[
\eta = 1 - \frac{T_c}{T_H}
\]

*Equation 2-1: Carnot efficiency (temperatures are in Kelvin)*
The thermal efficiency of fossil fuel power stations is generally around the 40% mark, although efficiencies of up to 60% have been achieved by Combined Cycle Gas Turbine (CCGT) plants, when calculated on a Lower Heating Value (LHV) basis, which ignores the latent of heat of vaporization of water, and a Gross Output basis, where the energy output is measured at the generator terminals. The first CCGT power station to achieve such efficiencies is gas-fired and opened at Baglan Bay in Wales in 2003 (19). In current generation nuclear power stations the steam is heated to lower temperatures than in fossil fuel power stations. As a result nuclear power stations are generally 30-35% thermally efficient, although an efficiency of 42% has been achieved by British Energy’s Advanced Gas-cooled Reactor (AGR) (20).

Renewable Energy

In 2008, renewable forms of energy, such as bio-fuel, hydro, wind, solar and tidal sources, constituted only 6% of electricity production in the UK. The proportion of UK electricity coming from renewable sources is set to increase significantly over the coming years, however, as European and global climate change agreements come into force. The UK government has committed to provide at least 15% of its total energy use by 2020 from renewable sources. This energy use includes heating and transport as well as electricity production. In order to achieve this target both the quantity and proportion of electricity production from renewable sources will have to increase five-fold in the period 2008 to 2020, from 22 TWh to 117 TWh and 6% to 30% respectively, as Table 2-1 shows:

<table>
<thead>
<tr>
<th></th>
<th>2008</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Energy</td>
<td>Renewable Energy</td>
</tr>
<tr>
<td></td>
<td>TWh</td>
<td>TWh</td>
</tr>
<tr>
<td>Electricity</td>
<td>387</td>
<td>22</td>
</tr>
<tr>
<td>Heat</td>
<td>711</td>
<td>7</td>
</tr>
<tr>
<td>Transport</td>
<td>598</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td>1,695</td>
<td>39</td>
</tr>
</tbody>
</table>

Table 2-1: Final energy consumption in 2008 and projected for 2020 (N.B. The heat and transport sectors exclude electricity used in these sectors which is included in the electricity section) - reproduced from (21)
The plan to achieve the 2020 target is illustrated in Figure 2-8. Electricity for rail travel is included in electricity generation’s share, rather than transport’s share. It can be seen that approximately 60% of the electricity to be produced from renewable sources by 2020 (if the target is achieved) will come from wind power, which will be equivalent to approximately 18% of the total UK electricity production by 2020. The next biggest proportion will come from bio-fuels, with only small amounts coming from hydro, wave and tidal power.

Wind Power

Wind power is an intermittent source of energy which relies on the weather being suitable. Whilst efficiency is an important measure for technologies using fuels which have cost and are limited, it has little relevance in the case of wind power. Nevertheless wind turbines are designed so that the aerodynamic efficiency of the blades or rotor approaches as close to the theoretical limit as possible, Betz’s limit of 59.3%\(^2\). Typically, aerodynamic efficiencies of 50% can be practically achieved for wind speeds below rated (23). A much more useful measure of the effectiveness of a wind turbine to produce power is the Capacity Factor, sometimes called the Load Factor, which is defined in Equation 2-2:

\[\text{Capacity Factor} = \frac{\text{Actual Energy Output}}{\text{Potential Energy Output}}\]

\(^2\)Albert Betz in 1919 concluded that no wind turbine can convert more than 59.3% of the kinetic energy of the wind into mechanical energy turning a rotor. This limit assumes an ideal, mass-less rotor with an infinite number of blades and an axial, incompressible flow (24).
Typically capacity factors for wind farms in the UK vary between 20% and 40%, averaging about 30%. Manufacturers design turbines for particular wind conditions, through selection of the ratio of the swept area of the rotors to the installed capacity, to minimize the cost of electricity production. Despite wind power’s intermittent nature, it has been selected to lead the way in the UK to achieving the 15% target for renewable source energy production by 2020.

The Rest

Bio-fuels are set to become the second largest provider of electricity from renewable sources, after wind power, by 2020. The energy flow from primary energy in the fuel to electrical energy is similar to the fossil fuel case, with the majority of the primary energy lost in the conversion of heat to mechanical work. Thermal efficiencies of 20-40% can typically be obtained (26).

The development of wave and tidal power makes up only a small part of the plan to substantially increase renewable-based electricity production by 2020, somewhat surprisingly given that the UK has wave power levels that are amongst the highest in the world and extensive tidal range resources, particularly in the Severn Estuary, which are regular and predictable unlike wind. The main reason for the lack of planning for tidal power by 2020 is expense. In Scotland, however, plans are afoot to produce 1.2 GW of electricity from sites off Orkney and the Caithness and Sutherland coasts (27). It has been estimated that the construction of two large barrages across the river Severn could contribute to more than 5% of the electricity supply, when measured against 2006 levels of electricity production in the UK (28). The government, however, scrapped the project in October 2010 due to cost concerns.
Will the UK Meet its Renewable Energy Target?

The National Grid has connection agreements in place to add approximately 27,000 MW of capacity from renewable sources to the UK electricity network by 2020, on top of the 4,950 MW already in place, although only 20% of the proposed projects have planning permission as of November 2010 (29). Moreover, in April 2009, Jim Skea, a member of the UK government's advisory Committee on Climate Change, warned that achieving the target of 15% of energy needs from renewable technologies by 2020 would be “a very big struggle” (30).

Others too remain sceptical that the targets of both 15% of energy and 30% of electricity from renewable sources by 2020 will be achieved, with possibly less than 17% of electricity production coming from renewable sources by then (31).

What Could the UK Electricity Mix Look Like by the Opening of High Speed Two?

Predictions of the electricity mix in the UK by the time of a possible opening of the High Speed Two link between London and Birmingham in 2026 should be treated with caution. Significant political will is required if such ambitious changes to power generation in the UK are to be carried out, all the more so given the current economic climate in the UK. If the 2020 target of 30% of electricity generation derived from renewable sources is achieved, the electricity mix could be similar to that given in Figure 2-9 below:

Where we will get our electricity from 2020

![Figure 2-9: The potential electricity mix in 2020 if the UK is to meet its 2020 obligations (32)]
Between now and the potential opening of High Speed 2 in 2026, however, all but 1 of the 10 nuclear power stations currently operating in the UK are set for closure. Several new nuclear power stations have been planned and proposed, which should provide approximately 20 GW (gigawatts of electrical energy) by the early 2020s (33). The 30% target for renewable sources of electricity is likely to be missed, however, if new gas-fired power stations continue to be used, rather than renewable sources, to plug the gap left by the decommissioning of the country’s nuclear and older coal-fired power stations.

2.2.2 Flow of Electrical Energy from the Power Station to the Train’s Current Collector

The electricity grid in the UK is traditionally divided into the high-voltage transmission network (voltages of 275kV and above) and lower-voltage distribution systems (132kV and below). Electrical energy from the power stations flows through both networks in the form of 3-phase alternating current (AC). For high speed rail applications, such as the High Speed 1 line between London and Paris, step down transformers at substations lower the voltage to 25kV AC, from where the electrical energy is sent along overhead lines suspended above the rails to be picked up by the train’s current collector.

Figure 2-10 shows a schematic of the transmission and distribution of the electrical energy from the power station to electrified railway networks. For a 25 kV AC train system approximately 4% of the electrical energy which is supplied to the national grid by the power station is typically lost in transmission and distribution to the train’s current collector (34).
2.2.3 Electrical Energy Picked up by the Current Collector to Traction Energy Consumed at the Wheel

The 25kV electricity supply in the overhead line is picked up by the current collector, from where the electrical energy is distributed to different components of the train. The precise distribution of this energy depends on the train. Generally, the majority of the power supplied to the train during a journey is fed to the traction motors, whilst the rest is provided for ancillary services, like lighting, heating and air-conditioning.
In electrically-powered high speed trains the tractive power is either supplied to two power cars, one at each end of the train rake, or distributed along a rake of Electric Multiple Units (EMUs). The French TGV is an example of a train with 2 power cars at each end, although many other high speed trains nowadays are EMUs, like the German ICE3, the Chinese CRH3 and the Japanese Shinkansen, which have the advantages of reduced maximum axle load and improved traction adhesion. Typically 80-85% of the electrical energy supplied to the train at the current collector is consumed both at the wheel and by the ancillary services, the rest of the energy being lost as heat from components in the vehicle's propulsion system such as the motors and transmission.

### 2.2.4 Breakdown of Primary Energy Consumption

Figure 2-11 below compares typical energy losses in electric rail vehicles discussed above with those in diesel-powered trains, starting with the primary energy in the fuel. The large loss associated with the conversion of heat into useful work for both cases is well illustrated.

*Figure 2-11: Primary energy consumption of typical inter-city electric (Class 390 Alstom Pendolino) and diesel (Class 221 Super-Voyager) trains - reproduced from (36)*
2.3  **Energy Consumption at the Wheel**

The energy consumed at the wheel can be split into three main components:

i. The energy consumed in accelerating the vehicle mass, the so-called inertial component\(^3\).

ii. The energy consumed in overcoming the mechanical and aerodynamic resistance acting on the vehicle.

iii. The energy consumed in overcoming the component of the weight of the vehicle parallel to the route gradient.

The degree to which each component contributes to the total energy consumed at the wheel depends on the type of train and route. Generally, a greater proportion of the total energy consumption at the wheel is used to overcome the resistance acting on the vehicle for high speed express services than for suburban commuter services, which have more stops and hence more energy directed towards accelerating the vehicle mass. The gradient component is dependent on the altitude of the start and end points of the journey in addition to the weight of the vehicle.

2.4  **Factors Influencing the Energy Consumption at the Wheel**

The main factors, associated with both the train and route, which influence the energy consumption of a journey are now reviewed.

2.4.1  **Train**

Aspects of train design can have a significant impact on the energy consumption of high speed rail journeys:

\(^3\) Taking into account an allowance for angular acceleration of rotating parts.
**Mass**

The effect of mass on the energy consumption of a journey is generally lower for high speed, express services than for stopping, commuter services, as the energy required to overcome the inertia of the vehicle is a lower proportion of the total energy consumption. The energy penalty of increased mass is further reduced by the fact that modern high speed trains are often equipped with regenerative braking systems, which can potentially feed back into the power supply as much as 80% of the kinetic energy of the train which would otherwise be lost as heat. Motivation to reduce the mass of trains is more linked to its effect on the dynamic loads exerted on the track. The unsprung mass is of particular importance, as it has a large influence on the magnitude of the P2 dynamic force peak, which is the cause of ballast damage and track top deterioration.

Rochard and Schmid in (37) attempted to calculate the financial benefit of reducing a high speed train’s mass by 1 kg. As a part of this work, it was calculated that 775 kWh of traction energy at the wheel could be saved by running a train 25% lighter than the existing Class 373 Eurostars between London St. Pancras and the UK portal of the Channel tunnel, which equates to 0.031 kWh per tonne-km. Using an electricity price of £0.05 / kWh, the cost of the energy saving due to the 25% mass reduction was estimated to be just 2% of the fleet purchase cost. This, however, was based upon an assumption that the price of energy remains constant, which is unlikely to be the case over the next few decades as the global demand for energy increases and new, more sustainable sources of energy are sought.

Japan provides a good example of how the mass and more specifically the mass per seat of high speed trains has been reduced through technological development, as Figure 2-12 illustrates. There is large scatter in the data due to the many factors involved. The seating arrangement, such as the use of 2 + 2 and 3 + 2 seating, the class of each carriage, the presence of dining carriages and the size of toilet facilities all affect the total number of seats on the train. EMUs also have an advantage over locomotives in that all cars can seat passengers.
Standards also influence the mass per seat. For example, in Europe high speed trains are subject to structural crashworthiness standards in accordance with Technical Standards of Interoperability (TSIs), which stipulate that up to 6 MJ of energy be absorbed in the event of an end-to-end collision, of which at least 75% should be in the front part of the first vehicle and the remainder distributed over all the inter-car links down the train (41). Not only does design around the standards contribute to the mass of the vehicle but also passenger seats are not positioned in such ‘crush’ zones, thereby further driving up the mass per seat. In Japan, the focus is on crash prevention rather than mitigation and the structural crashworthiness standards are much less stringent than in Europe.

Technological developments of components, such as traction motors, have contributed to lowering the mass per seat of modern high speed trains, as has the switch from steel to aluminium body shells. In Japan such developments have clearly driven down the mass per seat, but in Europe such measures have been offset by measures for added comfort, such as more spacious seating and dining cars. A balance needs to be struck between the added appeal of the comfort provided and its effect on revenues and cost, both economically and to the environment. The drive for lighter and more energy efficient trains is starting to gather pace in Europe with the development of the lightweight Talgo Avril, which is set to have a mass per seat of 0.54 tonnes (42).
**Resistance**

For high speed services with few intermediate stops, the component of energy consumed in overcoming the resistance to motion of a train is a greater proportion of the total energy consumption than for lower speed, stopping commuter services. This is the case because the resistance to motion of any vehicle increases with the speed, and can be approximated by a quadratic function in the so-called Davis equation, as given in Equation 2-3:

\[
F_D = A + Bv + Cv^2
\]

*Equation 2-3: The Davis Equation*

There are two components of the resistance force acting on a train: mechanical and aerodynamic. Generally coefficients \( A \) and \( B \) relate to the mechanical resistance and \( C \) to the aerodynamic resistance. Figure 2-13 demonstrates how the aerodynamic resistance component becomes dominant for high speed applications:

*Figure 2-13: Variation in the mechanical and aerodynamic components of resistance with speed for a Class 373 Eurostar (43)*
Rochard and Schmid in (44) review the methods used to calculate the resistance to motion of trains, with a particular emphasis on the validity of various tools for calculating the resistance to motion of high-speed trains. Approaches taken in the UK, France, Germany and Japan are described and comparisons made with results from run-down tests. For high speed applications, it was concluded that the most significant aspects of the aerodynamic design of a train are: a streamlined nose and tail, cross-sectional area and perimeter, bogie shrouding and a smooth underside. Pantographs and inter-vehicle gaps were seen to be less significant. Bogie shrouding is of particular importance when it is considered that turbulence around the bogies accounts for up to 40% of the total aerodynamic drag (45).

Ito in (46) describes the techniques used to improve the aerodynamic characteristics of the Shinkansen during the development of the 700 series, achieving reductions in the noise and pressure fluctuations outside the car and aerodynamic drag. Improvements to the nose shape, car body surfaces, coupling parts and pantograph design are all described. Figure 2-14 below shows how the drag coefficient of the nose section of the 700 series has reduced to a quarter of the value for the 0 series and the aspect ratio, AR, the nose length divided by the car body cross-sectional hydraulic radius, has increased over two-fold:

<table>
<thead>
<tr>
<th>Type</th>
<th>Cd ratio</th>
<th>AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>4.4/1.77</td>
</tr>
<tr>
<td>100</td>
<td>84</td>
<td>5.5/1.77</td>
</tr>
<tr>
<td>300</td>
<td>58</td>
<td>6.0/1.68</td>
</tr>
<tr>
<td>700</td>
<td>25</td>
<td>9.2/1.65</td>
</tr>
</tbody>
</table>

*Figure 2-14: The development of nose shape in successive Shinkansen series (47)*
Other aspects

The operational speed clearly has a major effect on the energy consumption of a journey, as the resistance to motion increases with speed, according to the quadratic Davis equation. Even when ignoring the resistance to motion, the energy required to simply accelerate the train’s mass from rest to a certain speed increases with the square of the speed. Figure 2-15 below shows how the energy consumption at the wheel increases with the maximum operational speed of various rail journeys around the world:

![Graph showing energy consumption vs speed](image)

**Figure 2-15: Effect of maximum operational speed on the energy consumed at the wheel for the European single-deck trains: Øresundstogt, Regina, Arlandabanan, Class 90, X 2000, Class 91, Class 390, Flytoget, Eurostar, TGV PBKA, and ICE-3 (48)**

Signalling systems, for example ERTMS in Europe, can be used to reduce the energy consumption of high speed rail systems. Energy-efficient driving profiles, minimizing braking and maximizing the level of coasting possible for a particular timetable, are calculated at the control centre and recommendations sent wirelessly to the driver. Auxiliary services can also be shut down by the control centre once the train goes out of service. The Spanish national railway company, RENFE, has measured average energy savings of 21% from employing such energy-efficient driving strategies. Automatic Train Operation (ATO) is currently being developed for eco-driving with reference to the traffic condition (49).
Modern high speed rail lines are equipped with regenerative braking systems, which capture the kinetic energy of the train which would otherwise be lost as heat during braking. On alternating current (AC) systems, receptivity of the line is less of an issue than with direct current (DC) systems since resistive losses are significantly lower and power can be transformed up for use elsewhere on the national electricity grid. The percentage of the total energy drawn from the line, which can be saved with the use of regenerative braking, varies depending on the train and route, but typically lies in the range 10% - 20% (50).

2.4.2 Route

Various aspects of the route affect the energy consumption of a journey:

Gradient and Curvature

Gradients obviously affect the energy consumption as the component of the weight of the train can either add to or reduce the total resistance force acting on the train. Curves can also have an effect, not only on the resistance on the train, but perhaps more crucially because speed limits are imposed on curves with smaller radii as the wheel/rail lateral forces at high speeds can’t be compensated by cant alone. At lower speeds, the energy required to overcome the resistance on the train decreases.

Tunnels

Tunnels with a small bore in relation to the cross-sectional area of the train can have a significant impact of the energy requirement. Like with curves, speed limits are imposed in tunnels of small bore in order that the European Railway Agency’s (ERA’s) Technical Specification for Operability (TSI) for pressure changes inside tunnels and the International Union of Railway’s (UIC’s) baseline pressure comfort criteria are met (51). However, unlike with curves, the energy consumption of a train in a tunnel may still be higher than otherwise at lower speeds, as the resistance on the train significantly increases with the blockage ratio, the ratio of cross-sectional area of the train to the cross-sectional area of the tunnel.
Station stops

One would expect that extra station stops would increase the overall energy consumption of a journey. While this may be true, regenerative braking systems can substantially reduce the amount of kinetic energy that would otherwise be lost as heat during braking. In fact, as stopping at stations reduces the average speed of a journey, the increase in energy is further limited as the energy consumption to overcome the resistance on the train is reduced at lower speeds.

Another factor to consider is the number of passengers on board the train. A train full of passengers is more energy-efficient than an empty one, in that less energy is required to transport each passenger to their destination. When measured on a kWh/passenger basis, station stops can therefore decrease the energy consumption, if the presence of the stops increases passenger loading levels.

Route length

The total energy consumption of a journey is of course affected by its length. For this reason, the unit kWh/km is useful when comparing journeys of different lengths. However, the only distance of utility for the passenger is the distance between the end points, rather than the distance along the route. Routes, of course, are very rarely straight, whether by road, rail or air, which means that the distance travelled is always greater than the resultant or direct distance achieved, the great-circle distance, which is the shortest distance between two points on the surface of a sphere measured along a path on the surface of a sphere (the sphere being Earth in this case). A measure of the lack of straightness of a route, the so-called ‘sinuosity’ is defined in Equation 2-4:

\[
\text{Sinuosity} = \frac{\text{Actual distance travelled}}{\text{Great circle distance on Earth}}
\]

Equation 2-4: Definition of route sinuosity
The sinuosity of high speed rail routes can vary quite significantly and is larger in certain circumstances, where the land doesn’t allow straight running and where the route is ‘diverted’ to serve other population centres away from the end points. Table 2-2 shows some values of sinuosity for various rail routes and makes comparisons with the equivalent journey by road:

<table>
<thead>
<tr>
<th>Route</th>
<th>Great circle distance (km)</th>
<th>Mode</th>
<th>Sinuosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>London – Birmingham</td>
<td>160</td>
<td>Rail (proposed HS2)</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rail (existing WCML)</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Road</td>
<td>1.18</td>
</tr>
<tr>
<td>London - Paris</td>
<td>341</td>
<td>Rail (Eurostar)</td>
<td>1.44</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Road (including Eurotunnel)</td>
<td>1.35</td>
</tr>
<tr>
<td>Berlin - Nuremberg</td>
<td>379</td>
<td>Rail (ICE)</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Road</td>
<td>1.16</td>
</tr>
<tr>
<td>Madrid - Barcelona</td>
<td>506</td>
<td>Rail (AVE)</td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Road</td>
<td>1.23</td>
</tr>
<tr>
<td>Tokyo - Osaka</td>
<td>403</td>
<td>Rail (Shinkansen)</td>
<td>1.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Road</td>
<td>1.29</td>
</tr>
</tbody>
</table>

Table 2-2: Great circle distance and sinuosity of various routes - N.B. great circle and road distances calculated from (52); rail distances obtained from (53), (54) and (55)

One would expect flight paths to have sinuosities very close to 1, although with short-haul flights this may well increase substantially, as planes circle above an airport awaiting a landing slot. Since they are variable and dependent on the traffic conditions, flight sinuosities have not been included in Table 2-2.

2.5 Comparisons with Other Modes

2.5.1 Energy

As of today the other modes (except electrified rail) are almost all directly powered by fossil fuels rather than electricity. It is meaningless to compare the electricity consumed by a high speed train with the fuel energy consumed by other modes, as the (large) thermodynamic loss associated with the conversion of heat into useful work occurs prior to the point of electricity consumption whereas it occurs after the point of fuel consumption in a fossil-fuelled vehicle. Comparisons should instead be made with respect to the primary energy stored in the fuel (whether in the vehicle or at the power station).
When quoting the energy consumption of trains along different routes, whether it is measured at the wheel, line or power station (the primary energy), the unit of most often used is the kWh/passenger-km; the number of kilowatt-hours of energy consumed for each passenger travelling 1 km along the route. Despite the high sinuosity of some of the routes demonstrated above, the route distance is often used, rather than the distance of utility, the great-circle distance.

2.5.2 **Carbon Dioxide**

Another useful comparison is with respect to CO$_2$ emissions. It is generally accepted amongst the scientific community that Climate Change is occurring at least in part because of the man-made release of greenhouse gases into the atmosphere. CO$_2$ is the greenhouse gas which is emitted by the man-made burning of fossil fuels in most abundance, and so the unit of measurement of greenhouse gas emissions is grams of CO$_2$.

Other greenhouse gases are also emitted during fossil fuel extraction and combustion processes, for example methane (CH$_4$) and nitrous oxide (N$_2$O), which contribute to the greenhouse effect to differing degrees (for example, the greenhouse effect of a molecule of CH$_4$ is about 8 times that of a molecule of CO$_2$ (56)). To take into account the contribution of all the major greenhouse gases, the unit of measurement of greenhouse gas emissions becomes grams of CO$_2$ equivalent (gCO$_2$e).

2.5.3 **Conversion of Electrical Energy Consumption to Carbon Emissions**

Each year the UK’s Department of Energy and Climate Change (DECC) and the Department for Environment, Food and Rural Affairs (DEFRA) publish data to convert the use of different types of fuel, transport and electricity into equivalent carbon dioxide emissions. Direct and indirect emissions of the prominent greenhouse gases (GHGs): carbon dioxide (CO$_2$), methane (CH$_4$) and nitrous oxide (N$_2$O) are calculated for each unit of electricity consumed, taking into account losses during transmission and distribution of electricity.
The direct emissions originate from the combustion of fuel in power stations to generate electricity, whilst the indirect emissions are associated with the extraction and transport of primary fuels and the refining, distribution and storage of the finished fuels. The electricity consumed from a future high speed rail line in the UK can therefore be converted into equivalent carbon dioxide emissions, based on past data of conversion factors and future predictions of energy mix. Figure 2-16 below shows how direct emissions of CO₂ equivalent per kWh consumed have changed in the period 1990-2008. Based on the latest 5-year rolling average ending in 2008, 543 gCO₂e was emitted for every kWh of electrical energy at the point of consumption.

![Figure 2-16: Time history of the 5-year rolling average of greenhouse gas emissions per kWh of electricity consumed in the UK - data from (57)](image)

### 2.5.4 Comparisons with the Competing Modes

The other modes, with which a future intercity high-speed rail network in the UK would compete, are: road, existing rail and domestic air. Figures of direct emissions of equivalent CO₂ for the competing modes have been published in (58). The high speed Transrapid magnetic levitation (maglev) system developed in Germany and operational in China, regarded by some as a possible alternative to long distance rail travel in future decades, is also considered.
**Car Emissions**

The average car in the UK in 2010 had a fuel consumption of 33.5 mpg and emitted 208 gCO$_2$e/km, based on data from the Society of Motor Manufacturers and Traders (SMMT) on new car direct CO$_2$ emissions from 1997 to 2009 combined with testing cycle data from the Transport Research Laboratory (TRL) and an uplift of 15% agreed with the Department for Transport (DfT) to take into account further real-world driving effects on emissions (59). Between 1985-1986 and 1998-2000, the average occupancy per car in the UK decreased from 1.63-1.56 (60), meaning that if 1.6 persons per car is assumed, the average emissions of UK cars as of today is approximately 130 gCO$_2$e/passenger-km.

