Energy consumption and CO_2 impacts of High Speed Rail: ATOC analysis for Greengauge 21

Executive Summary

Although there is now a great deal of work on the *current* emissions of each of the main transport modes – road, air and rail – less work has been done to assess how these might change *in future*. But it is of course the position over the coming 40 years - the crucial period during which it will be necessary to stabilise carbon dioxide concentrations in the atmosphere in order to limit global warming to no more than 2^{o} Centigrade - that is most relevant to the policy debate about solutions to climate change.

This paper draws together work from a number of sources to estimate future direct carbon emissions of high speed rail compared with air and road to argue that its carbon advantage over the other modes is likely to improve over time and that concern about the carbon impact of rail at higher speeds needs to be put into context. This paper is solely about high speed rail, rather than all passenger trains which have been the subject of ATOC's earlier studies.

The paper takes the UK's statutory target to reduce greenhouse gas emissions by 80% by 2050 as a given. Assuming that this is achieved by moving to very low carbon sources of electricity in line with the Committee on Climate Change (CCC)'s plan, average carbon emissions from generation will fall by 90% and consequently the carbon impact of high speed rail will be very low. It is worth noting that the CCC's plan for the pathway to deliver the 80% target has not yet been finally endorsed by the Government: their response to the CCC is expected later this month. However, the CCC's work provides the best available long term indication of the likely future carbon intensity of UK generation.

On this basis, high speed rail's carbon advantage over air travel should improve substantially over time and its carbon advantage per pass-km over new cars will remain at least three times. Rail's advantage remains even after allowing for the full adoption of electric vehicles in place of internal combustion engine vehicles, as envisaged by both the King Review of Low Carbon Cars and the CCC.

Although in principle, as the speed of a train increases so does the energy needed to propel it (as the 2007 White Paper pointed out), this is only part of the story. There are four other important factors to bear in mind:

- Firstly, high speed railways tend to be high capacity railways. A double-deck, double-unit TGV Duplex train, for example, offers 1090 seats in twenty vehicles compared to the 439 seats that the 9-cars of a Pendolino can offer (a significant capacity advantage that would remain even after most of these have been extended to 11 cars).[1] High speed railways have higher load factors than the

[1] Significant clearance costs would of course be incurred to operate double-deck trains on existing UK rail infrastructure but it is expected that any UK high speed line would be built to a Continental loading gauge (as is High Speed 1) so that double-deck services might be possible on point-to-point journeys wholly made on the new infrastructure.

average of the rail network (Eurostar has a 70% load factor). The trains used are also typically longer, so that the aerodynamic drag of the front end of the train (which is a significant energy cost at high speed) is spread over perhaps 16 to 18 carriages rather than the UK norm of 8 to 10 carriages.

- Secondly, considerable effort is expended by train manufacturers in developing train designs that reduce drag. The futuristic designs of the latest Japanese Shinkansen trains, for example, are one of the key ways (along with light weight) that the Japanese have managed to reduce energy consumption per seat of successive generations of Shinkansen trains. The next generation of French TGV trains (the *Automotrice a Grande Vitesse* or AGV) will be single deck and are expected to reduce energy consumption by about 15% compared to existing TGV stock.

- Thirdly, since high speed trains use electricity they have access to a wide range of possible low carbon sources. The decrease in the carbon content of electricity expected from widespread use of renewables, nuclear and carbon capture and storage techniques to mitigate emissions from fossil fuel sources, will give high speed rail a particularly strong advantage over air travel, where there is no straightforward way of decarbonising the fuel supply.

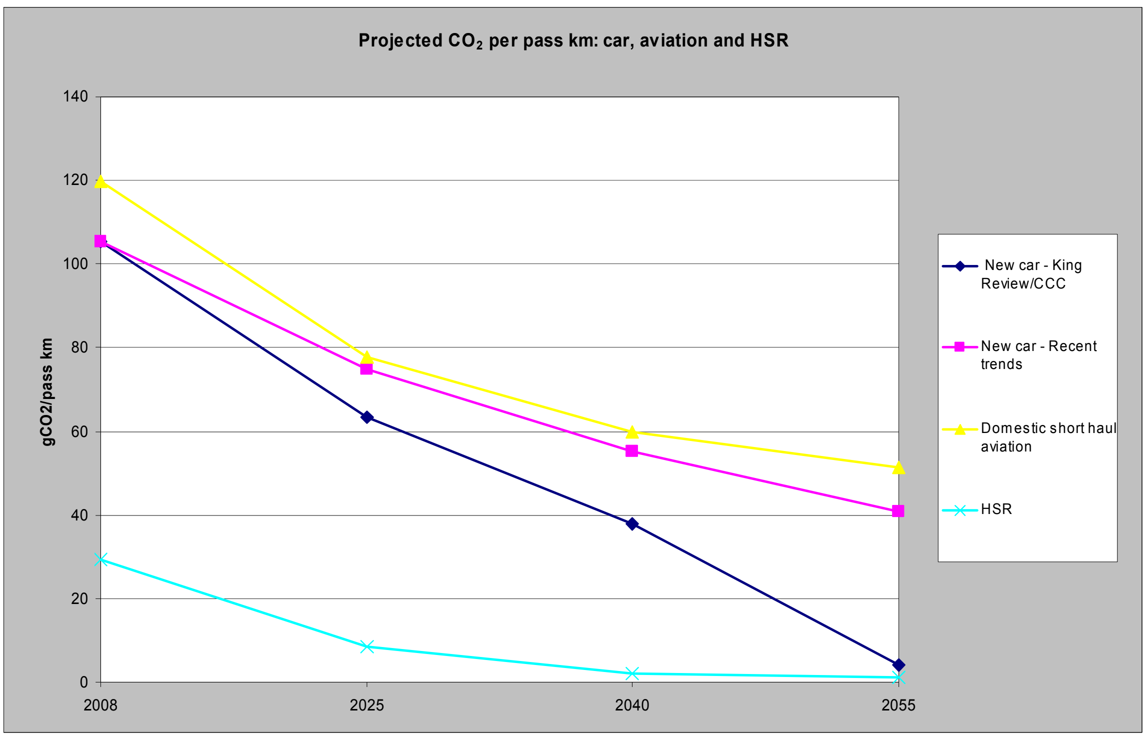
- Fourthly, and more fundamentally, high speed rail will draw traffic from other modes, from both short haul aviation and road. A high speed rail network in the UK brings with it the prospect of a substantial reduction in domestic air travel, with air routes between London, Manchester, Newcastle and Edinburgh/Glasgow likely to be scaled back hugely. Any increased rail carbon emissions from operating faster trains therefore needs to be set in the context of the emissions avoided through reduced air and road travel and through the ability to use more carbon efficient modes to access rail terminals. The Greengauge work is evaluating this potential mode shift currently and we expect to carry out further work on the net carbon position of rail in the light of this. We also intend to carry out further work on the carbon impact of construction of a high speed line, which is part of the overall carbon picture although the indications we have are that this would not significantly alter the analysis presented here.

To compare rail with car and aviation emissions, we have made estimates, in a way intended to be consistent with the work done for the CCC, of the steps that might be taken to reduce emissions of those modes.

In the case of road, the EU fleet-wide target of 130gCO_2 per vehicle-km, coupled with the roll out of near-market technologies, should lead to an improvement in car emissions per passenger km by perhaps 40% by 2025, although market acceptance of the vehicle powers and weights that are implied by the EU target is clearly a key uncertainty. Beyond this, the King Review envisages widespread use of electric vehicles, particularly after 2030. Under this scenario, we calculate that new car emissions per passenger km might fall from around 105gCO_2 now to 4gCO_2 by 2055. Recognising the challenging nature of the carbon reduction strategy for road, we have also created a second, higher forecast, based on an extrapolation of current trends in which there is continuing widespread use of cars powered by mineral oil-based fuel, albeit hybrids in the longer term. Under this scenario, new car emissions might fall to around 40gCO_2 per passenger km by 2055.

In the case of aviation, substantial improvements in aircraft design are expected – particularly wide-scale use of composite materials to reduce weight – alongside further improvements in engine design. In addition, significant savings can be made through operational changes such as allowing aircraft to fly along more direct routes and allowing continuous descent into airports rather than stepped descents which currently occur. The use of biofuels in aircraft is also being explored, although it is anticipated that a number of technical and operational issues would need to be resolved before such fuels could be widely used, and the net carbon savings from them would need to be carefully assessed. Even with quite significant changes, it is hard to envisage jet aviation emissions being reduced by much more than 60% by 2055 and this is already a quite challenging scenario. We calculate that, at best, aviation emissions per passenger km could fall from around 120g/CO_2 today to around 50g/CO_2 by 2055.

Our analysis is summarised in the following graph, which shows that high speed rail's carbon performance, assuming that the CCC's strategy is realised, should improve from about 30gCO_2 per passenger km today to as low as 1gCO_2 per passenger km in 2055.



Contents

ATOC analysis for Greengauge 21 on the CO_2 impacts of High Speed Rail

Introduction

This paper summarises:

- The available data on the energy consumption and related CO_2 impacts of high speed trains;
- The possible carbon reductions achievable by competing modes such as road and air over the period to 2050, based on analysis by the Government's Committee on Climate Change (CCC), and;
- The possible effect of decarbonisation of UK electricity generation, which is the principal strategy proposed by the CCC to reduce the UK's CO_2 emissions by 80% by 2050, on high speed rail's environmental performance.

The paper looks at the carbon emissions of each mode in turn but given the range of estimates that are available for the extent to which high speed rail would draw traffic from road and air through mode shift, it does not, for the moment, estimate the net carbon impact of high speed rail (i.e. the emissions from high speed rail minus the emissions that would have arisen if passengers had used other modes).

Similarly, this paper reviews the available data on direct carbon impacts of rail and other modes, including carbon emissions from electricity generation. It does not consider the lifecycle carbon impacts associated with the construction of vehicles and supporting infrastructure.

These are areas we will return to as the Greengauge and other High Speed Rail work progresses.

Background

Both the 2006 Eddington Transport Study and the 2007 Rail White Paper both suggested that the environmental case for high speed rail was relatively weak. In particular the White Paper suggested that increasing train speed from 200km/h to 350km/h would require a 90% increase in energy. Set against the modelled reductions in journey times from HSR (of around 25%), this was perceived to be too high a price to pay.

Underlying this conclusion was the fact that the energy consumed by a train depends on a number of factors but that at high speeds it is strongly affected by the square of the velocity through aerodynamic drag. Thus, all other things being equal, an approximate 40% increase in train speed would lead to a doubling of energy demand.

However, there are two factors to consider when assessing the energy and carbon impact of HSR:

- The energy consumption of the high speed trains to be used (which is driven by the design characteristics of the vehicle including its mass and drag) and;
- The carbon intensity of the electricity used to power the train.

In terms of energy consumption, light weight and aerodynamic design can play a major role in reducing the energy penalty associated with the aerodynamic drag impact of higher speed. Similarly the design of the route, particularly the steepness of gradients and location of station stops, can also have an important influence.

Importantly, in terms of climate change impact, it is not the use of energy *per se* that is the problem, rather it is the CO_2 associated with the burning of hydrocarbons used to provide the energy. Thus, given that any new high speed line in the UK would be electrically-powered, it is the carbon intensity of the electricity used to power the trains that is of most interest.

Electric high speed rail has an important advantage in this regard since the evidence suggests that it is easier to reduce the carbon intensity of electricity generation than of the mineral oil-based fuel sources of competing modes, air and road. This is because electricity can either be generated directly from non-carbon sources such as nuclear power or renewables, or from fossil fuel sources where the carbon dioxide produced can be captured at the point of combustion through carbon capture and storage (CCS). Oil-based sources, on the other hand, rely on combustion on the transport vehicle itself, making CCS practically impossible to achieve, and the main decarbonisation options are the widespread use of biofuels (which is likely to be constrained by land take) and, in the case of road, hydrogen solutions (fuel cells) and conversion to electric battery operation.

Energy consumption of high speed trains

In principle, there are two components of the energy consumption of a train:

- The energy needed to accelerate the train up to speed, which is converted into the kinetic energy of the train;
- The energy needed to overcome resistance to motion in order to maintain speed.

In relation to the first of these, the kinetic energy needed to get a train up to speed is proportional to the mass of the train (making it desirable to keep weight down) and the square of the velocity. Kinetic energy can be recovered through a dynamic (regenerative) brake but the efficiency of recovery is not perfect, so the energy saving is only partial. This means that for high speed operation, minimising station stops is particularly important since otherwise this kinetic energy has to be replaced after every station and is never fully recovered through regenerative braking.

In relation to the second, the energy required to keep the train moving is defined by two elements, one proportional to the velocity, and the other to the velocity squared. The multipliers applied to these elements are known as the Davis Coefficients, after the research engineer that first proposed them in the 1920s: the first element is essentially driven by friction and the second by aerodynamic drag.

The coefficient of the first element is fairly small, since modern trains have low friction bearings, and a steel wheel rolling on a steel rail is inherently more efficient than, for example, a rubber tyre on a tarmac road. The velocity squared element is, however, almost entirely determined by aerodynamic resistance. The reason behind some of the futuristic designs of most modern high speed trains is to minimise drag. Most of the drag is associated with the 'front end' of the train rather than its length, thus the longer the train the lower (proportionately) the drag. However, there are limits to what can be achieved through aerodynamic design and this velocity squared component remains the dominant factor in high speed operation: unlike the kinetic energy which is a 'one-off' cost when accelerating from rest, this aerodynamic load is continuous.

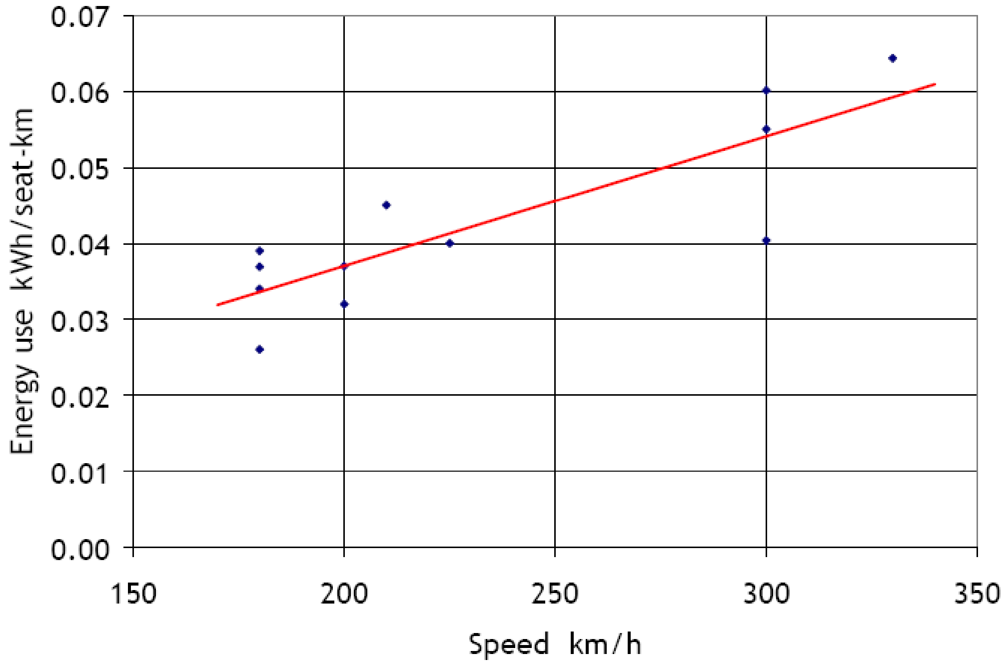
One way of mitigating the energy penalty for high speed trains is to ensure a high seat capacity, so that the energy per seat kilometre compares favourably with that of slower, conventional trains. This can be achieved more easily on new build systems where structural constraints are likely to be less restrictive meaning that double-deck or even trains wider than the normal UK loading gauge could be used, although this would of course limit the train's ability to serve "off route" destinations. For example, the Eurostar trains were constrained to use the third rail network South of London and so have a lower seating density per unit of energy consumed compared with the TGV Duplex trains that were built very shortly afterwards.

In addition to high seating capacity, successful high speed operations such as Shinkansen in Japan and Eurostar have healthy load factors, often in excess of 70%, since they are designed to support point-to-point traffic. This is much higher than the average for the UK network as a whole, which encompasses a variety of traffic flows. Because of the higher load factor, high speed train operators compare very favourably to competing airlines on a CO_2 per passenger km basis.

The other possibility for minimising energy consumption is to ensure that trains maintain a largely constant speed, free of adverse signals and speed restrictions so the kinetic energy to accelerate the train to line speed is not being repeatedly consumed and then dissipated. Again this is much easier to achieve on new build systems and both Shinkansen and TGV operate on dedicated infrastructure, in part to avoid conflict with other, slower traffic types.