**Existing Rail**

As of 2010 average direct emissions from UK existing rail were 56.5 gCO$_2$e/pass-km, a figure which is based on calculations of total electricity and diesel consumed by the railways for the year 2007-2008 and the total number of passengers. The CO$_2$ emissions for electric trains are calculated using the 2006 power generation mix for the UK.

**Domestic Air**

As of 2010 average direct emissions from UK domestic flights were 171.5 gCO$_2$e/pass-km, based on an average passenger loading of 64.5 % and using an uplift of 10% to correct underestimation of real-world emissions by the Core Inventory of Air Emissions (CORINAIR) methodology.
**Maglev**

Maglev is not usually considered a competing mode of high speed rail because there are currently no high speed inter-city Maglev systems in the world. The only operational high speed Maglev system in the world connects Shanghai with its airport. Several years ago, however, the UK government studied the case for building a high speed Maglev network between the country’s major cities. Based on data, made available to Kemp and Smith by Transrapid in (61), the energy consumption (presumed at the guideway) of a potential Maglev line on a 700 km journey from London to Edinburgh with 11 intermediate stops was estimated to be somewhere between 59 kWh/seat and 87 kWh/seat, depending on whether 0 % or 100 % regenerative braking is assumed, which equates to 0.08 - 0.12 kWh/seat-km. Based on 2008 power generation, this corresponds to 50 - 80 gCO$_2$/seat-km.

**Previous studies**

Several studies have been undertaken in the past to compare the energy consumption of high speed trains with other modes. Some prominent work was carried out in this area by Kemp in (62). The primary energy consumption of high speed trains running at 225 km/h and 350 km/h was compared with that of a typical passenger aircraft and car on a journey between London and Edinburgh. It was calculated that, per seat, the 225 km/h train would consume as much fuel as the car and the 350 km/h train would use as much as the plane assuming electricity is derived from fossil fuels as Figure 2-17 shows:

![Figure 2-17: Fuel consumption / passenger: London – Edinburgh (63)](image-url)
Alvarez in (64) takes issue with Kemp’s work, arguing that his results and conclusions don’t tally with Spain’s operational experience of high speed rail. Comparisons are made between Kemp’s results for the energy consumption per seat of a journey between London and Edinburgh and that between Madrid and Barcelona. Comparisons between different trains and routes must always be treated with caution, however, as the length, route topography and train seating arrangement can significantly affect the kWh/seat figure. Nonetheless, Alvarez calculates the energy consumption per seat along the 620 km route from Madrid to Barcelona to be 25 kWh/seat, less than 50% of Kemp’s figure of 57 kWh/seat for a shorter, 600 km journey between London and Edinburgh. Alvarez then goes on to analyze the effect of the mode shift away from air brought about by the opening of a high speed rail route between Madrid and Barcelona.

It can be seen from Figure 2-18 below that generally rail dominates the market for journeys up to 3 hours, with air dominating for longer train journeys. Alvarez used such a relationship between the train/air market share and journey time to optimize the high speed train’s average speed with regards to total CO₂ emissions between Madrid and Barcelona, the optimum average speed found to be approximately 360 km/h.

Figure 2-18: Relationship between the train’s share of the train + plane market and journey time (65)
The Association of Train Operating Companies (ATOC) in (66) analyze the CO₂ emissions of high speed rail and make comparisons with other modes up to 2055. Predictions of passenger loading and CO₂ intensity of the different modes are the main drivers of environmental performance and are central to the investigation.

Network Rail in (67) compares the greenhouse gas emissions of conventional and high speed rail services. Several analyses of occupancy levels, carbon intensity of electricity generation, embedded emissions and modal shift were carried out. High-speed rail is predicted to emit on average 9% more greenhouse gases per seat-km than equivalent conventional rail in 2025, with this figure dropping to 4% over the 30 year life of the trains due to the predicted decarbonisation of the UK’s electricity supply. Due to higher passenger loading predictions, per passenger-km, a high-speed train in the UK would be expected to emit 15 % less greenhouse gases than conventional rail in 2025 and 19 % less over the 30-year life of the trains, increasing further when modal shift and demand creation are factored in.

Thus far in this literature review analysis of the energy consumption of high speed rail and its performance against its competitors has concentrated on the operational energy requirement. Energy is also consumed elsewhere, during the construction of the infrastructure and vehicles. A whole lifecycle analysis of energy consumption gives a better indication of total emissions associated with a particular mode of transport. Libardo and Trabucco in (68) compare the lifecycle energy requirements of high speed rail and air transport services. Whilst the operational energy consumption per seat-kilometre of air is significantly higher than that of high speed rail, infrastructure is limited to the end points, which is not the case for rail (or road). By studying a hypothetical passenger link between two cities, the sum of the energy embodied in the construction of the vehicles and infrastructure and the operational energy is calculated for different daily capacities, route lengths and rail infrastructure costs per kilometre. It is found that for a large capacity of 40,000 seats per day and a low infrastructure cost of € 20m / km the operational energy requirement of a high speed line per seat-kilometre constitutes approximately 70% of the total energy requirement. However, for a low capacity of 5,000 seats per day and a high infrastructure cost of € 50m / km, this figure drops to 10 %. It is concluded that high speed rail is only advantageous over air in terms of total embodied energy per seat-kilometre when the capacity of the system is high.
2.5.5. **Comparisons of High Speed Rolling Stock**

Figures 2-19 and 2-20 below compare the energy consumption of various different types of high speed and conventional, electrically powered rolling stock, using data provided by the RSSB. It is seen that whilst the energy consumption at the current collector of UK conventional trains appears to be consistently around 0.03 to 0.04 kWh/seat-km, European high-speed trains consume anywhere between 0.04 and 0.065 kWh/seat-km. The Japanese Shinkansen trains are significantly more energy-efficient than their European rivals, consuming anywhere between 0.023 and 0.033 kWh/seat-km. The double-decker TGV-2N appears to be the most energy-efficient of the European trains at 0.04 kWh/pass-km. The higher energy-efficiency of the Japanese Shinkansen is attributed to its lower mass and denser seating arrangement, afforded by less stringent crashworthiness standards in particular. It should be noted that in this analysis, the unit of distance, the kilometre, refers to the route length rather than the great circle distance.

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**Figure 2-19: Energy consumption at the current collector of various UK electric trains (69)**

**Figure 2-20: Energy consumption at the current collector of various high-speed trains throughout the world (70)**
2.6 Discussion

2.6.1. Brief Overview of Literature

Modern high speed rail systems are usually electrically powered from the grid. When discussing energy consumption it is important to state where the energy is measured from. Typically only 35-40% of the primary energy in the fuel at fossil fuel and nuclear power stations is converted into electrical energy at the terminals, although this figure can vary from 30% to 60% depending on the type and design. The losses associated with the transmission and distribution of electrical energy to the current collector and the line-to-wheel efficiency of the train are much lower.

Whilst thermodynamic losses at the power station are the concern of power engineers, the railway engineer can still influence the remaining energy flow from the current collector to the wheel. Many factors influence the energy consumption of a journey at the wheel, from train-based parameters like mass, resistance and maximum operational speed, to route-based parameters like the gradient, line speed, and the number of stops.

A review of existing studies into the operational energy consumption and CO$_2$ emissions of high speed rail has been carried out. In a study of different high speed trains throughout the world the Japanese Shinkansen come out on top in terms of energy efficiency. Markedly different conclusions are drawn regarding the operational energy and CO$_2$ performance of high speed rail compared to its competing modes depending on the assumptions made, in particular the load factor and power mix.

Although this thesis concentrates on the operational traction energy requirement and direct CO$_2$ emissions of high speed rail, it is important to note that Libardo and Trabucco also demonstrated the importance of the consideration of a whole lifecycle analysis, particularly for systems of high cost and low capacity.
2.6.2. **Knowledge Gaps**

Three main knowledge gaps surrounding the operational traction energy consumption and direct CO\textsubscript{2} emissions of high speed rail have been identified in this literature review:

- Whilst the effects on the energy consumption of many of the factors listed above have been individually investigated, a comprehensive study comparing all the relevant factors has not been found.

- Perhaps due to the political nature of the topic and the over-riding effect of certain parameters and assumptions, it is still unclear from the literature what advantage, if any, high speed rail has over its competitor modes of road, domestic air and existing rail, in terms of operational energy consumption and CO\textsubscript{2} emissions. In addition, journey time, an important consideration, is also often ignored in any comparison.

- Whilst figures of the operational traction energy consumption of various types of high speed train have been quoted in the literature, no detailed study appears to exist which compares their energy consumption and journey time on the same route. Additionally no study has been found which attempts to quantify the contributing factors towards differences in energy consumption between different types of high speed train. A good example of this latter point concerns comparisons of European and Japanese high speed train sets. Whilst the reasons given for the Japanese Shinkansen's lower energy consumption compared to its European competitors (lower tare mass and a denser seating arrangement) may well be correct, a detailed study is nevertheless required. Likewise no study has been found comparing other types of train in a similar manner, for example double-deckers and Maglev technology.
2.6.3. **Next Steps**

The thesis attempts to plug the knowledge gaps described above using the structure set out in Chapter 1, which the author hopes will inform high speed rail engineers, like those at HS2 Ltd, of the consequences in terms of operational traction energy consumption and direct CO₂ emissions of their rolling stock and route specifications.

For the reasons set out in the Introduction, the UK’s High Speed Two route provides the ideal backdrop with which to carry out such an investigation. In Chapter 3, the train and route data which is used to carry out the simulations are described before the results of the so-called baseline simulations are presented, around which all subsequent parametric studies conducted in this thesis centre.
References


2. Ibid.


4. Ibid.


7. Central Japan Railway Company (CJR). *The "N700-I Bullet".* Central Japan Railway Company (CJR); n.d.

8. Ibid. 3.

9. Ibid.

10. Ibid.


13. Ibid. 3.


16. Ibid. 3.

17. Ibid. 15.


22. Ibid.


25. Ibid. 23.


32. Ibid. 18.


35. Ibid.

36. Ibid.


38. Ibid. 5.


44. Ibid.


47. Ibid.

48. Ibid. 39.


58. Ibid.

59. Ibid.


64. Ibid. 55.


Ibid. 39.

Ibid.
Chapter 3: The Train Energy Simulator and Baseline Simulations

The simulator is described with details of the train, route and driving assumptions employed. Baseline simulations are then carried out to estimate the energy consumption and journey time of a high speed train travelling along the HS2 London to Birmingham route in both directions. The results are then validated against existing data. The influences of several parameters on the energy consumption are then investigated using a defined Key Performance Indicator (KPI).

3.1 The Train Energy Simulator

As described in Chapter 2, when estimating the energy consumption of any journey it is important to distinguish where exactly the energy is measured from. For example, for a particular journey the energy consumed at the wheel of a train is different to the energy picked up at the current collector, which is again different to the primary energy in the fuel consumed in the power station.

In the Train Energy Simulator, the energy consumed at the wheel is calculated by solving the vehicle’s equation of motion.
### 3.1.1 Equation of Motion

The equation of motion of the train is derived from the free-body diagram, shown in Figure 3-1:

![Free-body diagram of the train](image)

By resolving the forces parallel to the plane of the slope:

\[ M(1 + \varphi) \frac{d^2x}{dt^2} = F_{TB} - F_D - Mg \sin \alpha \]

**Equation 3-1: Equation of motion of a vehicle**

It can be seen from Equation 3-1 that the resultant acceleration of the vehicle depends on the component of the weight of the vehicle in the plane of the slope, the resistance force acting on the train (described by the characteristic Davis equation), and the tractive or braking effort applied by the driver of the train. A rotational inertia mass factor, \( \varphi \), is included as the energy input into the train is used not only to accelerate the train mass in a translational manner, but also to rotationally accelerate some of the train’s constituent parts, for example the wheels and motor components.

For any particular journey, the slope varies along the route and is usually described by discrete data. In addition, as rail routes have speed limits, so-called ‘line speeds’, which vary in a step-wise fashion with distance along the route, the tractive / braking effort applied by a driver also depends on a discrete set of data. For these two reasons Equation 3-1 is solved numerically. Curvature of the route is assumed to have a negligible effect on the train’s resistance.
3.1.2 Method of Solution

A computational model written in MATLAB SIMULINK, called the Train Energy Simulator, was developed by the author to solve the equation of motion for the vehicle in the time-domain, based on pre-defined route and train data and the driving strategy employed.

Variables, defined in MATLAB m-files, are input into the SIMULINK model at the simulation setup stage. The model itself has three further modules:

i. Control module – where the driving strategy is defined.

ii. Vehicle module – where the equation of motion for the vehicle is solved. The vehicle module is based on a version developed by previous members of the FRRC.

iii. Energy calculation module – where the energy consumed at certain points in the train’s propulsion architecture is calculated.

Figure 3-2 illustrates the calculation process:
Figure 3-2: Schematic of the Train Energy Simulator
Simulation Setup Module

Table 3-1 lists the variables relating to the train, route and control strategy, which are defined in m-files and loaded prior to the start of the simulation:

<table>
<thead>
<tr>
<th>Train-related</th>
<th>Route-related</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train mass</td>
<td>Gradient</td>
</tr>
<tr>
<td>Rotational inertia mass factor</td>
<td>Line speed</td>
</tr>
<tr>
<td>Mass of passengers</td>
<td>Station stops</td>
</tr>
<tr>
<td>Passenger load factor</td>
<td>Tunnelling</td>
</tr>
<tr>
<td>Train length</td>
<td></td>
</tr>
<tr>
<td>Resistance to motion</td>
<td></td>
</tr>
<tr>
<td>Efficiency between pantograph and wheel</td>
<td>Maximum operational speed</td>
</tr>
<tr>
<td>Efficiency of regeneration</td>
<td>Braking acceleration rate</td>
</tr>
<tr>
<td>Auxiliary Power Supply (APS)</td>
<td>Dwell time</td>
</tr>
<tr>
<td>APS Efficiency</td>
<td></td>
</tr>
<tr>
<td>Ttractive Effort</td>
<td></td>
</tr>
<tr>
<td>Braking Effort (friction and electrodynamic)</td>
<td>Time step</td>
</tr>
</tbody>
</table>

Control Module

The driving strategy employed is detailed in Figure 3-2 and is summarized as follows:

- From a stationary start, 100% of the available power is initially applied.

- 100 % power continues to be applied until either the line speed or the maximum operational speed is reached, whichever is lowest.

- On reaching line speed or the maximum operational speed, the power is reduced to balance the resistive forces acting on the train (the sum of the Davis equation and gradient resistances) with the tractive force. Where the net resistance force acting on the train is negative due to a steep downhill gradient, braking is applied to keep the train’s speed constant at the line speed / maximum operational speed limit.
On approach to either a reduction in the line speed or a station stop, a braking force is applied in order to obtain a deceleration rate of 8% of acceleration due to gravity, as recommended in (1). Electrodynamic braking is used where possible, at speeds greater than 20 km/h only. Where the braking effort required exceeds that which can be provided by electrodynamic braking, friction braking is used to provide the remaining braking force.

The dwell time for the train at each station is 2 minutes, after which the train moves on with maximum power applied initially.

**Vehicle Module**

The control decision for the current time step is input into the equation of motion for the train, as a tractive or a braking effort. The Davis equation and gradient resistance forces are calculated with reference to the train’s velocity and displacement at the current time step. The Davis equation resistance is simply a function of velocity and so is straightforward to calculate. The overall gradient resistance force acting on the train is calculated with reference to the average slope of the line at positions along the length of the train. The acceleration for the current time step is then calculated. The velocity and displacement for the next time step are calculated using standard MATLAB SIMULINK solvers.

**Energy Calculation Module**

The module calculates the energy consumed at the wheel, the energy drawn from the overhead line at the current collector and the energy recoverable during braking. In addition, all three components of energy consumption at the wheel (that is the energy consumed to overcome the inertia, Davis equation resistance and gradient resistance, as discussed in Chapter 2) are calculated individually to aid the subsequent parametric studies presented later in this chapter.
i. **Energy Consumed at the Wheel**

The energy consumed at the wheel is calculated by integration with respect to time of the product of the tractive force and velocity, as Equation 3-2 shows:

\[ E_W = \int_0^t F_T v \, dt \]

*Equation 3-2: Energy consumed at the wheel*

ii. **Gross Energy Drawn from the Overhead Line**

The gross energy drawn from the line is subsequently calculated by taking account of the efficiency losses between the train’s current collector and the wheels. Supply to the auxiliary power system is also included, as Equation 3-3 shows:

\[ E_L = \frac{E_W}{\eta_{L-W}} + \frac{P_{APS} \times t_j}{\eta_{APS}} \]

*Equation 3-3: Gross energy drawn from the line*

iii. **Energy Regenerated Back to the Line**

The energy regenerated back to the line is calculated with reference to the train’s characteristic braking curves. In the Train Energy Simulator the braking deceleration rate is assumed to be constant at 8% of the acceleration due to gravity, as discussed previously in the description of the Control module. The braking force applied is therefore not constant as it is adjusted to take account of the reduction in the Davis equation resistance with decreasing speed and any variation in the gradient.
During electric braking the traction motors provide a torque in reverse to the direction of rotation to decelerate the train and hence acts as a generator producing electrical energy in accordance with Fleming’s right-hand rule. There are two types of dynamic brake: rheostatic, where the electrical energy generated is lost as heat in resistors, and electrodynamic, which feeds the electrical energy back to the supply. The train also has friction brakes, which mechanically brake the train and, as with the rheostatic braking, convert the kinetic energy of the train into heat energy which is lost to the environment.

Electrodynamic brakes can only provide a certain quantity of braking force as seen in Figure 3-3 below, and do not operate at all at speeds below about 20 km/h, for which the braking force provided is too low.

![Braking curves of a high speed train (provided by HS2 Ltd) - scale omitted for confidentiality reasons](image)

For cases where the braking force is greater than that provided by electrodynamic braking, mechanical braking is used to make up the excess. The energy returned to the line during braking is calculated in the Train Energy Simulator according to Equation 3-4:
iv. **Components of Energy Consumption at the Wheel**

When splitting up the components of energy consumption at the wheel, it must be remembered that energy is only consumed when power is supplied to the wheels. Therefore, during coasting or braking, when the power is off, no energy is being consumed, even though the wheels are turning and the vehicle is moving.

The energy used to accelerate the vehicle mass and to overcome the Davis equation and gradient resistances are calculated according to Equations 3-5 to 3-7 below:

Equation 3-5: Energy consumption at the wheel to accelerate the vehicle mass (overcome inertia)

\[ E_i = \int_0^t M(1 + \varnothing) a v \, dt \text{ for } F_T > 0 \]

Equation 3-6: Energy consumption at the wheel to overcome the Davis equation resistance

\[ E_D = \int_0^t F_D v \, dt \text{ for } F_T > 0 \]

Equation 3-7: Energy consumption at the wheel to overcome the gradient resistance

\[ E_G = \int_0^t (Mg \sin \alpha) v \, dt \text{ for } F_T > 0 \]
For the purposes of this investigation, the component of energy at the wheel consumed in overcoming the Davis equation resistance, $E_D$, is split into 3 further components: the mechanical resistance, the nominal aerodynamic resistance in open air, and the total aerodynamic resistance including in tunnels, as Equations 3-8 to 3-10 show:

$$E_{D(A+Bv)} = \int_0^t (A + Bv) \, v \, dt \text{ for } F_T > 0$$

*Equation 3-8: Energy at the wheel to overcome the mechanical resistance*

$$E_{D(Cv^2)} = \int_0^t (Cv^2) \, v \, dt \text{ for } F_T > 0$$

*Equation 3-9: Energy at the wheel to overcome the nominal aerodynamic resistance (excluding tunnels)*

$$E_{D(TfCv^2)} = \int_0^t (TfCv^2) \, v \, dt \text{ for } F_T > 0$$

*Equation 3-10: Energy at the wheel to overcome the total aerodynamic resistance (including tunnels)*

The components of braking energy at the wheel, useful when considering regenerative effects, are calculated in a similar fashion, except that they only hold for negative values of tractive effort, i.e. during braking.

### 3.2 Train and Route Data

Baseline simulations are carried out using the following train and route data, provided by HS2 Ltd. The train data is based on the so-called ‘HS2 reference train’, a state of the art European high speed train. Route data is based on the London to Birmingham and reverse ‘preferred’ route proposed by HS2 Ltd towards the end of 2009. Tables 3-2 to 3-3 and Figures 3-4 to 3-5 show some of the parameters used in the baseline simulations. The Davis equation resistance shown is assumed to be for an unladen train. The mechanical components of resistance have been adjusted to take account of passenger mass at 70% loading. Regenerative braking is based on the curves shown in Figure 3-3.
Table 3-2: Station and tunnel information (provided by HS2 Ltd.)

<table>
<thead>
<tr>
<th>Station</th>
<th>Tunnel</th>
<th>London end</th>
<th>Birmingham end</th>
</tr>
</thead>
<tbody>
<tr>
<td>London</td>
<td>#1 (dia. 7.2m)</td>
<td>1.2</td>
<td>10.3</td>
</tr>
<tr>
<td>Intermediate #1</td>
<td>#2 (dia. 12.0m)</td>
<td>31.5</td>
<td>40.6</td>
</tr>
<tr>
<td>Intermediate #2</td>
<td>#3 (dia. 12.0m)</td>
<td>126.6</td>
<td>128.0</td>
</tr>
<tr>
<td>Birmingham</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3-3: Train-based parameters used for the baseline simulations (provided by HS2 Ltd.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tare mass (including 7 tonnes for water and other services)</td>
<td>MT</td>
<td>t</td>
<td>382</td>
</tr>
<tr>
<td>Rotational inertia mass factor</td>
<td>φ</td>
<td>%</td>
<td>4</td>
</tr>
<tr>
<td>Mass of passengers at 100 % load</td>
<td>MP</td>
<td>t</td>
<td>38</td>
</tr>
<tr>
<td>Passenger load factor</td>
<td>LF</td>
<td>%</td>
<td>70</td>
</tr>
<tr>
<td>Train length</td>
<td>LTRAIN</td>
<td>m</td>
<td>200</td>
</tr>
<tr>
<td>Maximum operational speed</td>
<td>VMAX</td>
<td>km/h</td>
<td>330</td>
</tr>
<tr>
<td>Efficiency between pantograph and wheel</td>
<td>ηLW</td>
<td>%</td>
<td>82.3</td>
</tr>
<tr>
<td>Efficiency of regeneration</td>
<td>ηr</td>
<td>%</td>
<td>80</td>
</tr>
<tr>
<td>Auxiliary Power Supply (APS)</td>
<td>PAPS</td>
<td>kW</td>
<td>275</td>
</tr>
<tr>
<td>APS Efficiency</td>
<td>ηAPS</td>
<td>%</td>
<td>85</td>
</tr>
<tr>
<td>Station dwell time</td>
<td>tDWELL</td>
<td>mins</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 3-4: London to Birmingham route details

Figure 3-5: Tractive effort and Davis equation resistance of the HS2 reference train (provided by HS2 Ltd.)
3.3. Baseline Simulation Results

Some typical outputs from the simulations are shown below in Figures 3-6 to 3-9. The results are shown in Table 3-4:

![Speed - distance history for the London to Birmingham simulation](image)

*Figure 3-6: Speed - distance history for the London to Birmingham simulation*

![Speed - time history for the London to Birmingham simulation](image)

*Figure 3-7: Speed - time history for the London to Birmingham simulation*

![Power drawn from the line - time history for the London to Birmingham simulation](image)

*Figure 3-8: Power drawn from the line - time history for the London to Birmingham simulation*

![Power regenerated to the line - time history for the London to Birmingham simulation](image)

*Figure 3-9: Power regenerated to the line - time history for the London to Birmingham simulation*
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Lon - Bir</th>
<th>Bir - Lon</th>
<th>Av.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Journey time</td>
<td>$t_J$</td>
<td>min:sec</td>
<td>48:00</td>
<td>48:01</td>
<td>48:01</td>
</tr>
<tr>
<td>Energy drawn from the line</td>
<td>$E_L$</td>
<td>kWh</td>
<td>4630</td>
<td>4455</td>
<td>4543</td>
</tr>
<tr>
<td>Energy returned (-ve) to the line</td>
<td>$E_R$</td>
<td>kWh</td>
<td>-396</td>
<td>-424</td>
<td>-410</td>
</tr>
<tr>
<td>Net energy drawn from the line</td>
<td>$E_{NET}$</td>
<td>kWh</td>
<td>4234</td>
<td>4031</td>
<td>4133</td>
</tr>
<tr>
<td>Energy for Auxiliary Power System</td>
<td>$E_{APS}$</td>
<td>kWh</td>
<td>259</td>
<td>259</td>
<td>259</td>
</tr>
<tr>
<td>Energy consumed at the wheel</td>
<td>$E_W$</td>
<td>kWh</td>
<td>3598</td>
<td>3453</td>
<td>3526</td>
</tr>
<tr>
<td>Energy at the wheel to overcome gradient resistance</td>
<td>$E_G$</td>
<td>kWh</td>
<td>93</td>
<td>-12</td>
<td>41</td>
</tr>
<tr>
<td>Energy at the wheel to overcome Davis equation resistance</td>
<td>$E_D$</td>
<td>kWh</td>
<td>2565</td>
<td>2495</td>
<td>2530</td>
</tr>
<tr>
<td>Energy at the wheel to accelerate vehicle mass (overcome inertia)</td>
<td>$E_I$</td>
<td>kWh</td>
<td>940</td>
<td>971</td>
<td>956</td>
</tr>
<tr>
<td>Energy at the wheel to overcome mechanical component of Davis equation resistance</td>
<td>$E_{D(A+Bv)}$</td>
<td>kWh</td>
<td>322</td>
<td>317</td>
<td>320</td>
</tr>
<tr>
<td>Energy at the wheel to overcome aerodynamic component of Davis equation resistance (excluding tunnels)</td>
<td>$E_{D(Cv^2)}$</td>
<td>kWh</td>
<td>2137</td>
<td>2078</td>
<td>2108</td>
</tr>
<tr>
<td>Energy at the wheel to overcome aerodynamic component of Davis equation resistance (including tunnels)</td>
<td>$E_{D(TICv^2)}$</td>
<td>kWh</td>
<td>2244</td>
<td>2178</td>
<td>2211</td>
</tr>
<tr>
<td>Energy leaving the train at the wheel during braking (-ve)</td>
<td>$E_B$</td>
<td>kWh</td>
<td>-826</td>
<td>-942</td>
<td>-884</td>
</tr>
<tr>
<td>Energy leaving the train at the wheel during regenerative braking (-ve)</td>
<td>$E_{RB}$</td>
<td>kWh</td>
<td>-821</td>
<td>-937</td>
<td>-879</td>
</tr>
<tr>
<td>Energy to overcome gradient resistance during regenerative braking</td>
<td>$E_{RB(G)}$</td>
<td>kWh</td>
<td>19</td>
<td>-100</td>
<td>-41</td>
</tr>
<tr>
<td>Energy to overcome Davis equation resistance during regenerative braking</td>
<td>$E_{RB(D)}$</td>
<td>kWh</td>
<td>94</td>
<td>129</td>
<td>112</td>
</tr>
<tr>
<td>Energy to overcome inertia during regenerative braking</td>
<td>$E_{RB(I)}$</td>
<td>kWh</td>
<td>-934</td>
<td>-966</td>
<td>-950</td>
</tr>
<tr>
<td>Energy to overcome mechanical component of Davis equation resistance during regenerative braking</td>
<td>$E_{RB(D(A+Bv))}$</td>
<td>kWh</td>
<td>20</td>
<td>25</td>
<td>23</td>
</tr>
<tr>
<td>Energy to overcome aerodynamic component of Davis equation resistance (excluding tunnels) during regenerative braking</td>
<td>$E_{RB(D(Cv^2))}$</td>
<td>kWh</td>
<td>61</td>
<td>88</td>
<td>75</td>
</tr>
<tr>
<td>Energy to overcome aerodynamic component of Davis equation resistance (including tunnels) during regenerative braking</td>
<td>$E_{RB(D(TICv^2))}$</td>
<td>kWh</td>
<td>74</td>
<td>105</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 3-4: London to Birmingham and return baseline simulation results (+ve ~ energy to train; -ve ~ energy from train)
3.4. Choice of Time Step

An investigation is carried out to determine the size of time step to use in the simulations. Smaller time steps lead to greater accuracy at the expense of simulation time. As Figures 3-10 and 3-11 demonstrate, the solutions for both the gross energy drawn from the line and the journey time for the London to Birmingham simulations appear to converge at a time step size of approximately 0.1 seconds. The time step used in all the simulations in the thesis is 0.05 seconds, which is the largest time step which outputs equal values of energy drawn from the line and journey time to the nearest kWh and second respectively as the smallest time step studied, 0.01 seconds.