Previous analyses

Professor Roger Kemp was commissioned by the Rail Safety and Standards Board (RSSB) in 2006 to review the energy consumption of different train types and compare these with cars and planes. His final report (RSSB, 2007) included an assessment of the energy consumption of Scandinavian trains generally operating at or close to 200km/h and European and Japanese high speed trains operating at >250km/h. This was used to derive a linear relationship between speed and energy use:



Source: RSSB, T618: Traction Energy Metrics, Dec 2007.

However, the relationship may not be as steep as the RSSB report suggests. For example, the above graph does not include Japanese Shinkansen trains which, because of their lightness, have lower energy consumption per seat km at 300km/h than most European trains operating at 200km/h. Similarly, energy consumption of the TGV Duplex (which is included on the graph) is in practice comparable in energy terms to trains operating at 200km/h.

Furthermore, Professor Kemp's analysis for RSSB might now be updated with more up-to-date information that is becoming available, In particular, energy consumption data provided by Eurostar originally gave a figure of 0.055 kWh/seat km but more recent in-service measurements suggest that energy consumption is significantly lower than this, around 0.041 kWh/seat km.

Comparison of high speed trains

The table below summarises the average energy consumption per seat km for a selection of different high speed trains.

It must be emphasised that the energy consumption of a train varies considerably with the number of starts and stops it makes, its service speed and the gradient of the lines it operates over. The data presented here should therefore only be regarded as approximate averages based on the current diagrams of each of the train types. We aim to update these numbers as new data becomes available.

The Virgin Pendolino is also included for reference: although its current maximum operating speed (200km/h) is significantly below that of dedicated high speed trains (~300km/h), it gives a useful indication of the energy consumption of 'conventional speed' intercity rail.

Train	Class 390 Pendolino (2003)	Class 373 Eurostar (1993)	TGV Reseau (1992-6)	TGV Duplex (1995-7)	Shinkansen 700 Series (1998)	AGV* (2008)
Speed (km/h)	200	300	300	300	300	300
Seating capacity	439	750	377	545	1323	650
Length (m)	215	394	200	200	400	250
Vehicles per unit	9	20	10	10	16	14
Tare mass (tonnes)	460	723	386	384	634	510
Mass per train metre (tonnes)	2.14	1.84	1.93	1.92	1.59	2.04
Mass per seat (tonnes)	1.05	0.96	1.02	0.7	0.48	0.78
Energy consumption (kWh/seat km)	0.033	0.041	0.039	0.037	0.029	0.033 (est.)

Sources: Virgin, Eurostar, Systra, RSSB (2007), Alstom.
*AGV based on 14-car train specification. Expected energy consumption from estimates provided by Systra assuming 300km/h operation.
Note: The figures in the table reflect best available information and will be updated as new data becomes available.

Despite the difficulty of comparing train types, the table suggests that whilst there is an energy penalty associated with increased speed it is certainly not as severe as the White Paper indicated and can be – and indeed has been – offset through reduced mass, better aerodynamics and increased seating capacity.

Japanese trains outperform their European counterparts for these reasons: relative to a Eurostar Class 373, a 700 Series Shinkansen has 75% more seats and 14% lower mass per train metre resulting in significantly lower energy per seat km. In large part this is because Shinkansen are both wider (allowing more seats per train metre) and lighter (being designed to different crashworthiness thresholds than European trains). Shinkansen trains also employ radical aerodynamics which significantly offset drag and therefore energy consumption at higher speed.

On the continent, TGV Duplex sets have a high seat capacity per metre of train length at no additional weight penalty. As such they have a noticeably lower mass and energy per seat compared to single-deck trains of the same generation.

Looking ahead, Alstom's next generation AGV, designed for operation at very high speed (max. 360km/h), demonstrates that design efficiencies aimed at reducing weight and increasing seat capacity can deliver energy consumption some 15% lower than that of existing TGVs at 300km/h.[2]

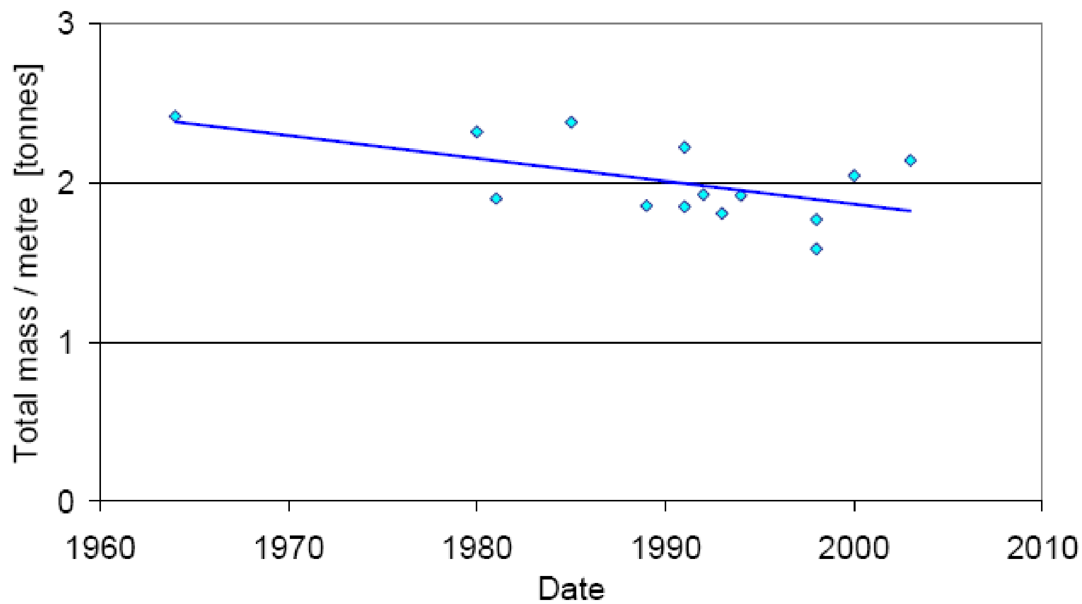
[2] Estimate from information provided by Systra.

However, many of the characteristics of Shinkansen and some mainland European high speed trains would prove problematic on existing rail infrastructure: for example, double-deck Duplex-style trains would require extensive clearance works on the 'classic' network and UK and European crashworthiness standards are probably more demanding than the Japanese equivalents. In addition, the Shinkansen have wider bodies compared to UK trains to enable higher seat capacity which would also conflict with UK gauge constraints.

Although it would be impractical to increase the loading gauge of large sections of the existing network, it might of course be possible to improve short sections of route (e.g. into city centres) to allow both high speed double deck and conventional stock to operate.

Design efficiency

From an energy efficiency perspective, Professor Kemp's work shows that progressive generations of international high speed trains have seen noticeable reductions in mass per metre:



Source: RSSB (2007)

The most significant reductions have tended to come in successive builds of Japanese Shinkansen – for example the 700 Series is 106 tonnes (14%) lighter than its predecessor the 300 Series, in large part due to reductions in weight of bogies, body and traction package.

Alstom's AGV has a maximum mass of 510 tonnes for a 14-car, 250m train set holding 650 seats. While this gives 2.04 tonnes per train metre (slightly above the weight 'trend') the mass per seat is similar to the TGV Duplex. This is achieved, in part, through distributed power which allows for more seats than previous generation single-deck high speed trains, which utilise two power cars. In effect, the power cars are used for seating thus reducing the energy requirement per seat. To compare, the AGV holds a slightly smaller number of seats to a Class 373 but in a little over half the train length.

In addition, the modular design of the AGV allows for improved matching of stock to demand i.e. 8, 11 or 12 car trains can be deployed where required to maximise seat utilisation and energy efficiency per passenger km.

Overall, the consumption rates identified above suggest that, applying the current average carbon intensity of the UK grid mix, the carbon performance of high speed rail would fall in the range of 25-30gCO_2 per passenger km (assuming a load factor of 70%). This is significantly better than the current CO_2 performance of competing modes, as the following section demonstrates. In addition, the carbon performance of rail would fall by a factor of five below this level if we made allowance for the fact that the UK rail industry currently takes its electricity from British Energy, which has average emissions of 122gCO_2/kWh.

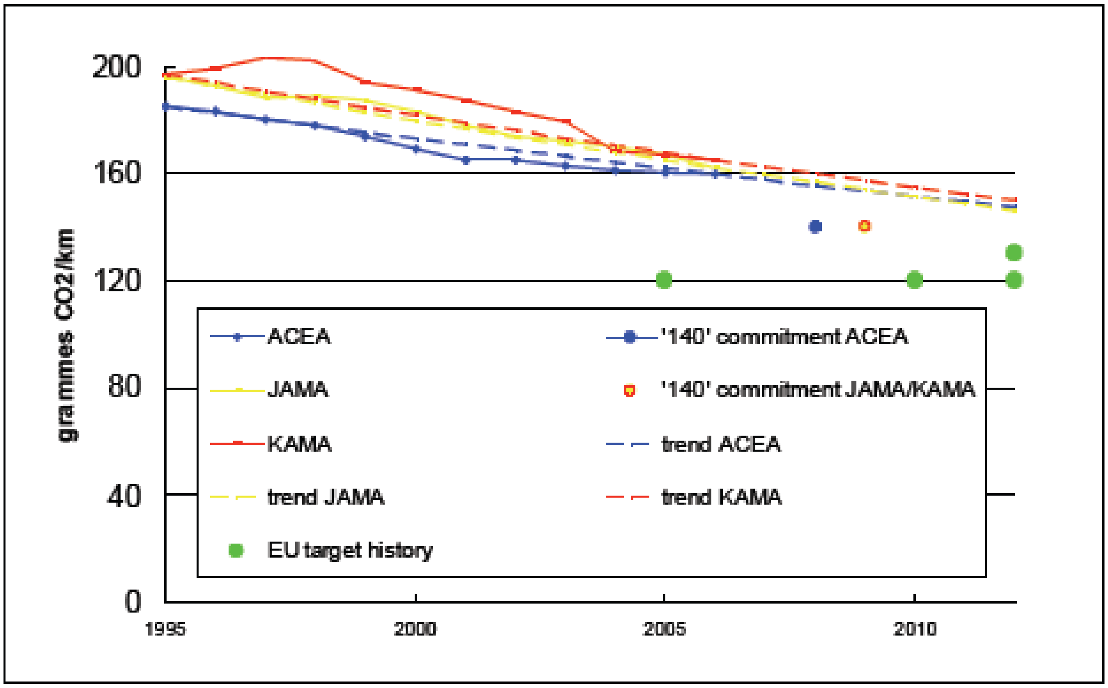
Comparison with car, short haul aviation

The next section identifies the current carbon performance of the competing modes, car and domestic short haul jet aviation.

Car

Under the manufacturer agreements established in 1998, the European car manufacturers, working through their trade association, ACEA, set a voluntary target to reduce average new car CO_2 emissions to 140gCO_2/km by 2008.[3] However progress has been modest and the 2007 average for new cars under ACEA was 157g/km[4], well above the 140g/km voluntary target:

[3] Japanese and Korean manufacturers (JAMA/KAMA) also committed to reach 140g/km by 2009.
[4] Transport & Environment new car CO_2 report (2008) and EU Commission data (Feb 2009).



Source: Transport & Environment Europe.

Latest SMMT data indicates that 2008 UK new car emissions were close to the ACEA average, at 158g/km. This represents a 16.8% reduction on 1997.[5] This reduction has been achieved, in large part, due to the increased penetration of diesel cars which are inherently more fuel-efficient but the limits to petrol to diesel substitution are now setting in.

Assuming an average passenger loading for cars of around 30%[6], this would equate to approximately 105gCO_2 per passenger km.

These figures relate to new cars. Of course, emissions from the average car in the fleet are higher as the fleet takes time to turn over. In the UK, 2008 average emissions from cars in use (post-1997) are estimated at 173.7g/km, 10% higher than the average for new cars.[7]

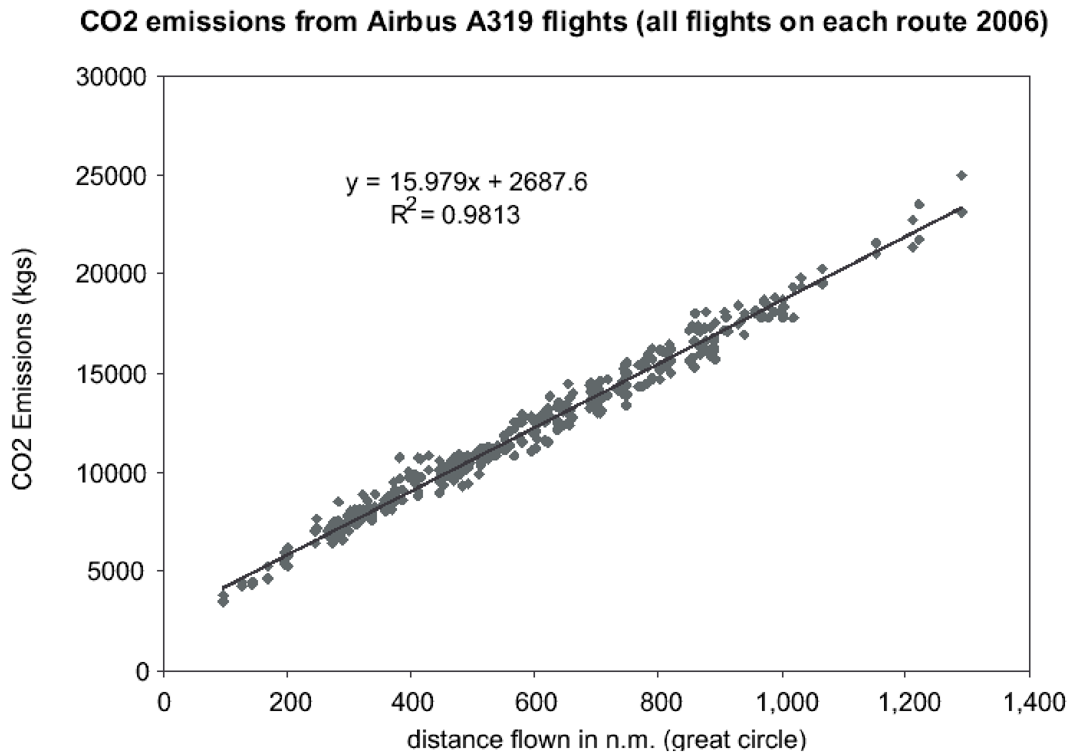
Short haul aviation

Most domestic air travel is largely dominated by the low cost carriers e.g. Easyjet and Ryanair as well as BA and British Midland. Both Easyjet and Ryanair have young fleets at approx. 3-4 years old: Easyjet mainly operate new Airbus 319s while Ryanair operate the Next Generation Boeing 737-800s.

Emissions for Easyjet A319s by distance flown are shown below. Using this relationship, it is possible to estimate emissions for domestic routes where the sector length is in the region 300-600km (160-300 n.m.) For London-Manchester (approx. 300km) emissions

[5] SMMT (2009).
[6] The National Travel Survey (NTS) gives average car occupancy of about 30%, assuming five seats per car.
[7] SMMT (2009).

are estimated to be in the region of 115gCO_2/seat km, or 135gCO_2/pass km assuming Easyjet's average loading of 85%.[8] For longer domestic routes such as London-Edinburgh/Glasgow (approx. 600km), emissions are around 85gCO_2/seat km or 100gCO_2/pass km.[9]



Source: Easyjet memorandum to Treasury Select Committee (Oct 2007).

This highlights the importance of sector distance for aircraft emissions: for shorter domestic flights, a larger proportion of the journey is taken up by the climb out to cruising altitude which is the most fuel-intensive element of the flight. Thus, all other things being equal, short flights tend to have higher emissions per seat km.

Although the 'Next Generation' Boeing 737-800 operated by Ryanair is slightly larger than the A319, its carbon performance is expected to be reasonably similar and so the above fuel consumption relationship is taken as a reasonable basis for domestic short haul jet flights.[10]

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[8] Easyjet Corporate Responsibility Report (2006). Note that this is an average loading across all Easyjet flights including short-haul international routes.

[9] On the basis that 2.518 kgCO_2 is emitted per litre of aviation fuel, this puts A319 fuel consumption in the range 4.5-3.3 litres per 100 seat km for a sector length of 300-600km. Note the calculation of emissions per seat and per passenger km take account of the higher seating capacity (156) on Easyjet's A319s compared to standard models (124).