![Figure 3-10: Gross energy drawn from the line (London to Birmingham) output by simulator versus time step](image1)

**Figure 3-10: Gross energy drawn from the line (London to Birmingham) output by simulator versus time step**

![Figure 3-11: Journey time (London to Birmingham) output by simulator versus time step](image2)

**Figure 3-11: Journey time (London to Birmingham) output by simulator versus time step**

3.5. Model Validation

A direct comparison with measured data is of course not possible, as the HS2 line has not been built yet. Data has been collected from four sources, however, with which the results from the simulator are compared.
Firstly, the same train and route data was input into a VISION model, the industry standard timetabling software in the UK, which output the journey time for the London to Birmingham route as 48:30, compared to 48:00 output by the Train Energy Simulator used in this thesis (2). A 30 second difference (approximately 1%) is deemed acceptable, especially when it is considered that the raw train and route data used were converted for use in the models entirely separately by different parties. In addition, whilst the overall driving strategies of both simulators were the same, there could well be small differences between the two algorithms.

Figure 3-12 below compares the acceleration profile of the HS2 reference train on a flat track obtained by the simulator with the same curve provided by the manufacturer. As illustrated, the acceleration of the HS2 reference train in the Train Energy Simulator is slightly greater than that indicated by the data provided by the manufacturer, which may be a contributing factor towards the observed difference in journey time output between the Train Energy Simulator and VISION models described earlier. The Train Energy Simulator accelerates the HS2 reference train from 0 to 349 km/h in 6:40, 4% less than the 6:58 figure provided by the manufacturer. Such a difference could be down to different assumptions of passenger loading levels and vehicle weight, a slight difference in the Davis equation resistance coefficients, a different rotational inertia mass factor, or a combination of each. Such a small change in the acceleration performance of the vehicle would have a negligible effect on the energy consumption and journey time outputs.

Figure 3-13 compares the energy consumption of the HS2 reference train output from the baseline simulations with data for other high speed trains around the world, presented towards the end of Chapter 2. The unit of comparison is the kWh/pass-km, where the energy is measured at the point of consumption, assumed to be the current collector, and the distance unit is the route length, not the great-circle distance as in the KPI defined in this thesis. Despite each train and route being unique, the fact that the energy consumption calculated for the HS2 reference train (the net energy drawn from the line) is similar to other European high speed trains in service gives the author confidence in the accuracy of the energy calculations, especially in light of the above 2 discussion points.
The fourth source of validation of the Train Energy Simulator involves simulations conducted of a 9-car Class 390 running on the WCML, the details and results of which are provided in Chapter 5. It is seen from the simulation results in Chapter 5 that the net energy consumption from the line of the Class 390 running on the WCML is 0.043 kWh/seat-km, where the distance unit refers to the Great Circle Distance between the two end points, not the route length. The RSSB recommend an energy consumption value of 0.040 kWh/seat-km (on a route kilometre basis) for the 9-car Class 390 running on the WCML in (4), which is in good agreement with the results output from the Train Energy Simulator.

### 3.6 Investigation of Train-Based Factors

The breakdown of components of energy consumed at the wheel is now used to investigate the ‘direct’ effects on the energy consumption of reductions in the train’s tare (unloaded) mass and aerodynamic resistance. The ‘indirect’ effects associated with a change in acceleration performance due to changes in mass and aerodynamic resistance are considered negligible.
Figure 3-14 below shows the breakdown of the components of the energy consumed at the wheel. It should be noted that a negative gradient resistance consumption is obtained on the downhill Birmingham to London route as the train gains kinetic energy from the gravitational potential energy it loses.

In addition to tare mass and aerodynamic resistance investigations, the effect of regenerative braking capability is studied. Where appropriate, the analysis is carried out at three points of energy measurement: the energy consumed at the wheel, the gross energy drawn from the line and the net energy drawn from the line (taking into account regeneration). Comparisons are then made with line-to-wheel efficiency, route sinuosity and passenger load factor in terms of the KPI discussed in Chapter 2, the kWh/pass-km, where the unit of distance refers to the direct great circle distance between the end points, the distance of utility for the passenger.

![Figure 3-14: Breakdown of the components of the energy consumed at the wheel](image)

3.6.1. **Tare Mass**

**Energy Consumed at the Wheel**

As seen from Equations 3-5 and 3-7 earlier, the inertia and gradient resistance components of the energy consumed at the wheel are both proportional to the train mass (including passengers). The mechanical component of resistance, represented by the terms independent of and dependent on train speed in the Davis equation, $A+Bv$, is also dependent on vehicle mass as described in (5).
The effect of tare mass on the energy consumption at the wheel is calculated using the relation shown in Equation 3-11, where $M$ is the original total mass of the train (including passengers), $M_T$ is the tare mass of the train and $M_P$ is the passenger mass. Figures 3-15 and 3-16 illustrate how the energy consumption at the wheel and its components vary with tare mass, when taking both the London to Birmingham and return routes combined. Figure 3-17 shows a breakdown of the percentage contribution of each component to the change of energy at the wheel due to variations in tare mass.

\[
(E_W)_{MT} = \frac{M_T + M_P}{M} \left( E_G + E_I + E_{D(A+Bv)} \right) + E_D(TICv^2)
\]

Equation 3-11: Effect of tare mass on the energy consumption at the wheel

![Graph showing energy consumption variation with tare mass](image1)

Figure 3-15: Variation of energy consumption at the wheel per route-km and its components with tare mass taking both the London to Birmingham and return routes combined

![Graph showing percentage change](image2)

Figure 3-16: Percentage change of energy consumed at the wheel with tare mass for both routes combined (compared to baseline values)

![Graph showing percentage contribution](image3)

Figure 3-17: Percentage contribution of each component to the change in energy consumed at the wheel due to variations in tare mass for both routes combined
From the gradient of the line labelled ‘Total’ in Figure 3-15 the energy at the wheel cost per route-kilometre of each tonne of tare mass is 0.018 kWh for the average of the two routes. When converted to percentages (see Figure 3-16) a 25% reduction in the tare mass produces approximately an 8-9 % decrease in the energy consumption at the wheel.

From Figure 3-17 it can be seen that 72% of the drop in energy consumption due to a reduction in tare mass is because of the reduction in the inertial requirement, thus demonstrating the fact that the train mass is more critical in terms of energy consumption for lower speed, stopping commuter services, for which the inertial component of the energy consumption at the wheel is significantly higher than the 27 % calculated for HS2 (from Figure 3-14 earlier). Most of the rest of the drop is because of the reduction in the Davis equation resistance requirement and only a small proportion is due to the reduction in the gradient force.

On any return journey the effect of the gradient is likely to be small since the gradient components from each route will mostly cancel each other out (a downhill gradient one way is an uphill gradient the other way). Both gradients don’t completely cancel each other out, however, as the locations where power is applied are not the same for both routes.

**Gross Energy Drawn from the Line (Excluding Regeneration)**

Conversion to the effect of mass on the energy drawn from the line (excluding electrodynamic braking) is a simple process in this case, as the line-to-wheel efficiency and the energy consumed by the Auxiliary Power Supply are assumed to be constant. Using the appropriate values from Table 3-4 and with reference to Equation 3-3 earlier, the energy drawn from the line cost per route-kilometre of each tonne of tare mass is 0.022 kWh. When expressed in percentage terms a 25% reduction in the tare mass produces a similar decrease in the energy consumption at the line as with the energy consumption at the wheel analysis, around 8 %.
Net Energy Drawn from the Line (Including Regeneration)

When calculating the effect of the tare mass on the net energy drawn from the line, the energy returned to the line during braking needs to be considered. For a larger vehicle mass, less of the energy which would otherwise be lost as heat during braking is recovered if the same regenerative braking curve is assumed. However, more powerful motors with greater capacity to regenerate energy back to the line may be installed for vehicles of greater mass in order to maintain the acceleration performance. In the analysis presented here, it is assumed that the energy regenerated varies proportionally with the total energy lost during braking throughout the regenerative phase, i.e. the energy at the wheel which would otherwise be lost as heat during the regenerative braking.

The variation of net energy consumption at the line with tare mass, \((E_{NET})_{MT}\), is calculated according to Equation 3-12 to 3-14. Taking both London to Birmingham and return routes combined, it is calculated that 0.016 kWh of extra electrical energy is consumed at the line per route-kilometre for every additional tonne onboard the train. In percentage terms a 25% reduction in the tare mass produces an approximate 6-7% decrease in the net energy consumption at the line.

\[
(E_L)_{MT} = \frac{(E_W)_{MT}}{\eta_{L-W}} + \frac{P_{APS} \times t}{\eta_{APS}}
\]

*Equation 3-12: Variation of gross energy drawn from the line with tare mass*

\[
(E_{RB})_{MT} = \frac{M_T + M_p}{M} \left( (E_{RB(G)}) + (E_{RB(I)}) + (E_{RB(D(A+B\nu))}) + (E_{RB(D(TFCv^2))}) \right)
\]

*Equation 3-13: Effect of tare mass on the components of braking energy during the regenerative phase*

\[
(E_{NET})_{MT} = (E_L)_{MT} + \frac{E_R}{E_{RB}} (E_{RB})_{MT}
\]

*Equation 3-14: Variation of net energy consumption at the line with tare mass (N.B. the braking energy is of opposite sign to the energy drawn from the line)*
3.6.2. Aerodynamic Resistance

Energy Consumed at the Wheel / Gross Energy Drawn from the Line

As observed previously, the Davis equation resistance component constitutes approximately 70% of the total energy consumed at the wheel. Of this 70%, approximately 90 % of the energy consumed in overcoming the Davis equation resistance is used to overcome the aerodynamic component, as seen from Table 3-4 earlier. The aerodynamic resistance itself therefore contributes to well over 60% of the total energy consumption of the journey at the wheel. As can be seen from Figure 3-18 below, the total energy consumed at the wheel decreases by over 16 % with a 25 % reduction in the aerodynamic resistance.

![Figure 3-18: Percentage change of energy consumed at the wheel with aerodynamic resistance for both routes combined](image)

As there is just a constant efficiency loss between the wheel and line (excluding regeneration), and the auxiliary power can be assumed to be negligible, clearly the energy drawn from the line (excluding regeneration) varies in approximately the same way.
Net Energy Drawn from the Line (Including Regeneration)

Clearly a reduction in the aerodynamic resistance will result in a larger requirement to brake, as less assistance is provided by the aerodynamic resistance to slow the train down. As with the tare mass investigation it is assumed in the analysis that the energy regenerated back to the line varies proportionally with the total braking energy during the regenerative phase.

The variation of net energy drawn from the line is calculated according to Equations 3-15, 3-16 and 3-17. The benefit of a 25% reduction in the aerodynamic resistance in terms of net energy drawn from the line is calculated to be 16-17% for the average of the London to Birmingham and return routes.

\[
(E_L)_{E_D(T_{Fc}v^2)} = \frac{(E_W)_{E_D(T_{Fc}v^2)}}{\eta_{L-W}} + \frac{P_{APS} \times t}{\eta_{APS}}
\]

*Equation 3-15: Variation of gross energy drawn from the line (excluding regenerative braking) with aerodynamic resistance*

\[
(E_{RB})_{E_B(D(T_{Fc}v^2))} = E_B(D(T_{Fc}v^2)) + E_B(G) + E_B(I) + E_B(D(A+BV))
\]

*Equation 3-16: Variation of energy at the wheel available for recovery with aerodynamic resistance*

\[
(E_{NET})_{E_D(T_{Fc}v^2)} = (E_L)_{E_D(T_{Fc}v^2)} + \frac{E_R}{E_{RB}}(E_{RB})_{E_B(D(T_{Fc}v^2))}
\]

*Equation 3-17: Variation of net energy drawn from the line (including regenerative braking) with aerodynamic resistance*

Tunnels

Tunnels affect the aerodynamic resistance acting on a train, as discussed in Chapter 2. The above analysis includes the effect of tunnels, and as seen from Table 3-4 earlier, the presence of the tunnels along the HS2 route contributes to an increase in the energy consumption at the wheel of 103 kWh, or approximately 3%, when taking the average of the London to Birmingham and return routes. As seen from Table 3-2 earlier, 19.6 km of the 175.3 km HS2 route is in tunnels, or 11%, meaning that on average the energy consumption along the part of the route in tunnels is 27% greater because of their presence (the ratio of 3:11 is 27%).
The relative size of train and tunnel affects the aerodynamic resistance acting on the train. A train with a cross-sectional area close to that of the tunnel bore acts like a piston in a cylinder, where the movement of air in front of and along the train is restricted by the surrounding wall.

Data provided by the HS2 reference train manufacturer is used here to investigate the effect of train and tunnel dimensions on the aerodynamic resistance acting on the train (and hence the energy consumption). The aerodynamic component of resistance is multiplied by a tunnel factor as seen in Equation 3-18. Figures 3-19 and 3-20 illustrate the relation between the average aerodynamic resistance acting on the HS2 reference train and the tunnel dimensions. In reality large transient pressure changes occur when a train enters a tunnel, which affect the aerodynamic resistance. The aerodynamic tunnel factors presented here are average values for the HS2 reference train in a 'typical' tunnel. Train and tunnel design, for example skin roughness, the number and frequency of ventilation shafts, influence the aerodynamic tunnel factor.

$$F_D(T_fC_v^2) = T_fC_v^2$$

*Equation 3-18: Calculation of tunnel factor*

![Figure 3-19: Relation between tunnel dimensions and aerodynamic tunnel factor for the HS2 reference train](image1)

![Figure 3-20: Variation of aerodynamic resistance force with blockage ratio and speed in a 10 km tunnel](image2)
From Figure 3-19 it is seen that the aerodynamic resistance increases with tunnel length and blockage ratio, reaching over three times its nominal, open-air value for tunnels 10 km in length and 7 m in internal bore. 90% of the internal cross-sectional area of the tunnel is assumed to be occupied by free air, the rest by solids for example the track foundations as assumed in (6).

It should be noted that the speed of a train inside tunnels is limited by Technical Specifications of Interoperability (TSI) safety criteria detailed in (7), which state that the maximum pressure variation in trains must not exceed 10 kPa, even in the event of a failure of the train’s sealing system and when two trains pass each other in a two-track tunnel. Additional criteria, which state that no more than a 0.5 kPa pressure change in any 1 second period, and no more than a 2.5 kPa pressure change in any 10 second period may occur inside a sealed train, have been drawn up by HS2 Ltd. to ensure satisfactory levels of passenger comfort are maintained in tunnels (large pressure gradients cause aural discomfort). Only in cases whereby two trains meet in a two-track tunnel may these criteria be violated, provided that (a) the comfort criteria are never exceeded by more than 40%; and (b) the TSI requirement is always met; and (c) the comfort criteria are exceeded for no more than 5% of the time both trains are in the tunnel (8).

3.6.3. Energy Regeneration

It clearly only makes sense to investigate the effect of energy regeneration on the net energy drawn from the line. As seen from Table 3-4 earlier, by taking the average of the two baseline simulations, 410 kWh out of the total 884 kWh leaving the train at the wheel during braking is regenerated back to the line, which equates to 46% of the total braking energy at the wheel and roughly 9% of the gross energy drawn from the line.

Figures 3-21 and 3-22 show the effect of the ability to recover energy which would otherwise be lost as heat during braking.
3.6.4. Comparisons with other Factors

The KPI used in this thesis and introduced in Chapter 2 for comparisons of energy consumption is the kilowatt-hour per passenger-kilometre (kWh/pass-km), with the kilometre referring to the unit of utilization as far as the passenger is concerned, the great-circle distance.

Figure 3-23 below uses this unit to compare the effect on the energy consumption of a 25% variation compared to baseline values of tare mass, aerodynamic resistance and regenerative capability with likewise changes to the line-to-wheel efficiency, route sinuosity and passenger load factor. The energy is taken as the net energy drawn from the line, including the effects of electrodynamic braking, and is expressed as a percentage of the baseline case. It should be noted that the regenerated energy percentage is with reference to the total energy which would otherwise be lost during braking. The line-to-wheel efficiency, route sinuosity and passenger loading levels vary by 25% either side of the baseline values, and in the case of the former two, their values are saturated at 100%; the line-to-wheel efficiency cannot be greater than 100% and the route sinuosity cannot be less than 100%. The mass of the passengers has been ignored in the passenger loading analysis, as a 25% change in the passenger load factor equates to less than a 3% change in the train’s tare mass.
From Figure 3-23 above, it can be seen that the passenger loading has the largest effect on the net energy consumption. As with any inverse relationship, the law of diminishing returns applies: the greater the passenger loading, the less the energy benefit for a given rise in the number of people. From simple Mathematics a 25% rise in the passenger loading from 70% to 95% yields a decrease in the energy consumption according to the KPI of over 25%. However, a 25% decrease in the passenger loading from 70% to 45% increases the energy consumption by over 55%. The same principle applies with the line-to-wheel efficiency, the only difference being a higher baseline value of 82.3% meaning that any increase produces a slightly lower improvement in percentage terms than the passenger loading.

The net energy consumption at the line varies proportionally with the sinuosity, as the great circle distance, which is the ratio of the route length to the sinuosity, is the denominator of the KPI. As in this case the sinuosity is so close to unity (109 %), a 25% increase in the sinuosity would increase the energy consumption according to the KPI by almost that value. For higher baseline values of sinuosity, the constant of proportionality would be less.
It is seen that the net energy consumption is generally less sensitive to percentage changes in the mass, aerodynamic resistance and braking energy regenerated, than to percentage changes in the line-to-wheel efficiency, route sinuosity and passenger loading. A 25% decrease in the tare mass and aerodynamic resistance yield approximately a 7% and 17% reduction in the net energy consumption respectively. Likewise, a 25% increase in the braking energy regenerated, as a percentage of the total braking energy available, yields a 5% reduction in the net energy consumption. These compare with a 19% reduction in the net energy consumption for an 18% increase in the line-to-wheel efficiency from 82% to 100%, an 8% reduction in the net energy consumption for a 9% decrease in the route sinuosity from 109% to 100% and a 26% reduction in the net energy consumption for a 25% increase in the passenger loading from 70% to 95%. Going the other way, whilst the energy penalties of increased mass, aerodynamic resistance and reduced regenerative braking are equal in magnitude to their benefits, a 25% increase in the sinuosity and 25% decreases in the line-to-wheel efficiency and passenger load factor carry energy penalties of 23%, 45% and 55% respectively.

### 3.7 Discussion

A computational model called the 'Train Energy Simulator' has been developed by the author to estimate the operational energy requirement of a single high speed train running along the proposed HS2 route. Simulations have been carried out on the proposed UK High Speed 2 line between London and Birmingham using train and route data provided by HS2 Ltd and the results have been validated against existing data. The components of energy consumption to accelerate the vehicle and to overcome the resistance and gradient forces acting on the vehicle were calculated to determine the effect of different parameters on the energy consumption.

Three train-based parameters were investigated, namely the tare mass, aerodynamic resistance and the regenerative braking capability and comparisons were made with variations in the line-to-wheel efficiency, the route sinuosity and passenger loading levels, based on the net energy consumption at the line (including the effects of electrodynamic braking) and the KPI introduced in Chapter 2.
Analysis suggests that the energy consumption is two to three times as sensitive to the aerodynamic resistance as to the tare mass for high speed routes. The influence of mass would be larger for slower, commuter routes with more stops and the influence of aerodynamic resistance would likewise reduce. Similarly, the influence of braking energy recovery would be greater for such commuter routes. Tunnels were also seen to have a significant effect on the component of energy consumption associated with aerodynamic drag, although as only 11% of the HS2 route studied is in tunnels, the energy increase associated with tunnels is limited to 3%.

The net energy consumption is far more sensitive to the route sinuosity, line-to-wheel efficiency and the passenger loading. A combined 25% reduction in the mass and aerodynamic resistance, and 25% increase in the proportion of braking energy returned to the line reduces the energy consumption by approximately 30%, the same energy saving obtained by increasing the passenger load from 70% to 100%.

In Chapter 4 the effects of the number of intermediate stops and the line speed profile on the energy consumption and journey time are investigated. A study is then conducted to calculate their effects based on a constant journey time analysis, along with the effects of shorter dwell times at stations.
References


4. Ibid.


8. Ibid. 6.
Chapter 4: The Influence of Route Parameters on the Energy Consumption

The effects on the energy consumption of the number of intermediate stops and the line speed profile are studied. Two analyses are carried out for each factor based on a variable and a constant journey time assumption. A further study into the effect of shorter dwell times on the energy consumption is carried out based on a constant journey time analysis. Comparisons are made with the results of the investigation in Chapter 3 before a final discussion.

4.1 Introduction

Parametric studies are carried out to quantify the influence on the energy consumption of changing the following route-based factors:

i. the number of intermediate stops along the proposed HS2 route, and

ii. the line speed profile along the HS2 route.

Two types of analysis are carried out for each of the above factors:

i. Variable journey time, whereby the energy and journey time relation is established for each factor, and

ii. Constant journey time, whereby the energy saving which could be obtained through removal of the intermediate stops or through an increase in the intermediate line speeds for the same journey time as in the baseline simulations, is calculated.
Based on a similar such constant journey time analysis, the energy benefit of reducing station dwell times is also examined. A modification to the Train Energy Simulator based on the bisection iterative technique was carried out to conduct the constant journey time analyses and is described in Section 4.2 below.

4.2. Simulator Modification - Bisection Iterative Technique

In order to achieve the desired journey time for each simulation, which for this investigation is the journey time obtained from each of the baseline simulations in Chapter 3, the maximum operational speed of the HS2 reference train is varied using the bisection iterative technique, as described as follows:

i. The maximum operational speed, $v_{\text{max}}$, for the first iteration of each simulation is set at the maximum operational speed of the HS2 reference train in the baseline simulations, 330 km/h.

ii. $v_{\text{max}}$ is then reduced in set increments (the size of which is chosen according to the scenario) and new simulations run until the journey time becomes larger than the baseline value.

iii. $v_{\text{max}}$ is then increased by an increment half the size of the previous ones and a new simulation is run.

iv. The value of the journey time achieved is then re-evaluated and $v_{\text{max}}$ is either increased or decreased by increments of successively halving sizes for each simulation until the tolerance of the journey time is achieved, which in this study is +/- 0.5 seconds compared to the baseline simulations of Chapter 3.
4.3 Effect of Intermediate Stops

4.3.1 Variable Journey Time Analysis

Four scenarios are studied for both the London to Birmingham and return routes. In all cases the simulation parameters are identical to the baseline case except for the intermediate stop locations:

i. Both intermediate stops (#1 and #2) absent.

ii. Intermediate stop #1 (nearest London) absent.

iii. Intermediate stop #2 (nearest Birmingham) absent.

iv. Intermediate stop #3 added, 88 km from London, as investigated in (1), where the train would otherwise be travelling at maximum speed.

Figures 4-1 to 4-4 show the speed - time history of each scenario together with that of the baseline case for the London to Birmingham route:

![Figure 4-1: Speed - time profiles of scenario (i) and the baseline case for London to Birmingham](image-url)
Figures 4-2, 4-3, and 4-4 show the speed-time profiles of scenario (ii), scenario (iii), and scenario (iv) and the baseline case for London to Birmingham, respectively.

Figures 4-5 and 4-6 show the relationship between the energy consumption and the journey time achieved by varying the number of intermediate stops as in scenarios (i) to (iv), taking the average of the London to Birmingham and return routes combined:
The benefit of regenerative braking in limiting the energy penalty of extra stops is highlighted by the above two figures. From Figure 4-6 in particular, it is seen that regenerative braking reduces the energy penalty of having a third intermediate stop by approximately half, from 8% to approximately 4%. It should be noted that the HS2 reference train uses a combination of mechanical and electrodynamic (regenerative) braking. With entire in-service regenerative braking, like in the Shinkansen N700, the energy penalty of extra stops would be negligible. It is even conceivable that a greater number of stops could reduce the energy consumption of trains with full regenerative braking, as any efficiency losses in electricity regeneration and increase in the inertia (accelerating mass) requirement are outweighed by the reduction in the Davis equation resistance component associated with lower speeds.

An approximately linear relation is found between the energy consumption (whether measured at the wheel or line, gross or net) and journey time penalties of intermediate stops. From Figure 4-6, adding an intermediate stop in a region where the train would otherwise be travelling at full speed (330 km/h) increases the net energy drawn from the line by 4% and the journey time by 10%. Removal of both intermediate stops reduces the net energy drawn from the line by 3% with a corresponding journey time saving of 16%.
4.3.2. **Constant Journey Time Analysis**

The following three scenarios are investigated:

i. Both intermediate stops (#1 and #2) absent.

ii. Intermediate stop #1 (nearest London) absent.

iii. Intermediate stop #2 (nearest Birmingham) absent.

Scenario (iv), with a third intermediate stop added to the route, cannot be investigated as the journey time used for comparison in this analysis is that output from the baseline simulations with 2 intermediate stops; the maximum operational speed of the train required to travel the route with 3 intermediate stops within the same journey time as the baseline case (2 intermediate stops) would be higher than the allowable line speed and possibly the maximum speed the HS2 reference train is capable of.

Figures 4-7 to 4-9 show the speed - time history of each scenario together with that of the baseline case for the London to Birmingham route:

![Speed-time profiles](image)

*Figure 4-7: Speed - time profiles of scenario (i) and the baseline case for London to Birmingham*
Figures 4-8 and 4-9 show the variation of energy consumption with scenario, taking the average of the London to Birmingham and return routes combined:

**Figure 4-8: Speed - time profiles of scenario (ii) and the baseline case for London to Birmingham**

**Figure 4-9: Speed - time profiles of scenario (iii) and the baseline case for London to Birmingham**

Figures 4-10 and 4-11 show the variation of energy consumption with scenario, taking the average of the London to Birmingham and return routes combined:

**Figure 4-10: Variation of energy consumption with each scenario for both routes combined**

**Figure 4-11: Percentage variation (compared to baseline) of energy consumption with each scenario for both routes combined**
From Figure 4-11 above, it is seen that unlike with the variable journey time analysis presented previously the regenerative braking capability of the HS2 reference train only slightly reduces the energy penalty of intermediate stops for the constant journey time analysis. Energy savings of approximately 20% and 35% could be achieved with the removal of 1 of and both the intermediate stops respectively. In the case whereby intermediate stops are located in a region of the route where the train would otherwise be travelling at the maximum operational speed (330 km/h in this analysis), any savings obtained by removal of such stops would be greater. Much of the energy saving achieved by removal of intermediate stops is due to the reduction in the Davis equation resistance requirement through lower, allowable maximum operational speeds.

4.4 Effect of Line Speed

4.4.1. Variable Journey Time Analysis

Three line speed profiles are studied for both the London to Birmingham and return routes in which the maximum operational speed of the HS2 reference train is varied between 250 km/h, today's minimum speed at which a new line can be considered high speed according to the UIC/EU definition in (2), and the maximum line speed in 10 km/h increments. All other simulation parameters are identical to the baseline case for each scenario studied.

The 3 line speed profiles studied are described as follows:

i. 'Baseline' line speed profile - as used in the baseline simulations presented in Chapter 3, named the 'optimized' line speed in the original traction energy analysis for HS2 Ltd. in (3).
ii. 'Maximized' line speed profile - as presented in the original traction energy analysis for HS2 Ltd. in (4). The line speeds differ from the 'baseline', or 'optimized', profile as follows:

a) At baseline (optimized) line speeds of 0 to 69 km/h, the maximized line speed is equal to the original baseline line speed.
b) At baseline (optimized) line speeds of 70 to 99 km/h, the maximized line speed is 10 km/h greater than the baseline line speed.
c) At baseline (optimized) line speeds of 100 km/h to 219 km/h, the maximized line speed is 20 km/h greater than the baseline line speed.
d) At baseline (optimized) line speeds of 220 km/h to 330 km/h, the maximized line speed is 30 km/h greater than the baseline line speed.

iii. 'No' line speed profile - there are no line speed restrictions along the entire route, meaning the speed of the train is only limited by its maximum capable speed, 360 km/h in the case of the HS2 reference train.

Figure 4-12 below illustrates the three different line speed profiles investigated. It should be noted that the maximized line speed profile as described in (5) is on some sections of the route 400 km/h instead of the 360 km/h illustrated here. As the maximum capable speed of the HS2 reference train is limited to 360 km/h, the 400 km/h line speed level is irrelevant in this analysis.

![Figure 4-12: Comparison of the 'baseline', 'maximized' and 'no' line speed profiles](image-url)
As stated previously, the maximum operational speed of the HS2 reference train is varied between 250 km/h and the maximum line speed of the profile (330 km/h for the 'baseline', and 360 km/ for the 'maximized' and 'no' line speed profiles) in 10 km/h increments.

Figures 4-13 and 4-14 show a selection of speed-time histories of the HS2 reference train for the London to Birmingham run:

**Figure 4-13: Speed - time profiles for the 330 km/h maximum operational speed case of each line speed profile**

![Figure 4-13](image)

**Figure 4-14: Speed - time profiles for the 330 km/h and 250 km/h maximum operational speed cases of the baseline line speed profile**

![Figure 4-14](image)

Figures 4-15 and 4-16 below illustrate how the energy consumption and journey time vary with line speed profile and maximum operational speed, taking the average of the London to Birmingham and return routes combined:
From the above figures it is seen that there exists a significant trade-off between net energy drawn from the line and journey time. Taking the baseline line speed profile case, an energy saving of over 25% can be achieved by reducing the maximum operational speed from 330 km/h to 250 km/h, at a time cost of approximately 7 minutes for each route.

The above figures also illustrate an 'equal energy, time saving' advantage of employing the maximized and no line speed profiles instead of the baseline profile. The maximized line speed profile can achieve a time saving of approximately 1 minute per journey for the same energy consumption as the baseline case, whilst the no line speed case can achieve a 2-3 minute time saving.

The shape of the curves in Figures 4-15 and 4-16 can be explained by the law of diminishing return between time and speed, as shown in Equations 4-1 and 4-2, in addition to the dependence of the Davis equation resistance on the speed squared.

\[ t = \frac{x}{v} \]

*Equation 4-1: Distance-speed-time relation*

\[ \Delta t = -\frac{x}{v^2} \Delta v \]

*Equation 4-2: Change in time for a given change in speed for a constant speed journey*
4.4.2. **Constant Journey Time Analysis**

Whilst the bisection iterative technique can be used to carry out a constant journey time analysis into the effect of employing the 'maximized' and 'no' line speed profiles instead of the 'baseline' profile, it is not required in this case; such an analysis can be carried out simply from observation of Figures 4-15 and 4-16 presented in the previous section. It is clear that employing the 'maximized' instead of the 'baseline' line speed profile saves approximately 5% energy (net energy from the line) for the same journey time, whilst using no line speeds at all saves 11%.

4.5. **Effect of Reduced Dwell Times**

4.5.1. **Constant Journey Time Analysis**

The following two scenarios are investigated:

i. Station dwell time of 1:00.

ii. Station dwell time of 1:30.

Figure 4-17 shows the speed - time history of each scenario together with that of the baseline case for the London to Birmingham route:

*Figure 4-17: Speed - time profiles of each scenario and the baseline case for London to Birmingham*
Figures 4-18 and 4-19 show the variation of energy consumption with scenario, taking the average of the London to Birmingham and return routes combined. It is seen that a 6% energy saving can be achieved for the same journey time by reducing the dwell time from 2:00 to 1:30, whilst reducing the dwell time to 1:00 allows an 11% energy saving to be achieved.

Figure 4-18: Variation of net energy drawn from the line with each scenario (including baseline - 2:00) for the average of both routes combined

Figure 4-19: Percentage variation of net energy drawn from the line with each scenario (including baseline - 2:00) for the average of both routes combined

4.6 Summary

The effect of three route-based factors: the number of intermediate stops, the line speed profile and the dwell time on the energy consumption of a journey have been investigated. Two types of analysis have been carried out for the intermediate stops and line speed profile investigations: a variable journey time and a constant journey time analysis. For the dwell time investigation only a constant journey time analysis has been conducted. All parametric studies have been carried out with respect to the baseline simulations conducted in Chapter 3.

In the variable journey time analyses the relationship between the energy consumption and journey time is established for the variation in the parameter under investigation. For the constant journey time analysis, an iterative technique based on the bisection method is employed to establish a parameter's effect on the energy consumption, whilst keeping the journey time equal to that of the baseline simulations.
Figure 4-20 summarizes the results from the investigations in Chapter 4 and compares the effect of each route parameter with the findings from Chapter 3:

It is clear from the above figure that the influences on the energy consumption of the route-based parameters investigated in this chapter are significant. It is seen that variations in journey time, achieved by changes to the maximum operational speed, influence the energy consumption to a much greater degree than variations in any of the factors investigated in Chapter 3, including the passenger load (at a baseline value of 70%). Increasing the journey time by approximately 15% (7 minutes in each direction for the London to Birmingham route) reduces the energy consumption according to the defined KPI by the same amount as if all the seats were occupied instead of just 70% as in the baseline simulations. Of course, with lower baseline values the passenger loading has a greater effect.
Moving on to the constant journey time analyses, the route sinuosity significantly influences the energy consumption. The relation is, in fact, a mirror image about the vertical axis of that between energy and journey time achieved by varying the maximum operational speed. In calculating the constant journey time energy effect of sinuosity, it should be remembered that route sinuosity and average speed along the route are proportional to each other for a given journey time. Having a straight route with a sinuosity of 1 would reduce the energy consumption according to the defined KPI by 20%, when based on a constant journey time analysis, the same saving as if the passenger loading was increased from the baseline figure of 70% to 87%.

The constant journey time effect of intermediate stops is also seen to be very significant compared to the other parameters, both from this chapter and the last. Removal of either of the intermediate stops reduces the energy consumption by 20% and removal of both by 35%, equivalent to increasing the journey time by approximately 20% (10 minutes each way) and a greater reduction than that achieved by increasing the passenger load from 70% to 100%.

Whilst the constant journey time energy effect of maximized and no line speeds as well as 1:00 and 1:30 dwell times are smaller in comparison with most of the other route parameters investigated in this chapter, they are nonetheless seen to be significant when compared to the parameters investigated in Chapter 3.

4.7. Discussion

The significance of the effect of route based parameters using a constant journey time analysis has been demonstrated. In practice not all the route-related energy reducing measures outlined above are achievable. Intermediate stops clearly exist because of passenger demand for them and the route sinuosity clearly depends on such factors as the lie of the land and the location of population densities. The importance in terms of energy consumption of minimizing these parameters has nonetheless been demonstrated.
Another factor which is never achieved in practice is the removal of all line speeds, so that the speed of the train is limited only by its maximum speed capability. Many of the line speed restrictions along the HS2 route occur towards the ends of the line, where the line is in built up areas. Such restrictions can exist because of tight curves necessitated by urban obstacles, narrow single track tunnelling, as is the case at the London end of the HS2 route and noise regulations. The 'maximized' line speed profile has however been drawn up by the engineers at HS2 Ltd. The energy case for operating the HS2 train at these greater speeds in the lower line speed regions to allow for speed reductions at the higher end has been demonstrated.

Two route-based factors which may well be possible to change are the journey time itself and the dwell time. Clearly a trade off exists between lower journey times desired by society and business and the corresponding energy requirement. Operating the HS2 reference train at 300 km/h instead of 330 km/h reduces the energy consumption by 10%, while increasing the journey time by less than 2 minutes each way between London and Birmingham. Similarly, lowering the maximum operational speed from 330 km/h to 270 km/h reduces the energy consumption by 20% at a time cost of only just over 4 minutes each way. Clearly with such small time penalties there is a strong case for reducing the maximum operational speed from 330 km/h. As demonstrated earlier in the chapter, from an energy viewpoint train speeds at the lower end should first be maximized before looking to increase the maximum operational speed.

Dwell times are clearly required at stations to allow passengers on and off the trains. Whilst 2:00 is the standard dwell time assumed, energy savings of over 10% could be achieved by reducing this to 1:00. On a recent trip to Japan the author measured dwell times on the Shinkansen network, a high speed, high capacity rail system famous for its efficient operation. The results of the timings are shown in Table 4-1 below:
<table>
<thead>
<tr>
<th>Date</th>
<th>Journey</th>
<th>Station</th>
<th>Dwell Time [min:sec]</th>
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<tr>
<td>4th Oct '11</td>
<td>Kyoto to Tokyo</td>
<td>Odawara</td>
<td>1:12</td>
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<td></td>
<td></td>
<td>Shin-Yokohama</td>
<td>1:17</td>
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<td></td>
<td>Shinagawa</td>
<td>1:08</td>
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<tr>
<td>JR-Central</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7th Nov '11</td>
<td>Tokyo to Sendai</td>
<td>Omiya</td>
<td>2:08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sendai</td>
<td>2:18</td>
</tr>
<tr>
<td></td>
<td>Sendai to Morioka</td>
<td>Sendai</td>
<td>6:11*</td>
</tr>
<tr>
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<td></td>
<td>Furukawa</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Kurikomakogen</td>
<td>1:29</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ichinoseki</td>
<td>1:25</td>
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<td></td>
<td>Mizusawaesashi</td>
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<tr>
<td></td>
<td></td>
<td>Kitakami</td>
<td>5:27**</td>
</tr>
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<td></td>
<td></td>
<td>Shin-Hanamaki</td>
<td>0:57</td>
</tr>
<tr>
<td>JR-East</td>
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</tr>
<tr>
<td>8th Nov '11</td>
<td>Morioka to Shin-Aomori</td>
<td>Iwate-Numakunai</td>
<td>1:30</td>
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<tr>
<td></td>
<td></td>
<td>Ninohe</td>
<td>1:18</td>
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<td></td>
<td></td>
<td>Hachinohe</td>
<td>1:37</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Shin-Aomori-Towada</td>
<td>1:01</td>
</tr>
<tr>
<td>9th Nov '11</td>
<td>Shin-Aomori to Tokyo</td>
<td>Shichinohe-Towada</td>
<td>1:07</td>
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<td>Hachinohe</td>
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</tr>
<tr>
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<td>Ninohe</td>
<td>1:22</td>
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<td>Iwate-Numakunai</td>
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</tr>
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<td></td>
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<td>Ueno</td>
<td>1:23</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td>2:07</td>
</tr>
<tr>
<td></td>
<td>Average without * and **</td>
<td></td>
<td>1:26</td>
</tr>
</tbody>
</table>

Table 4-1: Author's dwell time measurements on the Shinkansen network. N.B. * refers to timetabled dwell times of 6 minutes and ** refers to a delay

From Table 4-1, it is seen that whilst the average dwell time measured was approximately 2 minutes, as in the baseline simulations presented here, when ignoring the timetabled 6 minute dwell times at the major stations of Sendai and Morioka as well as the delay at Kitakami on 7th November 2011, the average dwell time of intermediate stops is only 1:26. From this small study, dwell times averaging 1:30 have been shown in Japan to be achievable for intermediate stops.
Shorter dwell times are achievable through the use of intelligent train control preventing the train from reaching a particular location unnecessarily early as well as through methods to encourage more efficient passenger flow at the platform-train interface. In Japan a plethora of information is available to passengers indicating where the doors of each carriage for a particular service will open and showing how to queue at each door in a manner which will not affect the rest of the passenger flow along the platform as Figures 4-21 and 4-22 show. In addition it is clear to the author that the passengers in Japan understand their role in making the system run efficiently.

![Figure 4-21: Information on the location of carriage doors](image1)

![Figure 4-22: Waiting in line at the carriage doors](image2)

Whilst there may be an issue as to whether shorter dwell times lead to difficulties of boarding and alighting trains for elderly and disabled passengers as well as for passengers with young children, the constant journey time energy benefit of an average 1:30 intermediate station dwell time instead of 2:00 has been shown to be significant, approximately 6% in this analysis.

In Chapter 5, the results from simulations in Chapters 3 and 4 are used to compare the energy consumption of the HS2 reference train with its competing modes. In addition, comparisons are made in terms of carbon dioxide emissions.
References


3. Ibid. 1.

4. Ibid.

5. Ibid.
Chapter 5: Energy and Carbon Dioxide
Comparisons with Other Modes

Comparisons are made between the energy consumption and journey time of the HS2 reference train calculated previously and those of the competing modes of transport: road, domestic air and existing rail. Comparisons with road and domestic air are made in terms of primary energy using existing published data for fuel consumption. Comparisons with existing rail are made in terms of electrical energy based on simulations carried out on the West Coast Main Line (WCML). Carbon dioxide emissions are also considered.

5.1. Introduction

The relationship between the energy consumption and journey time of the HS2 reference train running on the London to Birmingham route through variation of the maximum operational speed was established in Chapter 4. With existing road and air transport predominantly powered through the combustion of fossil fuels, comparisons with the HS2 reference train need to be made in terms of primary energy stored in the fuel. Comparisons with existing rail are made in terms of the electrical energy consumption at the line. With the High Speed 2 line planned for 2026 (at the earliest), future scenarios of fuel efficiency and CO₂ emissions are also considered.

5.2. Conversion of Electrical Energy to Primary Energy

As discussed in Chapter 2, primary energy consumption is only important when considering fuels of a finite resource, for example fossil fuels and nuclear fuel. Assuming a 35% thermally-efficient power station (whether fossil fuelled or nuclear powered) and a further 5% loss of primary energy in the transmission and distribution of electrical energy to the train leaves 30% of the primary energy to be picked up at the current collector.
5.3. Carbon Dioxide Emissions of HS2

As stated in Chapter 2, based on the latest 5-year rolling average ending in 2008, 543 gCO2e is emitted for every kWh of electrical energy at the point of consumption. By 2020 however, at least 6 years before HS2 is set to be operational, the UK should have at least 30% of its electrical power supply originating from renewable sources if it is to meet its European and global climate change obligations. Two scenarios of CO₂ emissions are therefore envisaged in the analysis: the end of 2008 5-year rolling average figure of 543 gCO2e / kWh and a figure based on the potential electricity mix in 2020 as detailed in Figure 2-9. For the purposes of this investigation the 2020 figure is estimated to be 362 gCO2e / kWh, the 2008 value multiplied by the ratio of the percentage of power generation by fossil fuels in 2020 to that in 2008 as detailed in Figures 2-7 and 2-9 in Chapter 2. Coincidently it can be seen that according to this method the potential 2020 power generation mix is 1/3rd less CO₂ intensive than the 2008 scenario.

5.4. Comparisons with the Car

5.4.1. Energy Consumption and CO₂ Emissions of the Car

The Lower Heating Value (LHV) of petrol is approximately 115400 Btu / gal(US), whereas that for diesel is 128700 Btu / gal(US), equivalent to about 8.9 kWh / l and 10.0 kWh / l respectively (1). The average fuel consumption of UK cars as of 2010 was 33.5 mpg (Imperial, which equates to 11.9 km / l), with petrol cars averaging 30.9 mpg and diesel 38.3 mpg (2). Assuming a vehicle-km mix between petrol and diesel cars of 68.9 % and 31.1 % respectively (3), combining the energy content and fuel consumption figures gives a primary energy consumption figure for cars of 0.81 kWh / km, which becomes 0.16 kWh / seat-km for a typical 5-seater.

With the fuel consumption of cars being driven down by the higher price of fuel at the pump along with the introduction of CO₂ emissions targets, a simple comparison of a future high speed train of the 2020s and beyond with an average 2010 car becomes implausible. Comparisons are also made therefore with possibilities of fuel consumption in the future.
In 2011 the most fuel efficient car sold in the UK was the Kia Rio Diesel 1.1 at 88.3 mpg (or 31.3 km / l), when measured using a combined urban / extra-urban driving cycle (4). With 5 seats in the car, the primary energy consumption of the Kia Rio becomes 0.064 kWh/seat-km. In the coming decades it is conceivable that on average future cars could achieve such fuel economies, if not higher.

As of 2010, the average UK car (directly) emitted 208 gCO₂e/km (5). As discussed in Chapter 2 there are also EU targets set to come into force limiting the average, quoted direct CO₂ emissions of new cars to 130 gCO₂e / km by 2015, although this figure was originally 120 gCO₂e / km by 2012 (6). Further potential reductions to 95 gCO₂e / km by 2020 are also under consideration (7).

Since CO₂ emissions are generally inversely proportional to fuel consumption and the Kia Rio Diesel 1.1 produces 85 gCO₂e / km (8) according to the specified combined driving cycle, CO₂ emissions of 95 g / km correspond to a fuel consumption of approximately 80 mpg. By the intended opening of HS2 in 2026 therefore, quoted average fuel consumption figures of new cars in the UK of 80 mpg are a possibility, along with CO₂ emissions of 95 g / km. By the end of the life-span of the 1st generation HS2 train fleet in the 2050s, average fuel consumption figures of all cars may well exceed this even when taking into account real-world driving.

Other forms of power, for example the electric car, may well be in some use by then. Exclusively electrically-powered cars are on the market now, for example the 5-seater lithium-ion battery powered Nissan Leaf, which can cover 109 miles based on the New European Driving Cycle (NEDC) test with its 24 kWh of battery capacity, leading to an energy consumption 0.14 kWh / km (9). Under real-world driving its range may reduce to as little as 62 miles, however (10). Four main obstacles to the widespread use of lithium-ion battery technology in cars remain, however: their short range, short life, expense and the rarity of significant known deposits of lithium around the world.

In the following analyses the energy consumption and CO₂ emissions of the HS2 reference train on the London to Birmingham HS2 route are compared with those of the car under 2 different scenarios:
i. Average UK car fuel consumption and direct CO$_2$ emissions in 2010 of 33.5 mpg and 208 gCO$_2$e/km respectively.

ii. Potential future UK car fuel consumption and direct CO$_2$ emissions of 80 mpg and 95 gCO$_2$e/km respectively.

5.4.2. Energy / Journey Time Comparison

Figures 5-1 to 5-2 show the energy / journey time relationship of the HS2 reference train at maximum operational speeds ranging from 250 km/h to 330 km/h using the baseline line speed profile, compared with the energy / journey time of the car for the 2 different scenarios above. In both scenarios the primary energy consumption is considered, which for the HS2 reference train is calculated using the 30% efficiency of conversion of primary energy to the electrical energy at the point of consumption as discussed in Section 5.2. The energy axis uses the Key Performance Indicator (KPI) unit the kWh / passenger-km, taking account of the sinuosity of the road and rail routes as discussed in Chapter 2. The journey time of the car between the London and Birmingham HS2 stations is assumed to be 2 hours 30 minutes. The fuel / energy consumption of the car for each scenario is assumed to be independent of passenger load.