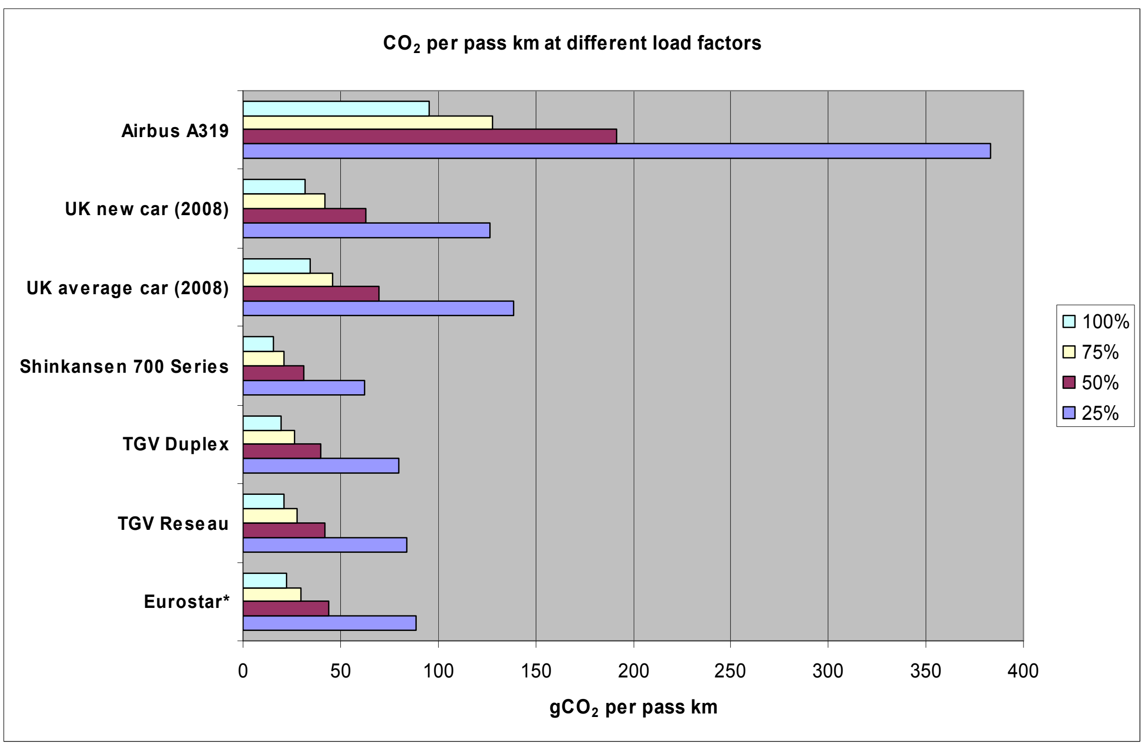
[10] Available Ryanair data indicates average fuel consumption of 3.5 litres per 100 Revenue Passenger Kilometres (RPK). With a load factor of 82% this gives approx. 2.9 litres per 100 seat km or 88gCO_2/pass km. Note however this is an average across all Ryanair flights, including international flights. Given the average passenger haul on Ryanair flights is just over 1000km, this fuel consumption is comparable with an A319 over the same sector length. It is therefore assumed that fuel consumption would be similarly comparable on shorter domestic routes.

Note that in this paper we have only considered the likely carbon impact of jet aviation over domestic short haul distances (300-600km). We have not considered the carbon impact of turboprop planes – which are more fuel efficient – nor the CO_2 emissions from longer air journeys which tend to be slightly more fuel efficient per seat km. Similarly, we have not included any additional allowance for the non-CO_2 impacts of jet aviation at altitude (radiative forcing).

Comparison of car, short haul aviation and high speed rail CO_2

Comparing the carbon performance of high speed rail with competing modes is problematic, in large part because load factors vary widely. Short haul air carriers operate a pre-booked, point-to-point service whereas high speed rail services cater for both pre-booked and 'walk-up' customers and, in addition, serve intermediate stopping points on a journey. Air services therefore tend to have higher load factors.

To illustrate the effect of load factors, the chart below gives a broad comparison of the current carbon performance (in gCO_2/pass km) of high speed trains against the SMMT UK car averages (above) and an Airbus A319 at a range of load factors between 25 and 100%:



Source: Rail data as above, SMMT as above for cars, Easyjet for Airbus A319 (based on assumed average fuel consumption for domestic routes over 300-600km) combined with DEFRA/NAEI emission factors for UK grid electricity, aviation fuel.
*Note: Eurostar performance based on the average UK grid emissions factor and does not reflect the lower carbon electricity actually used on the pan-European infrastructure Eurostar operates on when in international service.

This indicates that, at any given load factor, high speed rail already outperforms both car and short haul jet aviation even without electricity being decarbonised.

However, as discussed above, load factors vary across modes. Short haul low cost carriers tend to have very high loadings – around 80% or more – putting them close to 100gCO_2/pass km or sometimes less on longer routes. However, successful high speed rail services have similarly healthy load factors of around 70% which suggests high speed rail would still maintain a significant advantage on a per passenger km basis.

To illustrate this more clearly, taking the above numbers, along with typical average load factors for each mode, we estimate current CO_2 emissions per passenger km as follows:

Mode	Assumed load factor	gCO_2/pass km
Short haul aviation	80%	120
Car (new car average)	30%	105
High speed rail (TGV Reseau)	70%	30

Future developments in the rail, road and aviation sectors

For the purpose of Greengauge's study, the issue is how the carbon performance of the different modes, as well as the UK's grid mix, will change over time. We present some thoughts on this, looking forward to 2050 and slightly beyond. This is the date set in the Government's climate change planning work for an 80% reduction in CO_2 emissions.

A key assumption affecting both rail and car is the carbon intensity of the UK grid-electricity mix and the ambitious plans put forward in December 2008 by the Committee on Climate Change (CCC) to reduce this radically. If these plans were not realised, for whatever reason, this would be reflected in a higher CO_2 impact for each of these modes.

High speed rail

As noted above, Alstom's AGV is the newest generation very high speed train designed for operation at speeds up to 360km/h.

Alstom have made several significant steps in design that have reduced weight, improved aerodynamics and increased seating capacity per train metre (for a single deck train). For these reasons it is estimated that the AGV is some 15% more energy efficient than existing TGV stock.

Therefore were a new high speed network built in the UK to become operational from 2025, it would take advantage of latest generation, energy efficient trainsets. These could be expected to achieve an average energy consumption 'standard' of 0.033 kWh/seat km for 300km/h operation.

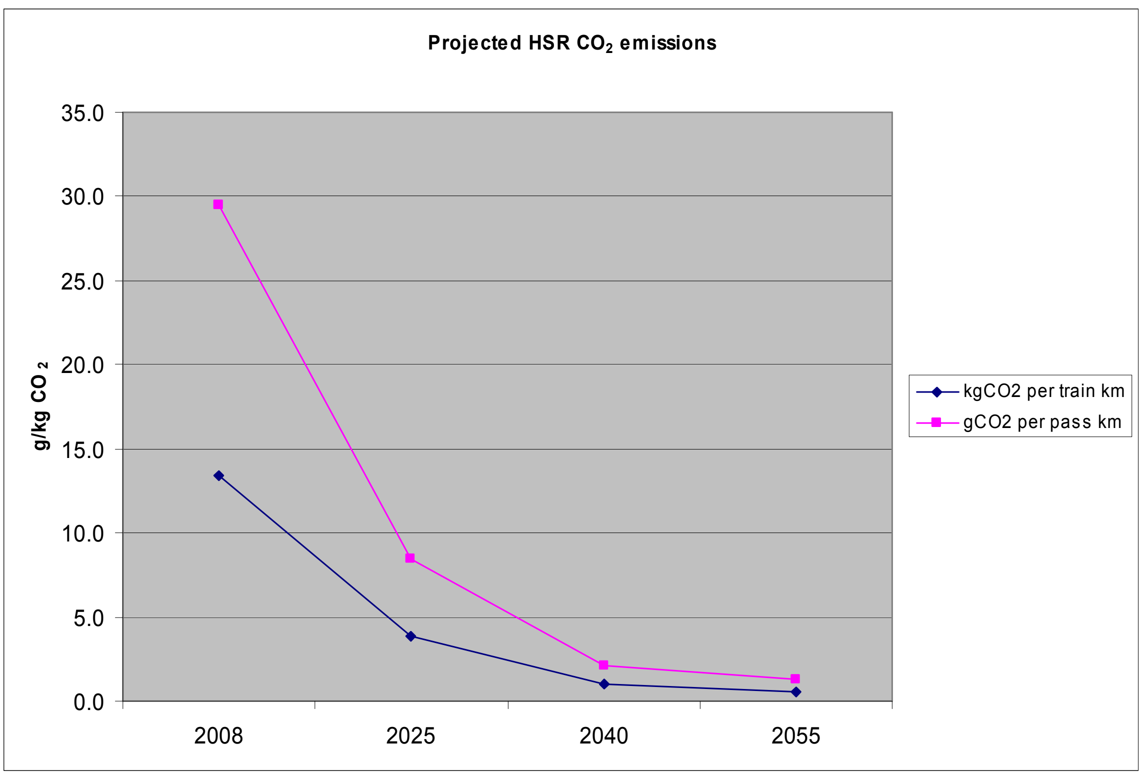
Looking further ahead to 2055, it is likely that a 'next generation' high speed train would be available and introduced into service. Assuming further efficiencies were possible (e.g. in the region of, say, 10% reflecting perhaps the use of lightweight composite materials) and with no further speed increases, this would reduce traction energy consumption and CO_2 per seat km still further.