![Figure 5-1: Primary energy consumption and journey time of HS2 compared to the 2010 average UK car (33.5 mpg) for different passenger loads and taking into account route sinuosity (1.09 for HS2 and 1.18 for road)](image1)

![Figure 5-2: Primary energy consumption and journey time of HS2 compared to a 80 mpg car for different passenger loads and taking into account route sinuosity (1.09 for HS2 and 1.18 for road)](image2)
The dependence of the energy consumption (based on the KPI defined in Chapter 2) on the passenger load is well demonstrated in the above two figures. On a per seat basis, i.e. a 100% passenger load, the HS2 reference train at all maximum speeds provides both an energy and a time saving over the UK average car in 2010. The primary energy consumption of the HS2 reference train is in fact equivalent to a car running with a fuel consumption of approximately 40 to 50 mpg, depending on whether the train is running with a maximum operational speed of 330 km/h or 250 km/h. The car only begins to offer a significant advantage for fuel consumptions above 60 mpg.

Taking into account likely passenger loading scenarios, approximately 50% to 70% for the HS2 reference train and 1.6 persons per car (including the driver), the primary energy consumption of the HS2 reference train is significantly lower than that of the 2010 car (at 33.5 mpg) and roughly equal to that of the car running at 80 mpg, a potential future average fuel consumption for UK cars in the coming decades.

5.4.3. CO₂ Emissions Comparison

Two scenarios are used to compare the direct CO₂ emissions and journey time of the HS2 reference train with those of a 5-seater car:

i. HS2 powered by 2008 UK electricity mix vs. average UK car emissions in 2010 (208 gCO₂e/km).

ii. HS2 powered by potential 2020 UK electricity mix (as detailed in Figure 2-9 in Chapter 2) vs. average UK direct car emissions in future decades of 95 gCO₂e/km.

Figures 5-3 and 5-4 illustrate the results:
Figure 5-3: CO₂ emissions and journey time of HS2 based on 2008 electricity generation compared to the 2010 average UK car (33.5 mpg) for different passenger loads and taking into account route sinuosity (1.09 for HS2 and 1.18 for road).

Figure 5-4: CO₂ emissions and journey time of HS2 based on 2020 electricity generation compared to a 95 gCO₂e/km car for different passenger loads and taking into account route sinuosity (1.09 for HS2 and 1.18 for road).

From analysis of the 2008 electricity mix and 2010 average UK car emissions case, it is seen that per seat-km, the HS2 reference train holds a significant advantage over the car in terms of CO₂ emissions, emitting the equivalent of a car running at approximately 60 to 80 mpg. The HS2 reference train could lose this advantage in the coming decades, however, without a reduction in the CO₂ intensity of UK power generation, as both Figures 5-3 and 5-4 show.

Taking into account likely passenger loading scenarios (approximately 50% to 70% for the HS2 reference train and 1.6 persons per car), on a per passenger-km basis, the HS2 reference train emits significantly less CO₂ in both scenarios.
5.5. Comparisons with Domestic Air

5.5.1. Energy Consumption and CO₂ Emissions of Domestic Air

As of 2010 calculated average direct CO₂ emissions from domestic flights in the UK were 173.3 gCO₂e / pass-km with a 64.5% passenger load factor, using the methodologies introduced in Chapter 2 and detailed in (11). Such a calculation however does not take into account route sinuosities, for which the Intergovernmental Panel on Climate Change (IPCC) suggest an average 9-10% uplift factor (12). In addition the calculation takes no account of the effect of water vapour contrails and high altitude emissions on radiative forcing (13). A multiplier of 1.9 is recommended as a central estimate to account for the additional effect of such factors on Climate Change based on the best available scientific evidence (14).

For air travel, direct emissions of 173.3 gCO₂e / pass-km (excluding non-CO₂ climate change effects) are equivalent to a fuel consumption of approximately 20 mpg / passenger based on data from (15). Since the Lower Heating Value (LHV) of kerosene-based jet fuel is 128100 Btu / gal(US) (16), or approximately 9.9 kWh / l, emissions of 173.3 gCO₂e / pass-km are equivalent to about 1.4 kWh / pass-km.

In addition to the 2010 scenario a potential 2050 scenario is considered, whereby the fuel consumption and therefore CO₂ emissions of air travel are reduced by an average of 0.8% per year between 2005 and 2050, as detailed in (17). Such a reduction would lead to 27% cuts in fuel consumption and direct CO₂ emissions per seat-km by 2050 compared to 2010 levels.

5.5.2. Energy / Journey Time Comparison

Since the distance from London to Birmingham is too small for air to have any of the mode share, for the purposes of this comparison journey times are instead stated per unit distance. For domestic air travel, the journey time per unit distance is based on a typical London to Edinburgh flight, covering the 535 km great circle distance in approximately 80 minutes (18, 19).
Figures 5-5 and 5-6 show the energy / journey time relationship of high speed rail compared with domestic air travel for the 2010 and potential 2050 scenarios respectively, using the journey time per unit distance on the horizontal axis as discussed. It is seen from Figure 5-5 that the journey time per unit distance of current domestic air travel is approximately half that of HS2, whilst the primary energy consumption per seat-km is approximately 6 to 8 times that of HS2. When considering the 2050 scenario for air travel, per seat-km domestic air travel still consumes between 4 to 5 times the primary energy of HS2 (assuming a 30% conversion rate of primary energy at the power station to electrical energy at the current collector). Per passenger-km the energy comparisons are similar as loading levels of domestic air travel are much the same as those expected for HS2.

**Figure 5-5:** Primary energy consumption and journey time per GCD-km of HS2 compared to the 2010 average UK domestic flight for different passenger loads and taking into account route sinuosity (1.09 for HS2 and 1.10 for air)

**Figure 5-6:** Primary energy consumption and journey time per GCD-km of HS2 compared to the potential 2050 UK domestic flight scenario for different passenger loads and taking into account route sinuosity (1.09 for HS2 and 1.10 for air)
5.5.3. CO₂ Emissions Comparison

Two scenarios are considered:

i. Current (2010) UK domestic air (direct) emissions versus the emissions from the proposed HS2 line based on the 2008 UK power generation mix.

ii. Potential 2050 UK domestic air (direct) emissions versus the emissions from the proposed HS2 line based on the potential 2020 UK power generation mix, as detailed in Figure 2-9 in Chapter 2.

Figures 5-7 and 5-8 show how the direct CO₂ emissions from domestic air travel compare with the proposed HS2 line for the two scenarios described above. The calculation of CO₂ emissions incorporates the multiplier of 1.9 mentioned earlier to account for the non-CO₂ climate change effects of aviation (including water vapour, contrails, NOx etc):

![Figure 5-7: CO₂ emissions and journey time per GCD-km of HS2 (2008 power generation) compared to the 2010 average UK domestic flight for different passenger loads and taking into account route sinuosity (1.09 for HS2 and 1.10 for air) and non-CO₂ climate change effects of aviation](image)

![Figure 5-8: CO₂ emissions and journey time per GCD-km of HS2 (2020 power generation) compared to the potential 2050 average UK domestic flight for different passenger loads and taking into account route sinuosity (1.09 for HS2 and 1.10 for air) and non-CO₂ climate change effects of aviation](image)
From the above figures emissions per seat-km from domestic air travel are approximately 8 to 10 times those of HS2, taking into account the multiplier of 1.9 to represent the non-CO$_2$ climate change effects of aviation. Due to the similar loading level assumptions of domestic air travel and the proposed HS2 route, such a conclusion can also be drawn on a per passenger-km basis.

5.6. Comparisons with the West Coast Main Line (WCML)

5.6.1. Introduction

The West Coast Main Line (WCML) currently provides the quickest rail route from London to Birmingham with a journey time between the two cities around the 1 hour 20 minute mark. Class 390 ‘Pendolino’ trains run along the route with a maximum operational speed of 125 mph. Energy simulations are carried out in this section, using train and route data provided by the RSSB, to compare the energy consumption of the existing WCML between London and Birmingham and that of the proposed HS2 route.

5.6.2. Energy Modelling

Train and route data used for the modelling of a 9-car Class 390 train running on the WCML are shown in Figures 5-9 to 5-11 and Tables 5-1 to 5-3. It should be noted that the simulator drives the train to the timetable shown in Table 5-3 using an iterative technique similar to that described in Chapter 4 to find the required maximum speed of the train between each station. Due to a lack of available data, the aerodynamic resistance in all tunnels is assumed to be double the nominal, open-air value, as advised by the RSSB. Braking is assumed to be a mix of mechanical and electrodynamic. As no regenerative braking curve was available to the author, the proportion of braking energy, where regeneration is possible (above 20 km/h), which is returned to the line during a journey is assumed to be equal to that regenerated by the HS2 reference train.
Figure 5-9: Height and line speed profile of the WCML London to Birmingham route

Figure 5-10: Height and line speed profile of the WCML Birmingham to London route

<table>
<thead>
<tr>
<th>Station</th>
<th>Distance from London [km]</th>
<th>Tunnel</th>
<th>London end [km]</th>
<th>Birmingham end [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>London</td>
<td>0</td>
<td>#1</td>
<td>1.25</td>
<td>1.37</td>
</tr>
<tr>
<td>Watford Junction</td>
<td>28.0</td>
<td>#2</td>
<td>2.70</td>
<td>3.82</td>
</tr>
<tr>
<td>Coventry</td>
<td>151.3</td>
<td>#3</td>
<td>7.34</td>
<td>7.62</td>
</tr>
<tr>
<td>Birmingham International</td>
<td>168.5</td>
<td>#4</td>
<td>29.73</td>
<td>31.38</td>
</tr>
<tr>
<td>Birmingham New Street</td>
<td>181.7</td>
<td>#5</td>
<td>46.59</td>
<td>46.91</td>
</tr>
<tr>
<td></td>
<td></td>
<td>#6</td>
<td>65.58</td>
<td>65.84</td>
</tr>
<tr>
<td></td>
<td></td>
<td>#7</td>
<td>109.62</td>
<td>110.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>#8</td>
<td>123.60</td>
<td>125.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>#9</td>
<td>158.28</td>
<td>158.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>#10</td>
<td>181.19</td>
<td>181.41</td>
</tr>
</tbody>
</table>

Table 5-1: Station and tunnel information for the WCML
Figure 5.11: Tractive Effort and Resistance Curve of the 9-car Class 390 for $0 < v < 201$ km/h

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tare mass (including 7 tonnes for water and other services)</td>
<td>$M_T$</td>
<td>t</td>
<td>465</td>
</tr>
<tr>
<td>Rotational inertia mass factor</td>
<td>$\phi$</td>
<td>%</td>
<td>6</td>
</tr>
<tr>
<td>Mass of passengers at 100% load (seat capacity = 447)</td>
<td>$M_P$</td>
<td>t</td>
<td>34</td>
</tr>
<tr>
<td>Passenger load factor</td>
<td>$\text{LF}$</td>
<td>%</td>
<td>70</td>
</tr>
<tr>
<td>Train length</td>
<td>$L_{\text{TRAIN}}$</td>
<td>M</td>
<td>207</td>
</tr>
<tr>
<td>Maximum operational speed</td>
<td>$v_{\text{MAX}}$</td>
<td>km/h</td>
<td>201</td>
</tr>
<tr>
<td>Efficiency between pantograph and wheel</td>
<td>$\eta_{\text{L-W}}$</td>
<td>%</td>
<td>82.3</td>
</tr>
<tr>
<td>Percentage of total braking energy above 20 km/h regenerated</td>
<td>$(\text{BE}_{v&gt;20\text{km/h}})_R$</td>
<td>%</td>
<td>47</td>
</tr>
<tr>
<td>Auxiliary Power Supply (APS)</td>
<td>$P_{\text{APS}}$</td>
<td>kW</td>
<td>241</td>
</tr>
<tr>
<td>APS Efficiency</td>
<td>$\eta_{\text{APS}}$</td>
<td>%</td>
<td>85</td>
</tr>
<tr>
<td>Braking rate</td>
<td>$a_B$</td>
<td>%g</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 5.2: Train-based parameters for the 9-car Class 390 'Pendolino' on the WCML

<table>
<thead>
<tr>
<th>London to Birmingham [h:min]</th>
<th>Birmingham to London [h:min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>London Euston</td>
<td>0:00 (d)</td>
</tr>
<tr>
<td>Watford Junction</td>
<td>0:14 (d)</td>
</tr>
<tr>
<td>Coventry</td>
<td>0:59 (a)</td>
</tr>
<tr>
<td>Birmingham International</td>
<td>1:10 (a)</td>
</tr>
<tr>
<td>Birmingham New Street</td>
<td>1:22 (a)</td>
</tr>
</tbody>
</table>

| Birmingham New Street        | 0:00 (d)                     |
| Coventry                     | 0:21 (d)                     |
| Watford Junction             | 1:05 (a)                     |

Table 5.3: WCML timetable used in simulations

5.6.3. Simulation Outputs

Figure 5-12 shows the speed - distance history output from the simulation of the 9-car Class 390 on the London to Birmingham WCML route. Figures 5-13 and 5-14 compare the speed and power time histories of the Class 390 on the WCML with those of the HS2 reference train on the HS2 route:
As seen from the above figures, the greater maximum speed and acceleration performance of the HS2 reference train is due to its greater power requirement, over double that of the 9-car Class 390, despite the trains' similar size and capacity.
5.6.4. **Energy / Journey Time Comparison**

Figure 5-15 compares the net energy drawn from the line and journey time of the 9-car Class 390 on the WCML route with those of the HS2 reference train on the HS2 route. Figure 5-16 compares the net energy consumption at the current collector using the KPI defined earlier in the thesis, assuming a 100% load for a per-seat analysis:

![Figure 5-15: Comparison of the net energy drawn from the line and the journey time of the Class 390 on the average of the London to Birmingham and return WCML routes with those of HS2 (baseline line speed case)](image1)

![Figure 5-16: Comparison of the net energy consumption at the line (in terms of the defined KPI using a 100% load) and the journey time of the Class 390 on the average of the two WCML routes with those of HS2 (baseline line speed case)](image2)

It should be noted that the RSSB recommend an energy consumption value of 0.040 kWh/seat-km for the 9-car Class 390 running on the WCML in (20), which is in good agreement with the results from the simulations presented here. From Figures 5-15 and 5-16 it is seen that whilst the Class 390 consumes in total 26% less energy than the baseline case of the HS2 reference train, when using the KPI defined in this thesis this advantage reduces to 16%. In addition, the HS2 reference train at maximum operational speeds below approximately 280 km/h consumes less energy according to the KPI than the Class 390 on the WCML, whilst still providing a time saving of approximately 30 minutes each way.

Comparisons in terms of CO₂ emissions are the same as in terms of energy consumption as both modes are powered from the same source, the UK electricity grid.
5.6.5. Analysis of the Energy Difference Between the WCML and HS2 Baseline Simulations

Introduction

In this section the reasons for the difference in energy consumption between the WCML and the HS2 reference train are explored. The WCML simulations presented above are compared with the baseline cases of the HS2 reference train, first presented in Chapter 3.

Per Seat Analysis

The calculation of the difference in energy consumption according to the KPI between the WCML and HS2 simulations can be summarized in component form by Equation 5-1:

\[
\frac{E_{\text{NET,WCML}}}{N_sS_{GCD}} - \frac{E_{\text{NET,HS2}}}{N_sS_{GCD}} = \frac{1}{N_s \times s_{GCD}} \left( \frac{E_I + E_D + E_G}{\eta_{L-W}} + E_{APS} + E_R \right)_{\text{WCML}} - \frac{1}{N_s \times s_{GCD}} \left( \frac{E_I + E_D + E_G}{\eta_{L-W}} + E_{APS} + E_R \right)_{\text{HS2}}
\]

Equation 5-1: Difference in the KPI energy consumption between the WCML and HS2 simulations

The following train and route-based factors contribute towards the energy consumption difference between the two modes according to the KPI defined earlier in the thesis:

i. Mass per seat,
ii. Resistance per seat,
iii. Regenerated energy (during braking) per seat,
iv. Route sinuosity,
v. Speed profile.
Other factors, for example the efficiency of the drive system, the passenger load as a percentage of the number of seats and the energy expended by auxiliary power do not contribute to the difference in energy consumption between the two modes as they are assumed to be equal.

i. **Mass per seat**

Vehicle mass is assumed to affect the inertial, $E_i$, and gradient, $E_G$, components of the energy consumption at the wheel only. The effect of applying the mass per seat of the Class 390 'Pendolino' to the HS2 baseline simulations is found with reference to Equation 5-2, using the component breakdown of the net energy drawn from the line for the average of the two baseline simulations and mass and seat data for both the 9-car Class 390 and the HS2 reference train. The effects of vehicle mass on the energy returned to the line during regenerative braking and the speed profile, via the acceleration performance, are ignored and covered separately.

$$
\varepsilon_{M/S} = \left( \frac{100\%}{\eta_{L-W}E_{NET}} \right)_{HS2} \left\{ \left[ \frac{[M_T(1 + \phi) + M_P]_{WCML}(N_S)_{HS2}}{[M_T(1 + \phi) + M_P]_{HS2}(N_S)_{WCML}} - 1 \right] (E_i)_{HS2} \right. \\
+ \left. \left[ \frac{[M_T + M_P]_{WCML}(N_S)_{HS2}}{[M_T + M_P]_{HS2}(N_S)_{WCML}} - 1 \right] (E_G)_{HS2} \right\}
$$

*Equation 5-2: Calculation of the effect of applying the mass per seat of the Class 390 'Pendolino' to the HS2 baseline simulation*

ii. **Resistance per seat**

Vehicle resistance is assumed to affect the Davis equation resistance component, $E_D$, of the energy consumption at the wheel only. The effect of applying the resistance per seat of the Class 390 'Pendolino' to the HS2 baseline simulations is found with reference to Equation 5-3, using the speed profiles of the two baseline simulations, Davis equation resistance curves for both the 9-car Class 390 and the HS2 reference train and seat numbers of each train. As in (ii) the effects of vehicle resistance on the energy returned to the line during regeneration and the speed profile, via the acceleration performance, are ignored and covered separately.
iii. **Regenerated energy per seat**

The effect of applying the energy regenerated (during braking) per seat by the Class 390 'Pendolino' in the WCML simulations to the HS2 baseline simulations is found with reference to Equation 5-4:

\[
\varepsilon_{R/S} = \left( \frac{100\%}{E_{\text{NET}}^{\text{HS2}}} \right) \left( \frac{(F_D)_{\text{WCML}}(N_5)_{\text{HS2}}}{(F_D)_{\text{HS2}}(N_5)_{\text{WCML}}} - 1 \right)(E_R)_{\text{HS2}}
\]

*Equation 5-4: Calculation of the effect of applying the energy regenerated per seat by the Class 390 'Pendolino' in the WCML simulations to the HS2 baseline simulations*

iv. **Route sinuosity**

The effect of applying the route sinuosity of the WCML to the HS2 baseline simulations is found by calculating the great circle distance of the HS2 route which would correspond to the HS2 route's sinuosity being equal to that of the WCML, 1.13, as Equation 5-5 shows:

\[
\varepsilon_{\text{SINU}} = \left( \frac{\text{sinuosity}_{\text{WCML}}}{\text{sinuosity}_{\text{HS2}}} - 1 \right) \times 100\%
\]

*Equation 5-5: Calculation of the effect of applying the route sinuosity of the WCML to the HS2 baseline simulations*

v. **Speed profile**

The effect of applying the speed profiles of the WCML simulations to those of the HS2 baseline simulations is calculated as the difference between the sum of the percentage contributions (i) to (iv) and the energy difference in percentage terms between the two modes according to the KPI.
Table 5-4 shows the contributions of each of the above 5 factors towards the difference in the net energy drawn from the line by the two modes. Figure 5-17 graphically illustrates the results. It should be noted that the analysis is specific to the effect of applying the parameters of the WCML simulations to the HS2 baseline simulations. If the analysis was based on applying the parameters of the HS2 baseline simulations to the WCML simulations, whilst the percentage values would be different, the overall conclusions would remain the same.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effect on HS2 energy consumption, ε [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass per seat</td>
<td>+11</td>
</tr>
<tr>
<td>Resistance per seat</td>
<td>+70</td>
</tr>
<tr>
<td>Regenerated energy per seat</td>
<td>+1</td>
</tr>
<tr>
<td>Route sinuosity</td>
<td>+4</td>
</tr>
<tr>
<td>Speed profile</td>
<td>-102</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>-16</strong></td>
</tr>
</tbody>
</table>

Table 5-4: Effect on the KPI energy consumption (per seat-km) of applying various parameters of the Class 390 WCML simulations to the HS2 baseline simulations (using the average of the London to Birmingham and return routes)

It is seen that the disadvantages of higher mass and resistance per seat of the Class 390 are more than compensated for by the lower speed of the Class 390 on the WCML compared to the HS2 reference train. The major factor contributing to the lower energy consumption of the Class 390 on the WCML is the speed profile, whilst the most significant limiting factor towards this energy advantage is the greater resistance per seat of the Class 390.
The other 3 factors (mass per seat, regenerated energy per seat and route sinuosity) have only a relatively minor influence on the difference in the energy consumption between the two modes.

**Seat Density**

The density of seats on-board each train affects the energy consumption according to the KPI for a given percentage of passenger loading. The effect of factors (i), (ii) and (iii) above, the mass per seat, resistance per seat and regenerated energy per seat, on the KPI energy consumption also depend on the seat density.

Equation 5-6 below shows the calculation of the effect on the KPI energy consumption of applying the seat density of the 9-car Class 390 to the HS2 reference train. The seat area density of each train is calculated by dividing the seat capacity by the total area which could be used for seating (i.e. the total length of the train minus the end noses multiplied by the maximum exterior width of the train), which includes the space needed, for example, for the train body, inter-car connections, toilets, restaurant cars and luggage racks. Table 5-5 inputs seating area data for the 9-car Class 390 and HS2 reference trains into Equation 5-6 to calculate the effect of seat density:

$$
\varepsilon_{SD} = \left[ \frac{(N_S)_{HS2} (A_S)_{WCML}}{(N_S)_{WCML} (A_S)_{HS2}} - 1 \right] \times 100\%
$$

*Equation 5-6: Calculation of the effect of applying the seat density of the Class 390 'Pendolino' to the HS2 baseline simulations*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>9-car Class 390</th>
<th>HS2 ref. train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length (including end noses)</td>
<td>m</td>
<td>207 (source: RSSB)</td>
<td>201 (21)</td>
</tr>
<tr>
<td>Nose length x 2</td>
<td>m</td>
<td>13 - estimated</td>
<td>15 - estimated from (22)</td>
</tr>
<tr>
<td>Seating length</td>
<td>m</td>
<td>194</td>
<td>186</td>
</tr>
<tr>
<td>Maximum exterior width</td>
<td>m</td>
<td>2.73 - (23)</td>
<td>2.986 - (24)</td>
</tr>
<tr>
<td>Seating area</td>
<td>m²</td>
<td>530</td>
<td>555</td>
</tr>
<tr>
<td>Number of seats</td>
<td></td>
<td>447</td>
<td>510</td>
</tr>
<tr>
<td>Seat density</td>
<td>m⁻²</td>
<td>0.84</td>
<td>0.92</td>
</tr>
<tr>
<td>Effect of seat density, (\varepsilon_{SD})</td>
<td>%</td>
<td>+9</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Table 5-5: Effect on the energy consumption of applying the seat density of the Class 390 'Pendolino' to the HS2 baseline simulations (using the average of the London to Birmingham and return routes)*
**Constant Seat Density Analysis**

The effects of applying the mass and resistance of, and energy regenerated by, the Class 390 to the HS2 baseline simulations are calculated on a per unit seating area basis, thereby negating any seating area density effects, using Equations 5-7 to 5-9 below.

\[
\varepsilon_{M/SA} = \left(\frac{100\%}{\eta_L-W_{NET}}\right)_{HS2} \left\{ \left[ \frac{[M_T(1+\varnothing) + M_P]_{WCML}(N_S)_{HS2}}{[M_T(1+\varnothing) + M_P]_{HS2}(N_S)_{WCML}} \left(\frac{\varepsilon_{SD}}{100} + 1\right) \right] - 1 \right\} (E_{f})_{HS2}
\]

\[
+ \left\{ \left[ \frac{[M_T+M_P]_{WCML}(N_S)_{HS2}}{[M_T+M_P]_{HS2}(N_S)_{WCML}} \left(\frac{\varepsilon_{SD}}{100} + 1\right) \right] - 1 \right\} (E_{g})_{HS2}
\]

*Equation 5-7: Calculation of the effect of applying the mass per unit seating area of the Class 390 'Pendolino' to the HS2 baseline simulations*

\[
\varepsilon_{D/SA} = \left(\frac{100\%}{\eta_L-W_{NET}}\right)_{HS2} \left[ \int_{0}^{t_f} \left[ \frac{(F_D)_{WCML}(N_S)_{HS2}}{(F_D)_{HS2}(N_S)_{WCML}} \left(\frac{\varepsilon_{SD}}{100} + 1\right) \right] - 1 \right] (F_D)_{HS2} v_{HS2} \, dt
\]

*Equation 5-8: Calculation of the effect of applying the resistance per unit seating area of the Class 390 'Pendolino' to the HS2 baseline simulations*

\[
\varepsilon_{R/SA} = \left(\frac{100\%}{E_{NET}}\right)_{HS2} \left[ \left(\frac{(E_R)_{WCML}(N_S)_{HS2}}{(E_R)_{HS2}(N_S)_{WCML}} \left(\frac{\varepsilon_{SD}}{100} + 1\right) \right] - 1 \right\}(E_{R})_{HS2}
\]

*Equation 5-9: Calculation of the effect of applying the energy regenerated per unit seating area by the Class 390 'Pendolino' to the HS2 baseline simulations*

Figure 5-18 compares these effects with those from the previous, per-seat, analysis. It is seen that seat density, although a significant factor in itself, has little effect on the per seat analysis.
In Chapter 5 comparisons are made between the operational energy consumption of the HS2 reference train and that of the competing modes: road, domestic air and existing rail. Comparisons with road and domestic air are made in terms of primary energy using published UK government data for fuel consumption and assuming a 30% conversion of primary energy in the fuel at the power station to electrical energy picked up at the train's current collector. Comparisons with existing rail are made in terms of net electrical energy consumed at the line (including regeneration), based on simulations carried out of a 9-car Class 390 'Pendolino' train running on the WCML. Comparisons are also conducted in terms of direct CO₂ emissions. In all cases comparisons are made with respect to the KPI.