Taking this into account, the following scenario outlines the likely future CO_2 performance of high speed rail. Note that this includes a set of assumptions regarding reductions in the future carbon intensity of UK electricity generation as outlined by the CCC. These are discussed in more detail later in this paper.

Year	Assumptions
2008	• Energy per seat km as per current TGV performance at 300km/h • Grid mix estimated from CCC projections
2025	• New 300km/h AGV-style high speed trains operational: 14-car trains with 650 seats • Energy consumption per seat km equivalent to baseline 'standard' (0.033kWh/seat km) • Grid mix as per CCC projections
2040	• 2025-vintage trains still in operation • Grid mix as per CCC projections
2055	• 'Next generation' train introduced. 'Like-for-like' replacement e.g. same seating capacity etc., 10% more efficient than 2025-vintage • Grid mix as per CCC projections

Based on these assumptions, indicative high speed rail CO_2 emissions are as follows:

	2008	**2025**	**2040**	**2055**
kgCO_2 per train km	13.4	3.8	1.0	0.6
gCO_2 per seat km	20.6	5.9	1.5	0.9
gCO_2 per pass km (70% loading)	29.5	8.4	2.1	1.3

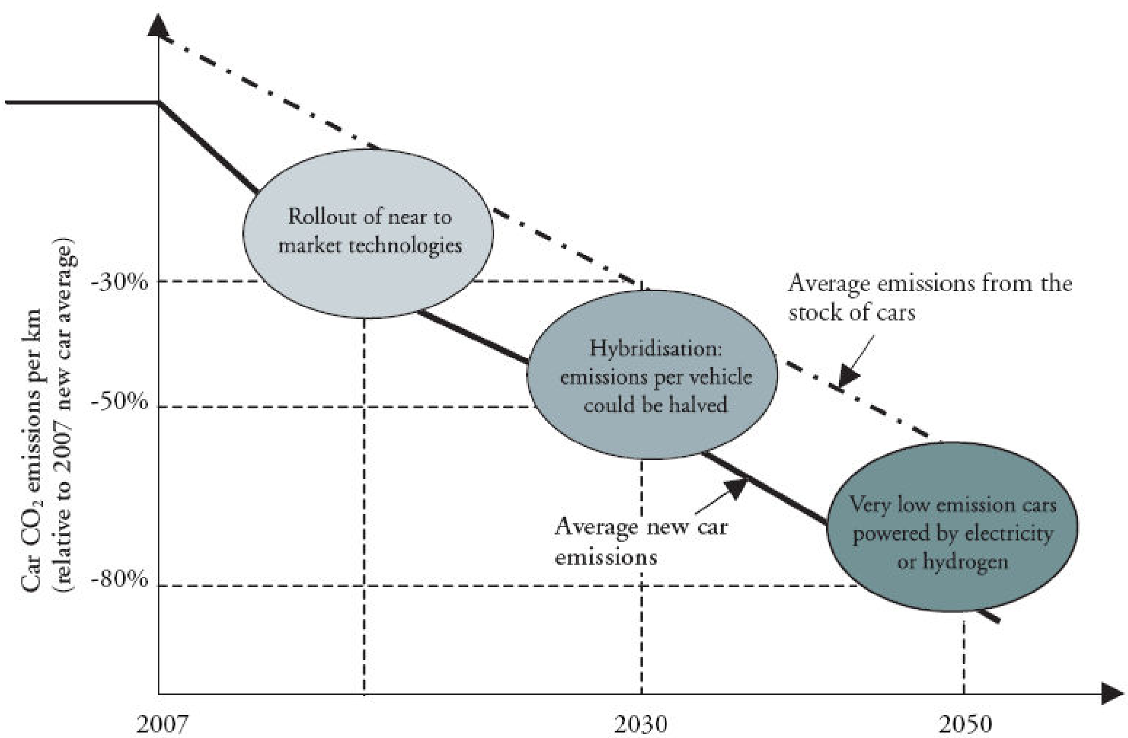


Road

In the short to medium term, the pace of reductions in CO_2 emissions from new cars will be largely driven by the targets put in place by the EC to succeed the existing manufacturer agreements. The new EC proposals will mandate reductions in emissions such that all new cars achieve tailpipe emissions of no more than 130gCO_2/vehicle km by 2015. (Note: this target falls to 120gCO_2/km when other efficiency measures are taken into account e.g. low rolling resistance tyres etc.).

Looking further ahead, the EU proposals set an indicative target of 95g/km by 2020. This is supported by both the 2007 King Review of Low Carbon Cars and the recent Committee on Climate Change work which suggest that, assuming a package of technologies are adopted along with increasing use of biofuels, an average of 100g/km (and possibly even 95g/km) for new cars sold should be achievable by 2020.[11]

It is worth reiterating that emissions from the average car in the fleet will lag behind reductions in new car emissions because of the relatively low pace of turnover of vehicles in the car fleet. CCC envisage that, even if new cars were able to achieve an average 100g/km by 2020, emissions from the average car may still be around 130g/km i.e. 30% higher. When considering relative impacts it is therefore important to distinguish between new and average.



Source: King Review of Low Carbon Cars, Part I (2007).

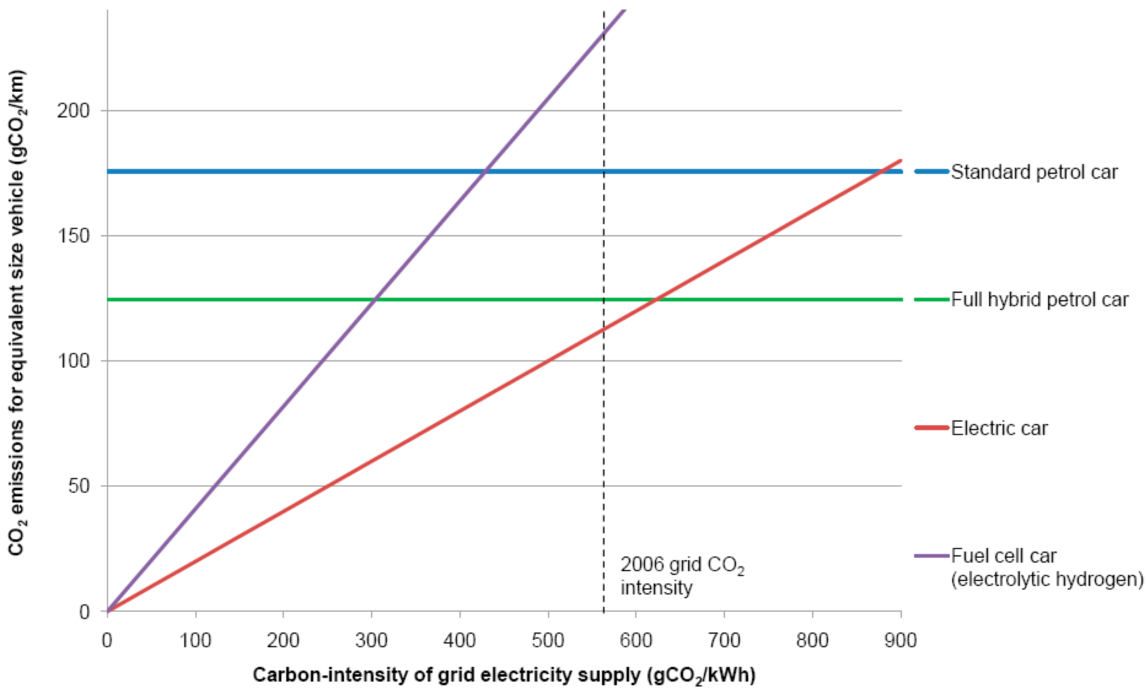
Analysis from the King Review illustrates that by around 2015-2020, assuming certain technologies can be brought to market, average CO_2 emissions for new cars could be 30% lower than today's average i.e. approx. 120g/km, in line with EU proposals. By

[11] Note: Importantly this assumes people buy the most fuel efficient vehicles in each size band and that efficiencies are not eroded by increases in car weight, power etc.

2030 this could fall by a further 20% as a result of widespread adoption of hybrid technology, to approx. 80g/km. Beyond this it is assumed that further efficiencies will come from advanced hybrid technologies although there are likely to be limits to what can be achieved in practice.

In the longer term, between 2040 and 2055, plug-in electric or fuel cell vehicles are likely to be the only realistic means of achieving significant cuts in per km CO_2. Both the CCC and King Review both place heavy emphasis on plug-in battery electric cars which would take advantage of progressive decarbonisation of electricity supply.

CCC projections indicate a standard electric car of this type would emit very low emissions per km, possibly lower than 25g/km, assuming electricity generation is substantially decarbonised.[12]



Source: CCC, Building a Low Carbon Economy, 2008.

- Factors influencing the pace of change

Three important factors will dictate the future pathway of car emissions:

- The impact of heavier, more powerful cars offsetting fuel efficiency gains (which has been the trend to date in many countries, once the one-off benefits of switching from petrol to diesel vehicles are allowed for);
- The development of hybrid and plug-in electric cars;
- The pace of electricity decarbonisation.

[12] This is broadly in line with the King Review which suggests an 80% cut to e.g. around 30g/km is feasible by 2050. The difference is likely to be down to assumptions made regarding the pace of electricity decarbonisation.

Beyond 2020-2025 it becomes difficult to estimate these factors with any certainty. However it is clear that most of the fuel efficiency gains of recent years have, to some degree, simply countered increases in car weight and power. As such, while efficiencies of e.g. 30-40% may be achievable in technical terms, moves towards larger vehicles could offset some of these gains.[13]

As regards plug-in electric vehicles (and electric hybrids), significant developments in battery technology will be required before such vehicles could begin to penetrate the mass market. This is principally due to the fact that batteries with high energy density – and therefore range – are required. Lithium-ion batteries appear to be the most attractive solution, having a high energy:weight ratio, however there remain considerable technological barriers to be overcome to deliver sufficient range per charge. In addition, lithium extraction is particularly energy intensive which suggests that life-cycle emissions from electric vehicles powered by lithium-ion batteries might be an issue unless low carbon energy sources can be used for this. Extraction is also likely to have wider environmental impacts given the location of some lithium reserves (e.g. in the Bolivian Andes).

Furthermore, lithium is a relatively scarce mineral resource and therefore any concerted move towards lithium-ion battery technology in the road sector could well carry a heavy raw material cost penalty.

As a consequence, two different scenarios have been developed for this work. One is based on a set of assumptions broadly in line with the King Review/CCC projections i.e. essentially progressive conversion to electric cars (note: for simplicity we have not considered fuel cell cars). The other is essentially an extrapolation of current trends in which it is simply assumed per km emissions fall at a constant rate, broadly in line with recent average annual reductions, and where there is continued widespread use of cars fuelled by mineral-oils. Both scenarios are not intended to be definitive, but rather they are designed to provide bounds to the range of possible outcomes.

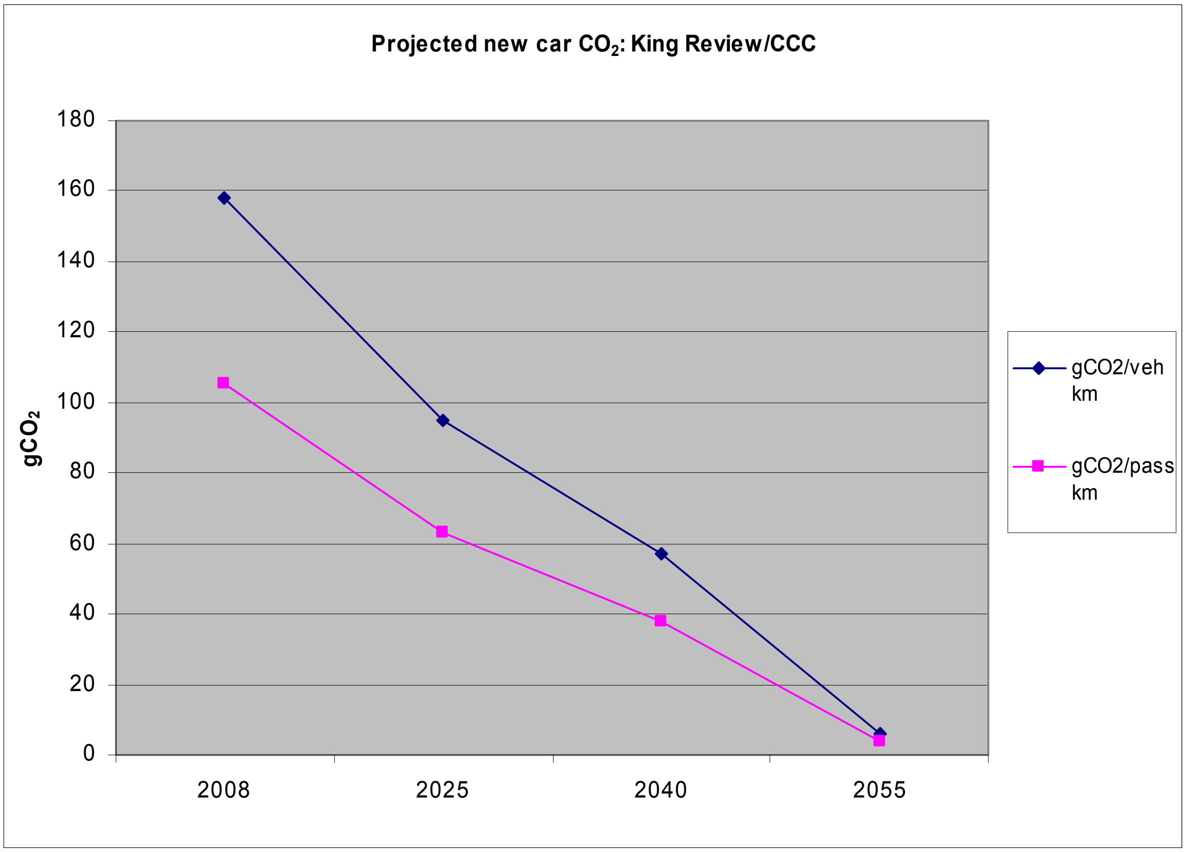
'King Review/CCC' scenario:

Year	Assumptions
2008	• Average new car emissions 158gCO_2/vehicle km
2025	• New car emissions 95g/km (42% reduction on 2007 per km emissions) as per King Review/CCC projections
2040	• New car emissions in 2040 57g/km (65% reduction on 2007 per km emissions) as a result of significant hybrid penetration. • Electric cars beginning to become widespread
2055	• All new cars assumed electric • Electric car energy consumption as per CCC estimates for standard vehicle (0.2 kWh per vehicle km) • Grid mix as per CCC projections • New car emissions 6g/km (96% reduction on 2007 per km emissions) as result of electric cars taking from heavily decarbonised electricity supply

Note: 2007 taken as comparator year for consistency with King Review (above).

[13] It is noticeable for instance that the average mass of cars sold in the EU has shown an almost unbroken upward trend since 1995 (Source: EU data).