Per seat-km the HS2 reference train consumes the primary energy equivalent to a car running at 40 to 50 mpg, meaning that it has a small advantage over the 2010 UK car, which averages approximately 33 mpg. The journey time saving achieved by the HS2 reference train is over 1 hour 30 minutes, roughly 60% of the original 2 hour 30 minute journey by car. With EU rules set to come into force to drive down the average fuel consumption of UK cars in the coming decades, by the time the HS2 line is operational in the 2020s and 2030s the high speed train may have lost its primary energy advantage per seat-km by then. Assuming average passenger load factors of 50 to 70% for the train and 1.6 persons for the car (including the driver), the HS2 reference train consumes the primary energy equivalent to a car running at approximately 80 mpg.
In terms of CO\textsubscript{2} emissions, on a per seat-km basis the HS2 reference train outperforms the car using today's power generation mix and average UK car emissions data. Basing the analysis on a potential 2020 scenario, with European regulations in force restricting average new car emissions to 95gCO\textsubscript{2}e/km and assuming the CO\textsubscript{2} intensity of UK power generation is reduced by a third from today's value, per seat-km the HS2 reference train and the car perform roughly equally. Per passenger-km, with the same loading assumptions as previously, the HS2 reference train emits considerably less CO\textsubscript{2} than the car. 

The HS2 reference train consumes only a fraction of the primary energy of domestic air on a per seat-km basis, whether assuming a 2010 or a potential 2050 scenario for domestic air, with average air emissions per seat-km reduced by 27% from today's level. The HS2 reference train also emits only a fraction of the CO\textsubscript{2} of domestic air irrespective of the scenario studied. Domestic air's poor performance is exacerbated by the added effect on Climate Change of high-altitude emission. A CO\textsubscript{2} multiplier of 1.9 is often used to take account of this. The journey time (per km in this analysis) of the HS2 reference train is roughly double that of domestic air.

Simulations indicate the Class 390 'Pendolino' train running on the WCML consumes approximately 15-20% less energy according to the KPI than the HS2 reference train (baseline simulation case), assuming equal percentage passenger load. A reduction in the maximum operational speed of the HS2 reference train from the baseline value of 330 km/h to 280 km/h puts the KPI energy consumption of HS2 on a par with that of the existing WCML, whilst still providing a journey time saving of approximately 30 minutes. Whilst the precise details of the comparison are subject to the assumptions used, the HS2 reference train holds a clear equal energy / journey time saving advantage over the existing WCML. The main reason for the HS2 reference train's advantage is its lower resistance per unit seating area compared to the Class 390, although other factors, for example the lower route sinuosity and higher seat density also contribute.

Chapter 6 uses the analysis technique from Section 5.6 to analyse the energy performance of the HS2 reference train with other types of high speed train design.
References


5. Ibid. 2.


7. Ibid.

8. Ibid. 4.


11. Ibid. 2.

12. Ibid.

13. Ibid.
14. Ibid.


16. Ibid. 1.


22. Ibid.


24. Ibid. 21.
Chapter 6: Energy Comparisons with Other High Speed Vehicles

Simulations are carried out of different types of high speed rolling stock running on the proposed London-Birmingham HS2 route, more specifically: the Transrapid maglev, the 400 metre long Shinkansen N700 and the double-decker TGV Duplex. The energy consumption / journey time relationship of these vehicle types is compared with that obtained for the HS2 reference train running along the same route and the 9-car Class 390 'Pendolino' running on the WCML. Analysis is undertaken to determine the contribution of various factors in determining the energy difference between each vehicle type and the HS2 reference train so that key features of vehicle design which help to drive down the energy consumption of high speed rail can be identified.

6.1. Introduction

The aim of Chapter 6 is to identify key areas of vehicle design which help to minimize the energy consumption of high speed rail travel. In order to do this simulations are carried out of different types of rolling stock running on the proposed London-Birmingham HS2 route, more specifically: the Transrapid maglev, the 400 metre long Shinkansen N700 and the double-decker TGV Duplex. Transrapid maglev technology is, of course, a mode of transport in its own right, but for the purposes of this investigation it is considered a possible alternative vehicle type to the HS2 reference train. For each vehicle type the relationship between the energy consumption and journey time is established and compared with that obtained for the HS2 reference train running along the same route and the 9-car Class 390 'Pendolino' running along the WCML route between London and Birmingham, calculated in Chapters 4 and 5 respectively. The energy / journey time relationship of each vehicle type running along the simulated route is obtained by variation of the maximum operational speed.
Analysis, similar to that first presented in Chapter 5 comparing the energy comparison of the HS2 reference train and the 9-car Class 390 running on the WCML, is undertaken to determine the contribution of various factors in determining the energy difference between each vehicle type and the HS2 reference train. Key features of vehicle design and specification which help to drive down the energy consumption of high speed rail travel are then identified.

6.2. **Comparisons with the Transrapid Maglev System**

6.2.1. **Introduction**

The only operational high speed magnetic levitation (maglev) system in the world today operates between Shanghai Pudong Airport and the Pudong area of Shanghai. With a maximum operational speed of 431 km/h, the Maglev train takes less than 8 minutes to travel the 30 km distance (1).

The vehicles are propelled by linear motors mounted under the edges of the concrete guide way, as shown in Figure 6-1 below. The sides of the vehicles are extended downward and a reaction rail wraps around the linear motor, as seen in Figure 6-2. The lift magnets, attached to the vehicle, are attracted to the motor stator and the gap is controlled between 8 and 14 mm by varying the current in the coil (2).

![Figure 6-1: Linear motor (3)](image1)

![Figure 6-2: Cross section of life magnet and reaction rail support (4)](image2)
6.2.2. **Energy Modelling**

Simulations are carried out of a Transrapid maglev vehicle running along the London to Birmingham HS2 route. In reality, the Transrapid maglev has a greater ability to negotiate gradient and curves than high speed trains, thus the route of a Transrapid maglev guideway could well be significantly different to that of the HS2 route. Examples of the greater route flexibility of the Transrapid maglev system compared to high speed rail include its ability to operate on gradients up to 10%, compared to 4% typically for high speed rail, and on curves with a minimum radius of 1.6 km at 300 km/h, compared to typically 3.2 km for high speed rail (5). Nevertheless, with no detailed route data available for a potential Transrapid maglev system, running the Transrapid on the HS2 route is sufficient for the purposes of this investigation. The vehicle data used for the Transrapid simulations are based on those used in the environmental assessment of a potential Transrapid maglev network in the UK in (6). The train consists of 10 cars and has a seating capacity of 876, with up to 6 seats per row.

Table 6-1 below summarizes some of the train data input into the simulation. It should be noted that the mass of the train was quoted as 640 tonnes fully laden. By using the same assumption as for the HS2 reference train that each passenger has a mass of 75 kg, the tare mass (including the mass of water required for hotel services) is arrived at. The rotational inertia mass factor is assumed to be 0 due to the linear nature of the propulsion system. Additionally, the overall efficiency of the drive and electrical supply systems is quoted as 77.2%, which includes the losses from the substation transformer and transmission to track. As the overall efficiency of the HS2 reference train would be of a similar value if the efficiency of the electrical supply system were included in the analyses from the previous chapters, it is assumed that the efficiency of the drive system of the Transrapid maglev is equal to that of the line-to-wheel efficiency of the HS2 reference train, 82.3%.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tare mass</td>
<td>$M_T$</td>
<td>t</td>
<td>574</td>
</tr>
<tr>
<td>Rotational inertia mass factor</td>
<td>$\phi$</td>
<td>%</td>
<td>0</td>
</tr>
<tr>
<td>Mass of passengers at 100 % load</td>
<td>$M_P$</td>
<td>t</td>
<td>66</td>
</tr>
<tr>
<td>Passenger load factor</td>
<td>$LF$</td>
<td>%</td>
<td>70</td>
</tr>
<tr>
<td>Train length</td>
<td>$L_{TRAIN}$</td>
<td>m</td>
<td>252</td>
</tr>
<tr>
<td>Efficiency of drive system</td>
<td>$\eta_{DRIVE}$</td>
<td>%</td>
<td>82.3</td>
</tr>
<tr>
<td>Efficiency of regeneration</td>
<td>$\eta_R$</td>
<td>%</td>
<td>80</td>
</tr>
<tr>
<td>Station dwell time</td>
<td>$t_{DWEEL}$</td>
<td>mins</td>
<td>2</td>
</tr>
</tbody>
</table>

*Table 6-1: Transrapid maglev parameters used for the simulations*

Data for the resistance and auxiliary power supply of the Transrapid maglev are shown in Figures 6-3 and 6-4. There are three components of drag: auxiliary drag, which is created by the electrical system producing auxiliary power for the train to feed levitation, air conditioning and lighting etc..., magnetic drag, analogous to the rolling resistance of rail vehicles, and aerodynamic drag. The shape of the auxiliary drag curve can be explained by the fact that at speeds of up to 20 km/h auxiliary power is collected by a contact system, so there is no auxiliary drag component below 20 km/h. Between 20 km/h and 70 km/h the requirement for auxiliary power by inductive pickup rises rapidly, meaning that the corresponding auxiliary drag also rises. As the requirement for power remains roughly constant beyond 70 km/h (see Figure 6-4), the auxiliary drag force follows an approximately constant power curve with respect to the vehicle velocity.

![Figure 6-3: Drag components of Transrapid maglev](image1)

![Figure 6-4: Auxiliary power demand versus speed for Transrapid maglev](image2)
Regenerative braking is assumed to be available at speeds above 20 km/h with an efficiency of 80%. No tractive effort curve of the Transrapid maglev has been made available to the author. It is therefore calculated with reference to acceleration performance data, shown in Figure 6-5. The acceleration data is assumed to be for a Transrapid maglev vehicle running on a level track and empty of any passengers. Based on these assumptions, the tractive effort curve, shown in Figure 6-6, is calculated as the difference between the inertia (accelerating) force and the overall resistance force.

As stated previously, the route data used for the Transrapid simulations are the same as those used for the HS2 reference train. The only two exceptions to this are:

i. The maximum line speed along the HS2 route is raised from 400 km/h to 500 km/h. All other line speeds are kept the same as in the previous analyses.
ii. Due to the larger cross-sectional area of the Transrapid maglev compared to the HS2 reference train (16 m\(^2\) (7) compared to 11 m\(^2\)) the tunnel factor used to multiply the aerodynamic component of resistance is different to that of the HS2 reference train. The calculation of the aerodynamic tunnel factor for the Transrapid maglev is carried out using the same formula as that for the HS2 reference train (detailed in Chapter 3) but with a different train cross-sectional area value. In reality the Transrapid has a unique formula for the average aerodynamic drag experienced in tunnels but this information is unavailable. For the purposes of this investigation and considering the small proportion of the route in tunnels, such an approach suffices. Table 6-2 details the tunnel factors used for the Transrapid maglev simulations:

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Distance from London</th>
<th>Tunnel factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>London end</td>
<td>Birmingham end</td>
</tr>
<tr>
<td>#1 (dia. 7.2m)</td>
<td>1.2</td>
<td>10.3</td>
</tr>
<tr>
<td>#2 (dia. 12.0m)</td>
<td>31.5</td>
<td>40.6</td>
</tr>
<tr>
<td>#3 (dia. 12.0m)</td>
<td>126.6</td>
<td>128.0</td>
</tr>
</tbody>
</table>

*Table 6-2: Aerodynamic tunnel factors for the Transrapid maglev and HS2 reference train*

The maximum operational speed of the Transrapid maglev is varied between 400 km/h and 500 km/h, the maximum capable speed of the vehicle, to establish the relationship between its energy consumption and journey time. As the line speed profile of any maglev line may differ significantly from that of HS2, due to the Transrapid's superior curving performance, simulations are run of the Transrapid running on the HS2 route under the following three line speed profiles:

i. Baseline line speed profile (as used in Chapter 3),
ii. Maximized line speed profile (as introduced in Chapter 4),
iii. No line speed profile (as introduced in Chapter 4).

The driving assumptions employed in the energy modelling of the Transrapid maglev are the same as with the HS2 reference train.
6.2.3. Simulation Outputs

Figures 6-7 to 6-9 show outputs from one of the Transrapid maglev simulations and compare them with those from the London to Birmingham HS2 baseline simulation (presented in Chapter 3):

Figure 6-7: Speed - time history of the Transrapid maglev running with a maximum operational speed of 500 km/h on the London to Birmingham route (with the baseline line speed profile) compared to that of the corresponding HS2 reference train baseline case.

Figure 6-8: Power - time history of the Transrapid maglev running with a maximum operational speed of 500 km/h on the London to Birmingham route (with the baseline line speed profile) compared to that of the corresponding HS2 reference train baseline case.

Figure 6-9: Power regenerated - time history of the Transrapid maglev running with a maximum operational speed of 500 km/h on the London to Birmingham route (with the baseline line speed profile) compared to that of the corresponding HS2 reference train baseline case.
The greater acceleration performance and maximum speed capability of the Transrapid are immediately noticeable from Figure 6-7. From Figure 6-8, the peak power requirement of the Transrapid maglev train on the HS2 line is approximately 5 times that of the HS2 reference train, whilst the seating capacity is only 1.7 times as great.

6.2.4. **Energy / Journey Time Comparison**

Figure 6-10 shows how the net energy consumption (including braking regeneration) of the Transrapid maglev varies with the journey time for different maximum operational speeds from 500 km/h to 400 km/h (extended down to 250 km/h - see dashed line) using each of the three line speed profiles investigated (baseline, maximized and no line speed profiles). Comparisons are made with the HS2 reference train and WCML simulations as calculated in previous chapters. Figure 6-11 compares the net energy consumption from the supply of each of the three modes using the defined KPI.

As the intermediate line speeds for a Transrapid maglev system are likely to be higher than for the HS2 reference train, due to the maglev's ability to negotiate curves at greater speeds than conventional high speed trains, the energy consumption and journey time of the Transrapid maglev travelling on the HS2 route are likely to sit somewhere in the region between the baseline and 'no' line speed graph lines, as shown in Figures 6-10 and 6-11.
The KPI energy consumption of the Transrapid maglev running with a maximum operational speed of 500 km/h is therefore likely to be somewhere between approximately 40% and 60% greater than that of the baseline case for the HS2 reference train, depending on the line speed profile used. The corresponding journey time saving of the Transrapid maglev is likely to lie between approximately 7 and 14 minutes each way along the HS2 route, or 15% and 29%.

From Figure 6-11 it is also seen that the Transrapid maglev holds an equal energy, journey time saving advantage over the HS2 reference train for journey times below approximately 50 minutes. In addition the journey time saving provided by the Transrapid maglev for the same energy consumption increases as journey times get shorter. One of the reasons for the 'less steep' energy / journey time relationship of the Transrapid maglev is its greater acceleration performance.

In the next section the reasons for the observed difference in KPI energy consumption between the Transrapid maglev and HS2 reference train are explored.

6.2.5. Analysis of the Energy Difference Between the Transrapid Maglev and HS2 Baseline Simulations

Introduction

A similar methodology is employed in this section to that used in Chapter 5 for the comparison between the WCML and the HS2 baseline simulations. In the following analysis the average of the HS2 baseline simulations is compared with the average of the Transrapid maglev simulations operating with a maximum speed of 500 km/h using the baseline line speed profile. The energy consumption of the Transrapid maglev in these simulations according to the KPI is 39% greater than that of the average HS2 baseline case.
**Per Seat Analysis**

The following train and route-based factors contribute towards the calculated energy consumption difference between the two modes using the KPI defined earlier in the thesis:

i. Mass per seat,

ii. Resistance per seat,

iii. Regenerated energy (during braking) per seat,

iv. Auxiliary energy per seat,

v. Speed profile.

Other factors, for example the efficiency of the drive system, the passenger load as a percentage of the number of seats and route sinuosity do not contribute to the difference in the energy consumption between the two modes as they are assumed to be equal.

Equations 6-1 to 6-4 show the calculation of the effect on the KPI energy consumption of applying parameters (i) to (iv) of the Transrapid maglev to the HS2 baseline simulations. As in the WCML analysis in Chapter 5, the effect of speed profile is calculated as the difference between the sum of the percentage contributions (i) to (iv) and the energy difference in percentage terms between the two modes according to the KPI.

\[
\varepsilon_{M/S} = \left( \frac{100\%}{\eta_{L-W} E_{NET}} \right)_{HS2} \left\{ \left[ \frac{M_T (1 + \Phi) + M_P}{M_T (1 + \Phi) + M_P} \right]_{TR} N_S_{HS2} - 1 \right\} (E_I)_{HS2}
\]

\[
+ \left\{ \left[ \frac{M_T + M_P}{M_T + M_P} \right]_{TR} N_S_{HS2} - 1 \right\} (E_G)_{HS2}
\]

*Equation 6-1: Calculation of the effect of applying the mass per seat of the Transrapid maglev to the HS2 baseline simulations*

\[
\varepsilon_{D/S} = \left( \frac{100\%}{\eta_{L-W} E_{NET}} \right)_{HS2} \int_{0}^{t_f} \left[ \frac{(F_D)_{TR} N_S_{HS2}}{(F_D)_{HS2} N_S_{TR}} - 1 \right] (F_D)_{HS2} v_{HS2} dt \text{ for } F_T > 0
\]

*Equation 6-2: Calculation of the effect of applying the resistance per seat of the Transrapid maglev to the HS2 baseline simulations*
\[ \varepsilon_{R/S} = \left( \frac{100\%}{E_{NET}^{HS2}} \right) \left\{ \left[ \frac{(E_R)_{TR}(N_S)^{HS2}}{(E_R)^{HS2}(N_S)^{TR}} - 1 \right] (E_R)^{HS2} \right\} \]

Equation 6-3: Calculation of the effect of applying the energy regenerated per seat of the Transrapid maglev to the HS2 baseline simulations

\[ \varepsilon_{APS/S} = \left( \frac{100\%}{E_{NET}^{HS2}} \right) \left\{ \left[ \frac{(E_{APS})_{TR}(N_S)^{HS2}}{(E_{APS})^{HS2}(N_S)^{TR}} - 1 \right] (E_{APS})^{HS2} \right\} \]

Equation 6-4: Calculation of the effect of applying the auxiliary energy per seat of the Transrapid maglev to the HS2 baseline simulations

Results

Table 6-3 shows the contributions of each of the above 5 factors towards the observed difference in the KPI energy consumption between the two modes. For the resistance per seat parameter, the components of drag, both non-aerodynamic and aerodynamic, have been separated. In addition the effect of the auxiliary component of drag has also been identified and optionally included in the auxiliary energy per seat analysis. Figure 6-12 graphically illustrates the results:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effect on HS2 energy consumption, ( \varepsilon ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass per seat</td>
<td>-4</td>
</tr>
<tr>
<td>Resistance per seat</td>
<td>-3 (non-aerodynamic: magnetic plus auxiliary = +15, aerodynamic = -18)</td>
</tr>
<tr>
<td>Regenerated energy per seat</td>
<td>-12</td>
</tr>
<tr>
<td>Auxiliary energy per seat</td>
<td>+4 (+17 if auxiliary drag is included)</td>
</tr>
<tr>
<td>Speed profile</td>
<td>+54</td>
</tr>
<tr>
<td>Sum</td>
<td>+39</td>
</tr>
</tbody>
</table>

Table 6-3: Effect on the KPI energy consumption (per seat-km) of applying various parameters from the Transrapid maglev simulations (at 500 km/h using baseline line speed profile) to the HS2 baseline simulations (using the average of the London to Birmingham and return routes)
It is seen that the advantages of lower mass and resistance per seat and higher regenerated energy per seat of the Transrapid maglev are outweighed by its greater auxiliary requirement and speed profile. In addition, applying the greater non-aerodynamic drag per seat of the Transrapid maglev to the HS2 baseline simulations would increase the energy consumption according to the KPI by 15%, whilst applying its aerodynamic component would reduce the energy consumption by 18%, resulting in the 3% reduction based on an overall resistance per seat basis. The major factor contributing towards the greater non-aerodynamic component of resistance of the Transrapid maglev compared to the HS2 reference train is the auxiliary drag.

**Seat Density**

As with the Class 390 / WCML analysis the effect of seat density is calculated according to Equation 6-5 and Table 6-4:

$$\varepsilon_{SD} = \left[ \frac{(N_S)_{HS2}}{(N_S)_{TR}} \frac{(A_S)_{TR}}{(A_S)_{HS2}} - 1 \right] \times 100\%$$

*Equation 6-5: Calculation of the effect of applying the seat density of the Transrapid maglev to the HS2 baseline simulations*
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Transrapid maglev</th>
<th>HS2 ref. train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length (including end noses)</td>
<td>m</td>
<td>252 (8)</td>
<td>201 (9)</td>
</tr>
<tr>
<td>Nose length x 2</td>
<td>m</td>
<td>14 - estimated from (10)</td>
<td>15 - estimated from (11)</td>
</tr>
<tr>
<td>Seating length</td>
<td>m</td>
<td>238</td>
<td>186</td>
</tr>
<tr>
<td>Maximum exterior width</td>
<td>m</td>
<td>3.7 - (12)</td>
<td>2.986 - (13)</td>
</tr>
<tr>
<td>Seating area</td>
<td>m²</td>
<td>881</td>
<td>555</td>
</tr>
<tr>
<td>Number of seats</td>
<td></td>
<td>876</td>
<td>510</td>
</tr>
<tr>
<td>Seat density</td>
<td>m²</td>
<td>0.99</td>
<td>0.92</td>
</tr>
<tr>
<td>Effect of seat density, $\varepsilon_{SD}$</td>
<td>%</td>
<td>-8</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 6-4: Effect on the KPI energy consumption (per seat-km) of applying the seat density of the Transrapid maglev to the HS2 baseline simulations (using the average of the London to Birmingham and return routes)

**Constant Seat Density Analysis**

The effects of applying the mass, resistance and auxiliary requirement of, and energy regenerated by, the Transrapid maglev to the HS2 baseline simulations are calculated on a per unit seating area basis, thereby negating any seating area density effects, using Equations 6-6 to 6-9 below.

$$
\varepsilon_{M/SA} = \left( \frac{100\%}{\eta_{L-W}E_{NET}} \right)_{HS2} \left\{ \frac{[M_T(1 + \Phi) + M_p]_{TR}(N_S)_{HS2} - 1}{[M_T(1 + \Phi) + M_p]_{HS2}(N_S)_{TR} \left( \frac{\varepsilon_{SD}}{100} + 1 \right)} \right\} (E_I)_{HS2}
$$

$$
+ \left\{ \frac{[M_T + M_p]_{TR}(N_S)_{HS2} - 1}{[M_T + M_p]_{HS2}(N_S)_{TR} \left( \frac{\varepsilon_{SD}}{100} + 1 \right)} \right\} (E_G)_{HS2}
$$

*Equation 6-6: Calculation of the effect of applying the mass per unit seating area of the Transrapid maglev to the HS2 baseline simulations*

$$
\varepsilon_{D/SA} = \left( \frac{100\%}{\eta_{L-W}E_{NET}} \right)_{HS2} \int_0^{t_f} \left( \frac{(F_D)_{TR}(N_S)_{HS2} - 1}{(F_D)_{HS2}(N_S)_{TR} \left( \frac{\varepsilon_{SD}}{100} + 1 \right)} \right) (F_D)_{HS2} \psi_{HS2} \, dt \text{ for } F_T > 0
$$

*Equation 6-7: Calculation of the effect of applying the resistance per unit seating area of the Transrapid maglev to the HS2 baseline simulations*
\[ \varepsilon_{R/SA} = \left( \frac{100\%}{E_{NET}} \right)_{HS2} \left\{ \frac{(E_R)_{TR}(N_S)_{HS2}}{E_{NET}} - 1 \right\} \left( E_R \right)_{HS2} \]

*Equation 6-8: Calculation of the effect of applying the energy regenerated per unit seating area by the Transrapid maglev to the HS2 baseline simulations*

\[ \varepsilon_{APS/SA} = \left( \frac{100\%}{E_{NET}} \right)_{HS2} \left\{ \frac{(E_{APS})_{TR}(N_S)_{HS2}}{(E_{APS})_{HS2}} - 1 \right\} \left( E_{APS} \right)_{HS2} \]

*Equation 6-9: Calculation of the effect of applying the auxiliary energy per unit seating area of the Transrapid maglev to the HS2 baseline simulations*

Figure 6-13 compares these effects with those from the previous, per-seat, analysis. It is seen that, as with the Class 390 comparison, seat density, although a significant factor in itself, has little effect on the per seat analysis.
6.3. Comparisons with the Japanese Shinkansen

6.3.1. Introduction

Japanese Shinkansen train sets are often quoted as being more energy efficient than their European rivals. In this section, data provided by JR-Central for a 16-car Shinkansen N700 is input into the Train Energy Simulator to estimate its energy consumption if it were to run on the proposed London to Birmingham HS2 route. The N700 is a wide-bodied (fitting 5 seats across a row instead of the conventional 4) Electrical Multiple Unit (EMU) train with distributed power supplied through AC asynchronous motors on 14 of the 16 cars.

6.3.2. Energy Modelling

Train data used for the modelling of the Shinkansen N700 train are shown in Figure 6-14 and Tables 6-5 to 6-6. Unlike with the HS2 reference train, at speeds of above 20 km/h braking is assumed to be entirely regenerative and at a rate of 6% of g. In calculating the aerodynamic tunnel factors, the Shinkansen N700 is assumed to have a cross-sectional area of 13 m$^2$, compared to 11 m$^2$ for the HS2 reference train.

![Figure 6-14: Tractive effort and resistance curve for the 16-car Shinkansen N700 (data provided by JR-Central)](image)
Table 6-5: Train-based parameters for the Shinkansen N700 (data provided by JR-Central)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tare mass (including 14 tonnes for water and other services)</td>
<td>$M_T$</td>
<td>t</td>
<td>616</td>
</tr>
<tr>
<td>Rotational inertia mass factor</td>
<td>$\phi$</td>
<td>%</td>
<td>5</td>
</tr>
<tr>
<td>Mass of passengers at 100 % load (seat capacity = 1323)</td>
<td>$M_P$</td>
<td>t</td>
<td>99</td>
</tr>
<tr>
<td>Passenger load factor</td>
<td>$LF$</td>
<td>%</td>
<td>70</td>
</tr>
<tr>
<td>Train length</td>
<td>$L_{\text{TRAIN}}$</td>
<td>m</td>
<td>400</td>
</tr>
<tr>
<td>Maximum operational speed</td>
<td>$v_{\text{MAX}}$</td>
<td>km/h</td>
<td>330</td>
</tr>
<tr>
<td>Efficiency between pantograph and wheel</td>
<td>$\eta_{L\text{-}W}$</td>
<td>%</td>
<td>82.3</td>
</tr>
<tr>
<td>Efficiency of regenerative braking</td>
<td>$\eta_R$</td>
<td>%</td>
<td>80</td>
</tr>
<tr>
<td>Auxiliary Power Supply (APS)</td>
<td>$P_{\text{APS}}$</td>
<td>kW</td>
<td>713</td>
</tr>
<tr>
<td>APS Efficiency</td>
<td>$\eta_{\text{APS}}$</td>
<td>%</td>
<td>85</td>
</tr>
<tr>
<td>Braking rate</td>
<td>$a_B$</td>
<td>%g</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 6-6: Tunnel factors for the 400m Shinkansen N700

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Distance from London</th>
<th>Tunnel factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1 (dia. 7.2m)</td>
<td>1.2</td>
<td>10.3</td>
</tr>
<tr>
<td>#2 (dia. 12.0m)</td>
<td>31.5</td>
<td>40.6</td>
</tr>
<tr>
<td>#3 (dia. 12.0m)</td>
<td>126.6</td>
<td>128.0</td>
</tr>
</tbody>
</table>

As with the HS2 reference train, the maximum operational speed of the Shinkansen N700 is varied between 250 km/h and 330 km/h. The baseline line speed profile is used.

### 6.3.3. Simulation Outputs

Figures 6-15 to 6-17 show outputs from the 330 km/h, London to Birmingham Shinkansen N700 simulation and compare them with those from the London to Birmingham baseline HS2 reference train simulation (presented in Chapter 3):

![Speed-time history of the Shinkansen N700](image)

*Figure 6-15: Speed-time history of the Shinkansen N700 running with a maximum operational speed of 330 km/h on the London to Birmingham route compared to that of the corresponding HS2 reference train baseline case*
As seen from Figures 6-15 to 6-17 above, the maximum power required to accelerate the 400 metre Shinkansen N700 series train is approximately double that of the 200 metre HS2 reference train. Since the tare mass of the Shinkansen N700 is significantly less than double that of the HS2 reference train (616 tonnes compared to 382 tonnes), the acceleration performance of the Shinkansen N700 is superior to that of the HS2 reference train.

### 6.3.4. Energy / Journey Time Comparison

Figure 6-18 shows how the energy consumption (including braking regeneration) of the Shinkansen N700 varies with journey time for maximum operational speeds between 250 and 330 km/h using the baseline line speed profile. Comparisons are made with the HS2 reference train and WCML simulations as calculated in previous chapters. Figure 6-19 compares the net energy consumption at the line of each of the three vehicle types using the defined KPI.
From Figure 6-19 it is seen that the KPI energy consumption of the Shinkansen N700 running with a maximum operational speed of 330 km/h is 37% less than that of the HS2 reference train for the same journey time. In addition, it can be seen that for the same energy the Shinkansen N700 running at 330 km/h completes the London to Birmingham journey in approximately 48 minutes compared to the HS2 reference train which completes the journey in approximately 60 minutes.

In the next section the reasons for the calculated difference in the KPI energy consumption between the Shinkansen N700 and the HS2 reference train are explored.
6.3.5. **Analysis of the Energy Difference Between the Shinkansen N700 and HS2 Reference Train**

*Introduction*

A similar methodology is employed in this section to that used in the Class 390 / WCML and Transrapid maglev analyses. In this section the average KPI energy consumption of the HS2 baseline simulations is compared with that of the Shinkansen N700 simulations operating with a maximum speed of 330 km/h. The energy consumption of the Shinkansen N700 in these simulations according to the KPI is 37% less than that of the average HS2 baseline case.

*Per Seat Analysis*

The following train and route-based factors contribute towards the observed energy consumption difference between the two modes using the KPI defined earlier in the thesis:

i. Mass per seat,
ii. Resistance per seat,
iii. Regenerated energy (during braking) per seat,
iv. Speed profile.

Other factors, for example the efficiency of the drive system, the passenger load as a percentage of the number of seats and route sinuosity do not contribute to the difference in the energy consumption between the two modes as they are assumed to be equal.

Equations 6-10 to 6-12 show the calculation of the effect on the KPI energy consumption of applying parameters (i) to (iii) of the Shinkansen N700 to the HS2 baseline simulations. As in the WCML and Transrapid maglev analyses, the effect of speed profile is calculated as the difference between the sum of the percentage contributions (i) to (iii) and the energy difference in percentage terms between the two modes according to the KPI.
\[
\varepsilon_{M/S} = \left(\frac{100\%}{\eta_{L-W}E_{NET}}\right)_{HS2} \left\{ \left[\frac{[M_T(1 + \Phi) + M_p]_{N700}(N_S)_{HS2}}{[M_T(1 + \Phi) + M_p]_{HS2}(N_S)_{N700}} - 1\right](E_i)_{HS2} \right. \\
+ \left. \left[\frac{[M_T + M_p]_{N700}(N_S)_{HS2}}{[M_T + M_p]_{HS2}(N_S)_{N700}} - 1\right](E_G)_{HS2} \right\}
\]

Equation 6-10: Calculation of the effect of applying the mass per seat of the Shinkansen N700 to the HS2 baseline simulations

\[
\varepsilon_{D/S} = \left(\frac{100\%}{\eta_{L-W}E_{NET}}\right)_{HS2} \int_0^{t_f} \left[\frac{(F_D)_{N700}(N_S)_{HS2}}{(F_D)_{HS2}(N_S)_{N700}} - 1\right](F_D)_{HS2}v_{HS2} \, dt \text{ for } F_T > 0
\]

Equation 6-11: Calculation of the effect of applying the resistance per seat of the Shinkansen N700 to the HS2 baseline simulations

\[
\varepsilon_{R/S} = \left(\frac{100\%}{E_{NET}}\right)_{HS2} \left[\frac{(E_R)_{N700}(N_S)_{HS2}}{(E_R)_{HS2}(N_S)_{N700}} - 1\right](E_R)_{HS2}
\]

Equation 6-12: Calculation of the effect of applying the energy regenerated per seat of the Shinkansen N700 to the HS2 baseline simulations

**Results**

Table 6-7 shows the contributions of each of the above 4 factors towards the observed difference in the KPI energy consumption between the two modes. Figure 6-20 graphically illustrates the results:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effect on HS2 energy consumption, $\varepsilon$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass per seat</td>
<td>-10</td>
</tr>
<tr>
<td>Resistance per seat</td>
<td>-26</td>
</tr>
<tr>
<td>Regenerated energy per seat</td>
<td>0</td>
</tr>
<tr>
<td>Speed profile</td>
<td>-1</td>
</tr>
<tr>
<td>Sum</td>
<td>-37</td>
</tr>
</tbody>
</table>

*Table 6-7: Effect on the KPI energy consumption of applying various parameters from the Shinkansen N700 simulations (at 330 km/h using baseline line speed profile) to the HS2 baseline simulations (using the average of the London to Birmingham and return routes)*
Figure 6-20: Effect on the KPI energy consumption (per seat-km) of applying various parameters of the Shinkansen N700 simulations (at 330 km/h, baseline line speed profile) to the HS2 baseline simulations. N.B. Percentages shown are relative to the average energy consumption of the two original HS2 baseline simulations.

It is seen that the major factors contributing towards the lower KPI energy consumption of the Shinkansen N700 are its lower mass per seat and lower resistance per seat.

**Seat Density**

As with the Class 390 and Transrapid maglev analyses the effect of seat density is calculated according to Equation 6-13 and is detailed in Table 6-8:

$$\varepsilon_{SD} = \left[ \frac{(N_S)_{HS2}(A_S)_{N700}}{(N_S)_{N700}(A_S)_{HS2}} - 1 \right] \times 100\%$$

*Equation 6-13: Calculation of the effect of applying the seat density of the Shinkansen N700 to the HS2 baseline simulations*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Shinkansen N700</th>
<th>HS2 ref. train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length (including end noses)</td>
<td>m</td>
<td>405 (14)</td>
<td>201 (15)</td>
</tr>
<tr>
<td>Nose length x 2</td>
<td>m</td>
<td>20 - estimated from (16)</td>
<td>15 - estimated from (17)</td>
</tr>
<tr>
<td>Seating length</td>
<td>m</td>
<td>385</td>
<td>186</td>
</tr>
<tr>
<td>Maximum exterior width</td>
<td>m</td>
<td>3.36 - (18)</td>
<td>2.986 - (19)</td>
</tr>
<tr>
<td>Seating area</td>
<td>m²</td>
<td>1294</td>
<td>555</td>
</tr>
<tr>
<td>Number of seats</td>
<td>-</td>
<td>1323</td>
<td>510</td>
</tr>
<tr>
<td>Seat density</td>
<td>m²</td>
<td>1.02</td>
<td>0.92</td>
</tr>
<tr>
<td>Effect of seat density, $\varepsilon_{SD}$</td>
<td>%</td>
<td>-10</td>
<td>N/A</td>
</tr>
</tbody>
</table>

*Table 6-8: Effect on the energy consumption of applying the seat density of the Shinkansen N700 to the HS2 baseline simulations (using the average of the London to Birmingham and return routes)*
Constant Seat Density Analysis

The effects of applying the mass and resistance of, and energy regenerated by, the Shinkansen N700 to the HS2 baseline simulations are calculated on a per unit seating area basis, thereby negating any seating area density effects, using Equations 6-14 to 6-16 below.

\[
\varepsilon_{M/SA} = \left( \frac{100\%}{\eta_L-WE_{NET}} \right)_{HS2} \left\{ \left[ \frac{[M_T (1 + \emptyset) + M_p]_{N700} (N_S)_{HS2}}{[M_T (1 + \emptyset) + M_p]_{HS2} (N_S)_{N700} \left( \frac{\varepsilon_{SD}}{100} + 1 \right)} - 1 \right] (E_i)_{HS2} \\
+ \left[ \frac{[M_T + M_p]_{N700} (N_S)_{HS2}}{[M_T + M_p]_{HS2} (N_S)_{N700} \left( \frac{\varepsilon_{SD}}{100} + 1 \right)} - 1 \right] (E_G)_{HS2} \right\}
\]

Equation 6-14: Calculation of the effect of applying the mass per unit seating area of the Shinkansen N700 to the HS2 baseline simulations.

\[
\varepsilon_{D/SA} = \left( \frac{100\%}{\eta_L-WE_{NET}} \right)_{HS2} \int_0^t \left[ \frac{(F_D)_{N700} (N_S)_{HS2}}{(F_D)_{HS2} (N_S)_{N700} \left( \frac{\varepsilon_{SD}}{100} + 1 \right)} - 1 \right] (F_D)_{HS2} v_{HS2} \, dt \text { for } F_T > 0
\]

Equation 6-15: Calculation of the effect of applying the resistance per unit seating area of the Shinkansen N700 to the HS2 baseline simulations.

\[
\varepsilon_{E/SA} = \left( \frac{100\%}{E_{NET}} \right)_{HS2} \left\{ \left[ \frac{(E_R)_{N700} (N_S)_{HS2}}{(E_R)_{HS2} (N_S)_{N700} \left( \frac{\varepsilon_{SD}}{100} + 1 \right)} - 1 \right] (E_R)_{HS2} \right\}
\]

Equation 6-16: Calculation of the effect of applying the energy regenerated per unit seating area of the Shinkansen N700 to the HS2 baseline simulations.

Figure 6-21 compares these effects with those from the previous, per-seat, analysis. It is seen that, as with the previous comparisons, seat density, although a significant factor in itself, has little effect on the per seat analysis.
6.4. Comparisons with the TGV Duplex

6.4.1. Introduction

In the previous analysis, simulations were carried out of the 400 metre-long Shinkansen N700 running on the London to Birmingham HS2 route. Another way to increase the passenger capacity of the train and hence the line is to introduce a second deck of seats on-board the train. In this section simulations are carried out of the TGV Duplex running on the same HS2 line, a double-decker train powered by 8 x 1100 kW-rated 3-phase synchronous traction motors located in 2 power cars (20).
6.4.2. **Energy Modelling**

Train data used for the modelling of the TGV Duplex train are shown in Figure 6-22 and Tables 6-9 and 6-10. As no tractive effort data was available to the author the curve has been backward-calculated using the Davis equation resistance equation and the acceleration characteristic of the HS2 reference train. Braking is assumed to be a mix of mechanical and electrodynamic. As no regenerative braking curve was available to the author, the proportion of braking energy, where regeneration is possible (above 20 km/h), which is returned to the line during a journey is assumed to be equal to that regenerated by the HS2 reference train. In calculating the aerodynamic tunnel factors, the TGV Duplex is assumed to have a cross-sectional area of 15 m\(^2\), compared to 11 m\(^2\) for the HS2 reference train.

![Figure 6-22: Tractive Effort and Resistance Curves used for the TGV Duplex simulations - resistance data from (21)](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tare mass (including 7 tonnes for water and other services)</td>
<td>(M_T)</td>
<td>t</td>
<td>387</td>
</tr>
<tr>
<td>Rotational inertia mass factor</td>
<td>(\phi)</td>
<td>%</td>
<td>4</td>
</tr>
<tr>
<td>Mass of passengers at 100 % load (seat capacity = 545)</td>
<td>(M_P)</td>
<td>t</td>
<td>41</td>
</tr>
<tr>
<td>Passenger load factor</td>
<td>(LF)</td>
<td>%</td>
<td>70</td>
</tr>
<tr>
<td>Train length</td>
<td>(L_{TRAIN})</td>
<td>m</td>
<td>200</td>
</tr>
<tr>
<td>Maximum operational speed</td>
<td>(v_{MAX})</td>
<td>km/h</td>
<td>330</td>
</tr>
<tr>
<td>Efficiency between pantograph and wheel</td>
<td>(\eta_{L-W})</td>
<td>%</td>
<td>82.3</td>
</tr>
<tr>
<td>Percentage of total braking energy above 20 km/h regenerated</td>
<td>((BE_{v&gt;20km/h})_R)</td>
<td>%</td>
<td>47</td>
</tr>
<tr>
<td>Auxiliary Power Supply (APS)</td>
<td>(P_{APS})</td>
<td>kW</td>
<td>294</td>
</tr>
<tr>
<td>APS Efficiency</td>
<td>(\eta_{APS})</td>
<td>%</td>
<td>85</td>
</tr>
<tr>
<td>Braking rate</td>
<td>(a_B)</td>
<td>%g</td>
<td>8</td>
</tr>
</tbody>
</table>

*Table 6-9: Train-based parameters for the TGV Duplex. N.B. tare mass (excluding water) and passenger numbers data from (22), all other data are assumptions based on HS2 reference train data*
As with the HS2 reference train, the maximum operational speed of the TGV Duplex is varied between 250 km/h and 330 km/h.

### 6.4.3. Simulation Outputs

Figures 6-23 and 6-24 show outputs from the 330 km/h, London to Birmingham TGV Duplex simulation and compare them with those from the London to Birmingham baseline HS2 reference train simulation (presented in Chapter 3):

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Distance from London</th>
<th>Tunnel factor</th>
<th>TGV Duplex</th>
<th>HS2 ref. train</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>London end</td>
<td>Birmingham end</td>
<td></td>
<td></td>
</tr>
<tr>
<td>#1 (dia. 7.2m)</td>
<td>1.2</td>
<td>10.3</td>
<td>4.40</td>
<td>2.97</td>
</tr>
<tr>
<td>#2 (dia. 12.0m)</td>
<td>31.5</td>
<td>40.6</td>
<td>1.71</td>
<td>1.48</td>
</tr>
<tr>
<td>#3 (dia. 12.0m)</td>
<td>126.6</td>
<td>128.0</td>
<td>1.15</td>
<td>1.11</td>
</tr>
</tbody>
</table>

*Table 6-10: Tunnel factors for the TGV Duplex - based on the formula used for the HS2 reference train*
As is seen from Figures 6-23 and 6-24 above, the speed profile of the TGV Duplex and HS2 reference train are identical due to the same acceleration and deceleration rate assumptions. The power drawn from the line by the TGV Duplex to produce the same speed profile to that of the HS2 reference train is greater, due to its higher mass and Davis equation resistance.

6.4.4. Energy / Journey Time Comparison

Figure 6-25 shows how the net energy consumption at the line (including braking regeneration) of the TGV Duplex varies with the journey time for maximum operational speeds between 250 and 330 km/h using the baseline line speed profile. Comparisons are made with the HS2 reference train and WCML simulations as calculated in previous chapters. Figure 6-26 compares the net energy consumption at the line of each of the three vehicle types using the defined KPI on a per-seat basis.

From Figure 6-26 it is seen that the energy consumption, in terms of the defined KPI, of the TGV Duplex is slightly higher than that of the HS2 reference train for all speeds in the specified range. At a maximum operational speed of 330 km/h, the energy advantage of the HS2 reference train according to the KPI is 4%. In the next section the reasons for the observed difference in the energy consumption, according to the defined KPI, between the TGV Duplex and the HS2 reference train are explored.
6.4.5. Analysis of the Energy Difference Between the TGV Duplex and HS2 Reference Train

Introduction

A similar methodology is employed in this section to that used in the previous analyses. In this section the average of the HS2 baseline simulations are compared with the average of the TGV Duplex simulations operating with a maximum operational speed of 330 km/h under the baseline line speed profile. The energy consumption of the TGV Duplex in these simulations according to the KPI is 4% greater than that of the average HS2 baseline case.

Per Seat Analysis

The following train and route-based factors contribute towards the observed energy consumption difference between the two modes using the KPI defined earlier in the thesis:

i. Mass per seat,
ii. Resistance per seat,
iii. Regenerated energy (during braking) per seat,

Other factors, for example the efficiency of the drive system, the passenger load as a percentage of the number of seats and route sinuosity do not contribute to the difference in the energy consumption between the two modes as they are assumed to be equal. In addition the speed profile is assumed to be the same for both vehicles since the acceleration, braking and line speed profiles of the TGV Duplex are based on those for the HS2 baseline simulations.

Equations 6-17 to 6-19 show the calculation of the effect on the KPI energy consumption of applying parameters (i) to (iii) of the TGV Duplex to the HS2 baseline simulations.
\[
\varepsilon_{M/S} = \left( \frac{100\%}{\eta_{L-W}E_{NET}} \right)_{HS2} \left\{ \left[ \left( M_T (1 + \Phi) + M_p \right)_{Dup} (N_s)_{HS2} - 1 \right] (E_I)_{HS2} + \left[ \frac{[M_T + M_p]_{Dup} (N_s)_{HS2}}{[M_T + M_p]_{HS2} (N_s)_{Dup}} - 1 \right] (E_G)_{HS2} \right\}
\]

Equation 6-17: Calculation of the effect of applying the mass per seat of the TGV Duplex to the HS2 baseline simulations

\[
\varepsilon_{D/S} = \left( \frac{100\%}{\eta_{L-W}E_{NET}} \right)_{HS2} \int_0^{t_f} \left[ \frac{(F_D)_{Dup} (N_s)_{HS2}}{(F_D)_{HS2} (N_s)_{Dup}} - 1 \right] (F_D)_{HS2} v_{HS2} dt \text{ for } F_T > 0
\]

Equation 6-18: Calculation of the effect of applying the resistance per seat of the TGV Duplex to the HS2 baseline simulations

\[
\varepsilon_{R/S} = \left( \frac{100\%}{E_{NET}} \right)_{HS2} \left\{ \left[ \frac{(E_R)_{Dup} (N_s)_{HS2}}{(E_R)_{HS2} (N_s)_{Dup}} - 1 \right] (E_R)_{HS2} \right\}
\]

Equation 6-19: Calculation of the effect of applying the energy regenerated per seat of the TGV Duplex to the HS2 baseline simulations

**Results**

Table 6-11 shows the contributions of each of the above 3 factors towards the observed difference in the net energy drawn from the line by the two modes. Figure 6-27 graphically illustrates the results:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Effect on HS2 energy consumption, $\varepsilon$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass per seat</td>
<td>-1</td>
</tr>
<tr>
<td>Resistance per seat</td>
<td>+5</td>
</tr>
<tr>
<td>Regenerated energy per seat</td>
<td>0</td>
</tr>
<tr>
<td>Sum</td>
<td>+4</td>
</tr>
</tbody>
</table>

*Table 6-11: Effect on the KPI energy consumption of applying various parameters from the TGV Duplex simulations (at 330 km/h using baseline line speed profile) to the HS2 baseline simulations (using the average of the London to Birmingham and return routes)*
It is seen that each of the 3 factors above only have a small influence on the energy consumption. The resistance per seat of the TGV Duplex contributes most significantly to its greater KPI energy consumption compared to the HS2 baseline simulations, increasing it by 5%.

**Seat Density**

As with the previous analyses the effect of seat density is calculated, although in this section the seating volume is considered instead of the seating area, reflecting the double-decker design of the TGV Duplex. Equation 6-20 details the calculation of the effect on the KPI energy consumption of applying the seat density of the TGV Duplex to the HS2 baseline simulations. Table 6-12 shows the results under the following 2 assumptions:

a) The volume available for seating includes the 2 power cars.

b) The volume available for seating excludes the 2 power cars

\[
\varepsilon_{SD} = \left( \frac{(N_S)_{HS2}(V_S)_{Dup}}{(N_S)_{Dup}(V_S)_{HS2}} - 1 \right) \times 100\%
\]

*Equation 6-20: Calculation of the effect of applying the seat density of the TGV Duplex to the HS2 baseline simulations*
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>TGV Duplex</th>
<th>HS2 ref. train</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length (including end noses)</td>
<td>m</td>
<td>200 (23)</td>
<td>200 (24)</td>
</tr>
<tr>
<td>Nose length x 2 - plus power cars x 2 for TGV Duplex (b)</td>
<td>m</td>
<td>15 - estimated from (26)</td>
<td>40 - estimated from (27)</td>
</tr>
<tr>
<td>Seating length</td>
<td>m</td>
<td>185</td>
<td>160</td>
</tr>
<tr>
<td>Maximum cross-sectional area</td>
<td>m²</td>
<td>15 (assumed)</td>
<td>15 (assumed)</td>
</tr>
<tr>
<td>Seating volume</td>
<td>m³</td>
<td>2775</td>
<td>2400</td>
</tr>
<tr>
<td>Number of seats</td>
<td>-</td>
<td>545</td>
<td>545</td>
</tr>
<tr>
<td>Seat density</td>
<td>m³</td>
<td>0.20</td>
<td>0.23</td>
</tr>
<tr>
<td>Effect of seat density, εSD</td>
<td>%</td>
<td>+27</td>
<td>+10</td>
</tr>
</tbody>
</table>

Table 6-12: Effect on the KPI energy consumption of applying the seat density of the TGV Duplex to the HS2 baseline simulations (using the average of the London to Birmingham and return routes)

It is seen from Table 6-12 that the power car arrangement of the TGV Duplex contributes substantially to its lower seating density when compared with the HS2 reference train. Applying the seating density of the TGV Duplex, based on assumption (a) (including the 2 power cars in the area available for seating), to the HS2 baseline simulations increases their energy consumption by 27%, compared to only a 10% increase when excluding the power cars in the analysis (assumption (b)).

Direct comparisons of seat density between the TGV Duplex and HS2 reference train should be treated with caution however, as the HS2 reference train with 510 seats on-board is not operating in service and much depends on the assumptions used. The rather surprising result that the double-decker TGV Duplex has a lower seating density compared to the HS2 reference train, even when using assumption (b), can, however, at least in part be explained by the presence of a restaurant/bar occupying a whole middle carriage and 3 (of the 8) carriages of 1st class seating, which, if all were occupied with 2nd class seating would reduce the energy consumption by over 25% (see (30)). The seating capacity of the HS2 reference train would not be as high as 510 if similarly one of its carriages was occupied by a bar and almost half of the remaining carriages consisted of 1st Class seating.
Constant Seat Density Analysis

The effects of applying the mass and resistance of, and energy regenerated by, the TGV Duplex to the HS2 baseline simulations are calculated on a per unit seating volume basis, thereby negating any seating volume density effects, using Equations 6-21 to 6-23 below.

\[
\varepsilon_{M/SA} = \left( \frac{100\%}{\eta_{L-W} E_{NET}} \right)_{HS2} \left\{ \frac{[M_T(1 + \varnothing) + M_p]_{DUP}(N_S)_{HS2}}{[M_T(1 + \varnothing) + M_p]_{HS2}(N_S)_{DUP} \left( \frac{E_{SD}}{100} + 1 \right)} - 1 \right\} (E_I)_{HS2}
\]

Equation 6-21: Calculation of the effect of applying the mass per unit seating volume of the TGV Duplex to the HS2 baseline simulations

\[
\varepsilon_{D/SA} = \left( \frac{100\%}{\eta_{L-W} E_{NET}} \right)_{HS2} \left\{ \int_0^t \left( \frac{(F_D)_{DUP}(N_S)_{HS2}}{(F_D)_{HS2}(N_S)_{DUP} \left( \frac{E_{SD}}{100} + 1 \right)} - 1 \right) (F_D)_{HS2} v_{HS2} \, dt \right\} \text{ for } F_T > 0
\]

Equation 6-22: Calculation of the effect of applying the resistance per unit seating volume of the TGV Duplex to the HS2 baseline simulations

\[
\varepsilon_{R/SA} = \left( \frac{100\%}{E_{NET}} \right)_{HS2} \left\{ \frac{(E_R)_{DUP}(N_S)_{HS2}}{(E_R)_{HS2}(N_S)_{DUP} \left( \frac{E_{SD}}{100} + 1 \right)} - 1 \right\} (E_R)_{HS2}
\]

Equation 6-23: Calculation of the effect of applying the energy regenerated per unit seating volume by the TGV Duplex to the HS2 baseline simulations

Figure 6-28 compares these effects, based on seating volume scenario (a), with those from the previous, per-seat, analysis. It is seen that seating density has a considerable effect on the analysis. The key observations to take from Figure 6-28 are that applying the mass and resistance per unit seating volume of the TGV Duplex to the HS2 baseline simulations reduces the KPI energy consumption by 7% and 12% respectively.
Figure 6.28: Comparison of the effect of applying various parameters of the TGV Duplex simulations to the HS2 baseline simulations on a per seat and a per unit seating volume basis - assumption (a)

6.5. Discussion

Simulations have been carried out of 3 types of vehicle running on the HS2 route (both London to Birmingham and the return): the Transrapid maglev, Shinkansen N700 and TGV Duplex. As found in Chapter 4, the energy comparison is highly dependent on the maximum operational speed assumed and hence journey time. Comparisons have therefore been drawn in terms of energy consumption (net energy drawn from the line including regeneration according to the KPI defined earlier in the thesis) and journey time.

The Transrapid maglev completes the London to Birmingham journey in shorter time, by between 7 and 14 minutes each way, and consumes between 40% and 60% more energy than in the HS2 baseline simulations, based on a maximum operational speed scenario of 500 km/h and depending on the line speed profile: baseline or no line speed restrictions. The Shinkansen N700 at 330 km/h consumes 37% less energy than the HS2 reference train for approximately the same journey time, under the same maximum operational speed and line speed scenarios. The TGV Duplex consumes 4% greater energy than the HS2 reference train according to the KPI, for the same journey time.
The contribution of different parameter to the calculated energy difference between each vehicle and the HS2 reference train according to the KPI has been found for each of the 3 types of train. Analyses have been conducted on a per seat and a per unit seating area or volume basis. There is one common theme across all 3 analyses: application of the lower resistance per unit seating space of the Shinkansen N700 and TGV Duplex, and lower aerodynamic resistance per unit seating space of the Transrapid maglev to the HS2 baseline simulations reduces the KPI energy consumption by between 12% and 20% in the simulations. Applying the mass per unit seating space of each vehicle to the HS2 baseline simulations reduce the KPI energy consumption to a lesser extent, by between 2% and 8%.

Since the vast majority of energy consumed in overcoming the resistance of a high speed train is due to the aerodynamic component, this is where the difference must lie. The aerodynamic component of resistance is dependent on a multitude of factors, nose, bogie and pantograph design to name but a few, which vary from vehicle to vehicle. There is however one aspect in common with all 3 types of vehicle analyzed: they all have a larger cross-sectional area than the HS2 reference train to the extent that they have the potential to have greater capacities for the same vehicle length: the wider Transrapid maglev and Shinkansen N700 hold 6 and 5 seats across a row in standard class respectively, instead of the conventional 4 as in the HS2 reference train, and the taller TGV Duplex holds 2 decks of seating, instead of the single deck of the HS2 reference train. Whilst the analysis of the aerodynamic resistance of the Transrapid maglev should be treated with caution, due to the different propulsion system compared to the other vehicle types resulting in no bogies and hence no bogie drag for example, the lower resistance per unit seating space of the Shinkansen N700 and TGV Duplex is significant.

Such energy savings (between 12% and 20% on a per unit seating area basis) achieved by the lower resistance of the Shinkansen N700 and TGV Duplex are too large to simply be attributed to better aerodynamic design. Whilst 400 metre trains offer some aerodynamic advantage over 200 metre trains on a per unit length basis (the aerodynamic coefficient in the Davis equation is often multiplied by 1.9 when converting from 200 metre to 400 metre long trains), any energy savings associated with a doubling of the vehicle length are likely only to be in the region of 5%.
The analysis presented in this chapter suggests that wider and taller high-speed rail vehicles have, by nature, lower resistances per unit seating space. At first, such a conclusion may appear counter-intuitive; aerodynamic drag is proportional to the cross-sectional area, as Equation 6-24 shows.

\[
F_D(C_Dv^2) = \frac{1}{2} \rho A_{XS} C_D v^2
\]

*Equation 6-24: Aerodynamic drag*

However, Equation 6-24 assumes a constant drag coefficient. In reality the distribution of pressure drag across the vehicle cross-sectional area is uneven. It is estimated that 40% of the total aerodynamic drag of a high-speed train is attributable to the presence of its bogies and wheel sets (31). Since the aerodynamic drag attributed to bogies is generally independent of whether the train is wide / tall-bodied or not, the reasons why larger-bodied trains have lower resistances per unit seating space than conventional designs are understandable.

The same reasoning can be used to explain the lower mass per unit seat spacing of the Shinkansen N700 and TGV Duplex compared to the HS2 reference train since the mass distribution of the train is unevenly distributed. The lower mass per unit seating area of the Shinkansen N700 can in part be attributed to the less stringent crashworthiness standards of the Japanese Shinkansen system compared to the TSIs of the European high speed railways. However, whilst larger-bodied vehicles generally require more powerful traction motors and bulkier bogies, the associated increase in mass with body size is not proportional.

The analysis presented in this Chapter suggests that wide-bodied (to accommodate 5 seats per row) and double-decker vehicles can offer total energy savings of up to 20%. Another factor which significantly influences the energy consumption according to the KPI is the propulsion system, whether through distributed traction or the use of power cars at each end of the train rake. Analysis of the TGV Duplex suggests the existence of the two power cars increases the energy consumption according to the KPI by over 15%, since they constitute wasted passenger space. Any wide-bodied or double-decker train should therefore be powered via distributed traction rather than via power cars to take full advantage of the lower energy consumption.
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Chapter 7: Conclusion

The thesis is reviewed before a summary of its main findings. Contributions which this thesis makes towards the furthering of knowledge in the subject area of high speed rail energy consumption are given. Implications of energy-efficient measures are then described. Finally further work arising from this thesis is recommended.

7.1. Thesis Review

As detailed in Chapter 1, the motivation behind this thesis was to try to establish whether high speed rail is an efficient means of passenger transport in terms of traction operational energy consumption and carbon dioxide emissions compared to the other modes, and to investigate its scope for improvement in these respects. In order to realize the thesis aims and fill gaps in the knowledge in the subject area, identified in Chapter 2, a computational model was developed and validated to calculate the operational energy consumption of a high speed train running on the proposed London to Birmingham HS2 route. Three further objectives were set:

- Establish the key factors which influence the operational energy consumption of a journey by high speed rail.

- Evaluate the performance, in terms of operational energy consumption and CO₂ emissions, of high speed rail in comparison with its competitor modes of road, domestic air and existing rail.

- Identify areas of vehicle design which could potentially contribute towards the minimizing of the operational energy consumption and CO₂ emissions of high speed rail.
In Chapter 3 baseline simulations were carried out to estimate the operational energy consumption of the HS2 reference train on the future line. Through analysis of the components of energy consumption at the wheel, the effect on the net energy drawn from the line (including regeneration) of variations of individual parameters, for example the tare mass and aerodynamic resistance, were quantified with respect to a Key Performance Indicator, the kWh/pass-km, where the distance unit refers to the great-circle distance between the end points of the journey, in this case the London and Birmingham termini.

The effects of variations in several route based parameters, such as the number of intermediate stops, the line speed profile, maximum operational speed and station dwell times, were investigated in Chapter 4 on a constant and a variable journey time basis. Comparisons were made with the train-based parameters analyzed in Chapter 3.

In Chapter 5 the KPI energy consumption and journey time relationship of the HS2 reference train was compared to that of the car and domestic air taking into account variations in the passenger load. Comparisons were made in terms of primary energy and the maximum operational speed of the HS2 reference train was varied between 250 km/h and 330 km/h to take account of the sensitivity of energy consumption to speed and journey time. In addition simulations were carried out of a 9-car Class 390 ‘Pendolino’ train running on the WCML to timetable. Comparisons were made with the HS2 reference train in terms of the KPI operational energy consumption. The effects of applying various parameters from the Class 390 / WCML simulations to the HS2 baseline simulations were quantified to establish the key reasons for the calculated energy difference between the two modes.

The final investigation in Chapter 6 compared the energy consumption and journey time relationship of the HS2 reference train with that of 3 types of high speed vehicle running on the same HS2 route: the Transrapid maglev, the Shinkansen N700 and TGV Duplex. As in the WCML simulations, the effects of applying different parameters of the 3 vehicle types to the HS2 baseline simulations were quantified in order to establish key areas of vehicle design which could contribute to minimizing the energy consumption of high speed rail.
7.2. Summary of Findings

In Chapters 3 and 4 the percentage change in the KPI energy consumption of the HS2 reference train due to percentage variations in the baseline values of different parameters was established. The energy consumption was most sensitive to journey time, brought about by changes to the maximum operational speed of the train. A reduction of the maximum operational speed of the HS2 reference train (using the baseline speed profile) from 330 km/h to 250 km/h resulted in energy savings of approximately 25% at a cost of less than 7 minutes (15%) in journey time each way. Other significant factors included passenger load and line-to-wheel efficiency. 25% reductions in the aerodynamic resistance and tare mass of the HS2 reference train yielded energy savings of 17% and 7% respectively.

On a constant journey time basis route sinuosity and the number of intermediate stops were shown to be significant factors. A straightening of the route, to the extent that the route sinuosity becomes 1 (with route length equal to the great-circle distance between the two end points), would yield an energy saving for the same journey time of 20%. Removal of either of the two intermediate stops would result in energy savings of 20% and removal of both intermediate stops would reduce the energy consumption by over 30%.

On a per seat basis and using the KPI defined earlier in the thesis the HS2 reference train consumes approximately the same primary energy as a car running at 40 or 50 mpg (14-18 km/l), whilst providing a journey time saving of approximately 1 hour 30 minutes each way. Since car loadings (of 1.6 persons per car) are significantly less than those anticipated for the HS2 reference train (60% to 70%) and the average fuel consumption of a car in the UK is approximately 33 mpg (as of 2010), per passenger the HS2 reference train holds a significant advantage over the car in terms of primary energy consumption. A similar conclusion is drawn in terms of CO₂ emissions. With EU regulations coming into force limiting the average CO₂ emissions of future cars and the development of hybrid and electric cars, the future HS2 train must be designed for maximum efficiency if it is to maintain its energy and CO₂ advantage over the car over its approximate 30 year life.
Assuming equal passenger loading levels, the primary energy consumption, according to the KPI, of the HS2 reference train is a fraction of that of domestic air travel, although the average journey time of domestic flights is less. The CO₂ advantage of high speed rail over domestic air is even greater if one considers the additional effect on Climate Change of CO₂ emissions high up in the atmosphere associated with air travel. Efforts are being made to reduce the fuel consumption and CO₂ emissions of air travel, but these are unlikely to be sufficient in the coming decades to overturn high speed rail's significant advantage in this respect without a fundamental shift in air propulsion technology.

The HS2 reference train in the baseline simulations consumed approximately 15-20% more energy according to the KPI than the Class 390 on the WCML. Reducing the maximum operational speed from 330 km/h to 280 km/h puts the energy consumption of the HS2 reference train on a par with the Class 390 on the WCML, whilst still providing a journey time saving of approximately 30 minutes each way. Whilst the precise details of the comparison are subject to the assumptions used, the HS2 reference train holds a clear equal energy / journey time saving advantage over the existing WCML. The main reason for the HS2 reference train's advantage is its lower resistance per seat (and per unit seating area) compared to the Class 390.

Through simulation and analysis of 3 different types of high speed rolling stock running on the HS2 line, it is concluded that wide-bodied (incorporating 5 seats per row) and double-decker trains can offer energy savings according to the KPI of up to 15% compared to a conventional design of the same train length, even with no associated increase in seating density. Such trains should, however, be powered via distributed traction rather than via power cars to take full advantage of the lower energy consumption, since the presence of power cars reduces the seating density and hence KPI energy efficiency.
7.3. Energy-Efficient Measures and their Implications

As seen from Chapters 3 to 6, there are several ways to significantly reduce the energy consumption of the HS2 reference train. Many energy reduction measures, however, have implications for the performance of the high speed rail system, which is investigated in this section.

7.3.1. Reduced Mass and Resistance

As has already been seen in Chapter 6 there is potential for the mass and aerodynamic resistance of the HS2 reference train per unit seating space to be reduced to the extent that the KPI energy consumption decreases by up to as much as 20%. Whilst a multitude of factors affect the mass or resistance of a vehicle, including motor type, bogie layout and pantograph design, the simulations of the Class 390, Transrapid maglev, Shinkansen N700 and TGV Duplex presented in Chapters 5 and 6 suggest body type, whether conventional, wide or double-decker, has a significant influence on the effect on the energy consumption of these 2 parameters.

Reductions in the mass and resistance of high speed rail vehicles have other benefits beyond lower energy consumption. Lighter vehicles, particularly via the light weighting of un-sprung parts of the train, exert lower dynamic forces on the track, resulting in lower rates of rail wear and track degradation and significant maintenance cost savings. There is a link between the total aerodynamic resistance force acting on a vehicle and the noise emitted. The flow of air along aerodynamically-efficient trains is "better attached to the surface over which it flows" thus reducing wall pressure fluctuations and hence the noise emitted.
There are, however, drawbacks of wide-bodied and double-decker train operation. In order for wide-bodied vehicles to operate on the UK network the required track separation stipulated by European TSIs would have to be increased, resulting in a greater land take associated with the construction of high speed railways and potentially larger diameter tunnels. In addition, due to their larger cross-sectional areas, the operation of wide-bodied and double-decker trains could increase the likelihood of issues arising from the generation and propagation of micro-pressure waves in tunnels. If unmitigated such waves can cause aural discomfort to passengers inside the train and large releases of acoustic energy at the tunnel exit, similar in sound to a grenade. Mitigation measures include sealed trains, increasing the diameter of the tunnel (the least favourable option due to the huge associated cost), train nose lengthening (the very reason for the Japanese Shinkansen trains' distinctive, elongated nose is micro-pressure wave mitigation in tunnels), tunnel entrance hoods and line speed restrictions in tunnels. In addition, larger train cross-sections increase the blockage ratio in a given tunnel proportionally which, as seen from Chapter 3, can have a severe and adverse effect on the energy consumption, particularly for routes with significant tunnelling.

7.3.2. Increased Regenerative Braking

The HS2 reference train in the simulations presented in this thesis used a mix of mechanical and regenerative braking to the extent that approximately 40-50% of the energy which could theoretically be recovered during braking was regenerated. High speed trains, for example the Shinkansen N700 modelled in this thesis, have the capability to use regenerative braking almost exclusively (apart from at very low speeds) to the extent that up to as much as 80% of the theoretically recoverable energy during braking can be regenerated (the 80% figure being due to the efficiency of the electricity generation during regenerative braking). As the analysis from Chapter 3 suggests, operational energy savings of approximately 7% could be achieved by adopting almost sole use of regenerative braking, as with the Shinkansen N700.
The increased use of regenerative braking has other benefits including a lower maintenance requirement for the accompanying mechanical brakes (mechanical brakes are nonetheless still required on a train in the event of an application of the emergency brakes). There is a limit, however, to how much negative torque a regenerative brake can provide. In order to provide sufficient total torque to arrest the train exclusively through the use of regenerative braking, effort is shared between sets of regenerative brakes distributed along the length of the train. The weight of the train should also be kept to a minimum and if necessary the braking rate should be reduced. As an example the Shinkansen N700 has a low mass per seat, 14 of its 16 axles powered and hence fitted with regenerative brakes, and a braking rate of only approximately 6% g, compared to 8% g assumed for the HS2 reference train.

### 7.3.3. Line-to-Wheel Efficiency

The effect of line-to-wheel efficiency, \( \eta_{L,W} \), on the KPI energy consumption is significant due to the inverse relationship between the two quantities. The efficiency between the line and wheels of high speed trains is approximately on average 80% for both power and regenerative braking phases over the length of a particular journey. Removal of this loss therefore has the potential to reduce the energy consumption of the HS2 reference train by approximately 20%.

Several components are required on board the high speed train to convert the 25kV AC electrical energy in the overhead line to the desired traction energy at the wheel, including transformers, power converters and motors, each with an associated efficiency. Significant improvements in the 80% efficiency between line and wheel are therefore difficult to achieve. However, incremental improvements in the overall line-to-wheel efficiency are being made. For example, it is estimated that the recent introduction of lighter permanent magnet motors in place of the established asynchronous AC motors for traction power has led to efficiency improvements around 2-3% (1).
7.3.4. **Passenger Loading**

As seen from the analysis in Chapter 3, passenger loading has a significant effect on the KPI energy consumption due to the inverse relationship between the 2 quantities, as with the line-to-wheel efficiency. Maximising the passenger loading levels is therefore crucial to minimizing the KPI energy consumption of the HS2 reference train. The locations served by the high speed line, its connectivity with other modes, journey time, efficiency of service, comfort, frequency of service and in particular ticket prices all affect the passenger usage.

Trade-offs exist between many of the factors listed above. For example increased comfort, through the fitting of in-car tables and a bar/restaurant, comes at a cost in terms of seat numbers and hence total passenger capacity. Intermediate stops increase journey time quite significantly, as shown in Chapter 4, but if positioned optimally to serve large populations they significantly increase passenger usage and hence revenues. The optimal trade-off between these factors should be sought with the aim of maximising passenger use, a key measure of the success of high speed rail implementation.

7.3.5. **Speed and Journey Time**

Journey time can have a significant influence on the energy consumption, as seen from Chapter 4. The analysis showed that journey time savings achieved through reductions in the number of intermediate stops and station dwell times could lead to significant energy savings on a constant journey time basis. Due to the law of diminishing returns of time with speed and the dependence of both vehicle kinetic energy and resistance on the speed squared, journey time savings achieved through increases in the maximum operational speed can come at a significant energy cost.

Speed also has a significant impact on other aspects of the railway beyond energy consumption. Dynamic forces exerted on the track and pantograph due to wheel, rail or overhead line irregularities, for example, increase with speed, leading to greater rolling stock and infrastructure maintenance costs. In addition aerodynamic noise increases roughly with the sixth power of the velocity \( (v^6) \) (2). Noise associated with the energy release from propagating micro-pressure waves at tunnel exits also increases significantly with speed.
Maintenance costs constitute a significant proportion of the total operational costs of a high speed railway and noise is always a significant concern for inhabitants living close to the line, the primary concern in the case of High Speed 1 (3). Taking the above factors into consideration together with the law of diminishing return between time and speed, journey time savings achieved through increases in maximum speed may not represent best value for money. Instead station dwell time reduction, better connectivity with the other modes and improvements to the existing transport infrastructure may offer greater overall journey time savings at a significantly lower energy, environmental and economic cost.

7.4. Contribution to Knowledge

The thesis has contributed to knowledge in the area of energy consumption of high speed rail in the following 3 ways:

- As far as the author is aware, no comprehensive comparison of the effects of different factors on the energy consumption of high speed rail has previously been conducted. In this thesis the effects of percentage variations in baseline values of different parameters on the energy consumption of a typical high speed rail system have been quantified according to the KPI: the kWh/pass-km, where the distance unit refers to the great circle distance between the end points. Comparisons have been made on a constant and variable journey time basis.

- A clear comparison of the energy consumption and CO$_2$ emissions of high speed rail with the car, domestic air and existing rail travel has been made using the UK case for power generation and taking into account variations in those factors, such as passenger load and journey time, which have a huge influence on the outcome. Existing comparisons, which the author has identified in the literature, have not taken into account the variability of such influential factors. Comparisons have also been made with respect to scenarios of energy consumption and CO$_2$ emissions in the coming decades.
As far as the author is aware, no comparison has been made of the energy consumption and journey time relationship of different types of high speed rail vehicle, including the Transrapid maglev, running on the same high speed rail route. Furthermore, no detailed study has previously been undertaken which attempts to quantify the contributing factors towards the observed energy difference between the different types of vehicle. Such analysis has been used in this thesis to inform railway engineers of the effects of design specification on the energy consumption and hence carbon dioxide emissions of a typical high rail system.

7.5. Further Work

Three areas of further work resulting from this thesis are recommended as follows:

- Only the operational, traction energy consumption was considered in this thesis. From a review of the existing literature, however, the operational requirement only makes up a part of the total, lifecycle energy requirement and CO₂ emissions of high speed rail systems. For a more comprehensive comparison of the energy consumption and CO₂ emissions of high speed rail compared to the other modes, a lifecycle analysis is required. The results of such analyses, however, depend very much on the assumptions made and there exists no standard, agreed method of conducting lifecycle comparisons of different modes. Further work is required in this area to develop a robust, standard approach to compare different modes according to a lifecycle analysis.

- A more detailed analysis of the effect of wide and double-decker bodies on the Davis equation resistance of high speed trains is recommended. Whilst the work presented in this thesis suggests that large body designs have lower aerodynamic resistances per unit seating space, resulting in energy consumption reductions of up to 15%, a more detailed analysis is required on a like for like basis, which ignores the effects of further factors for example pantographs, bogie design and train sealing.
The initial proposal of the London to Birmingham section of the HS2 network, made public in March 2010 in (4), was used for all investigations presented in this thesis. Since the modelling was conducted, some changes have been made to the route, most notably a significant increase in tunnel length through the Chiltern Hills. In addition details of the 2nd phase of the network, the Birmingham to Manchester and Leeds legs will soon be published. The Train Energy Simulator, developed by the author, is currently being used to carry out further traction energy calculations for HS2 Ltd's newly proposed routes.
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