		2008	2025	2040	2055
New car	**gCO_2 per veh km**	158	95	57	6
	gCO_2 per seat km	31.6	19	11.4	1.2
	gCO_2 per pass km (30% loading)	105.3	63.3	38	4

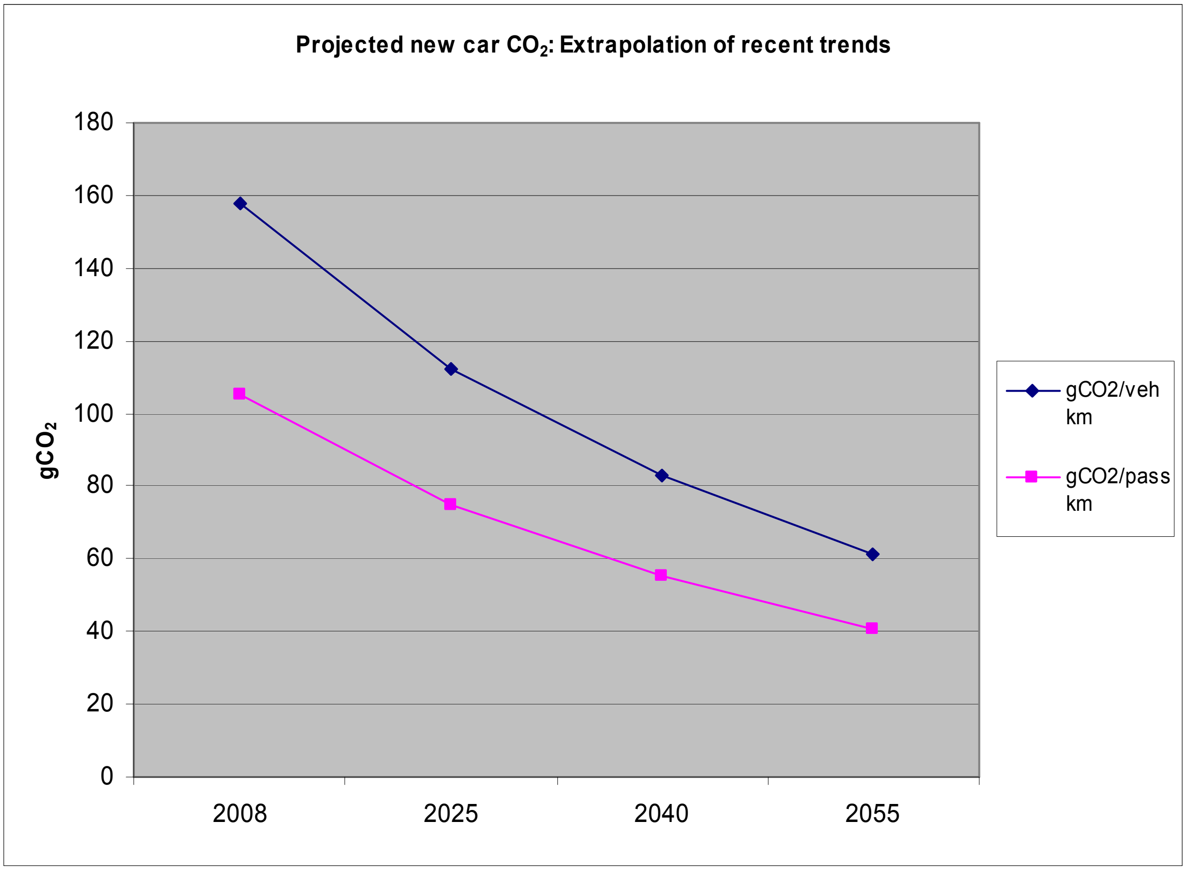


Extrapolation of recent trends:

Year	Assumptions
2008	• Average new car emissions 158gCO_2/vehicle km
2025	• New car emissions fall 2% p.a. to 2025 • New car emissions 32% lower than 2007 per km emissions
2040	• New car emissions continue to fall 2% p.a. from 2025-2040 • New car emissions 50% lower than 2007 per km emissions, mainly as a result of significant hybrid penetration.
2055	• New car emissions continue to fall 2% p.a. from 2040 onwards due to further efficiencies e.g. from advanced hybrids • New car emissions 63% lower than 2007 per km emissions • No widespread take up of electric cars

Note: 2007 taken as comparator year for consistency with King Review and previous scenario.

		2008	2025	2040	2055
New car	**gCO_2 per veh km**	158	112.1	82.8	61.1
	gCO_2 per seat km	31.6	22.4	16.6	12.2
	gCO_2 per pass km (30% loading)	105.3	74.7	55.2	40.8



Short haul aviation

The continued introduction of newer aircraft such as the Next Generation Boeing 737, Airbus A319 etc., will reduce the emissions per passenger trip from short haul air, as these aircraft are more fuel efficient.

Looking ahead there will be continued fuel efficiency gains. Work undertaken for the CCC suggests that new build planes introduced in 2025 could be 35-45% more carbon efficient than current (2006) new aircraft as a result of improvements in airframe design and engine efficiency:

Table 8.4 Summary and combination of evolutionary airframe improvements

Technology	Potential Aircraft CO_2 improvement	Earliest Availability	Retro-fit?	Key Technical Barriers
Winglets	1-2%	Now	Y	New – none Retrofit benefit is application dependent, leasing
Riblets	1-2%	2015-2020	Y	New – dev and certification Retrofit is application dependent, leasing
Laminar Flow (wings)	10-20%	Now-2020 Note 2	N	Manufacturing costs, maintenance costs Note 3
Laminar Flow (Nacelles)	1%	Now	Y	As Laminar flow wings but with less significance.
Lighter Materials (Composites)	10-20% Note 1	Now	N	Certification, manufacturing, repair, recycling
Active Airframe Health Monitoring	Up to 12%	2015-2025	N	Development test and evaluation costs, certification.
AVG New Production	**20-30%**	**By 2025**		
Retrofit	2-5%			

Source: QinetiQ. (2008) Aviation CO_2 *Emissions Abatement Potential from Technology Innovation*

Note 1: Generalised composite figures indicate a 10% reduction in fuselage and wing mass, with potential weight saving in the primary structure overall (including fuselage and wing) of no more than 25% and not more than 15% in the secondary structure, in commercial aircraft. Typically a 25% decrease in a/c weight gives ~10-15% savings in fuel usage, hence 25-40% reduction may result in 10-24% saving in fuel, this is conservatively expressed as 10-20%.

Note 2: Hybrid laminar flow control was previously demonstrated on a B757 aicraft in 1991, technically this could be implemented today.

Note 3: Increased sensitivities to surface imperfections, dirt/bugs/damage etc, lead to increased manufacturing and maintenance costs.

Table 8.5 Summary and combination of evolutionary engine improvements

Technology	Potential Aircraft CO_2 improvement	Earliest Availability	Retrofit?	Key Barriers
OPR, Materials, Cooling	3-5%	Now-2025	Y	None
Compressor and Turbine Aero	3-5%	Now-2025	Y	None
Cycle (GTF/UHB) Note	8-10%	2013-2025	N	Dev risk for larger gearboxes
AVG New Production	**15-20%**	**By 2025**		
Retrofit by Module Replacement	*0.5-1%*	*Now*		
Retrofit by new engine to 10 year old airframe	*5-7.5%*	*Now*		

Source: QinetiQ. (2008) *Aviation CO_2 Emissions Abatement Potential from Technology Innovation*

Note: GTF/UHB – Geared turbofan for lower thrust, Ultra high bypass for larger types.

Source: QinetiQ (2008) for CCC.[14]

[14] Note the savings in the two tables are not fully additive.

In addition, a range of improvements to operational practices/air traffic management (ATM) have been identified that could supplement the above technical efficiencies to further reduce CO_2:

Table 8.6 Summary and combination of operational/ATM improvements

Technology	Potential Aircraft CO_2 improvement	Earliest Availability	Retro-fit?	Key Barriers
Operations				
Ground towing	Up to 2%	2010s	N	Aircraft design, airport capacity
(Stop) Tankering	0.5%	Now	Y	Turn round time
Cabin dead weight reduction	<1%	Now	Y	Brand image, public expectations
Formation flight	1%	2020s	N	Coordination, risk
Optimum stage length	Up to 7%	2015-2040	N	New fleet , extended journey time, more airports, increased LTO risk and noise
Load factor maximisation	9% Max 3-6% feasible	Now	Y	Timetabling, frequency
Point-to-point	Possibly up to 5%	2015-2035	N	Smaller planes, airport size shift, route frequency
Air Traffic Management				
System delays and imperfect trajectories	3-8%	2020	N	System improvements already funded in parallel with capacity increase research
Total Improvement	**10-15%**	**2025**		
	Up to 25%	**2040**		Total aircraft and route redesign
Retrofit	4%			

Source: QinetiQ. (2008) *Aviation CO_2 Emissions Abatement Potential from Technology Innovation*

Source: QinetiQ (2008) for CCC.

In sum, the QinetiQ work for CCC envisages that, taken together, these potential savings would mean that a new, 2025-vintage aircraft flying in an improved operating environment would be 40-50% more efficient than a 2006 plane flying in a 2006 operating environment.

However, like rail vehicles, aircraft have long operating lifetimes (say 20-30 years) and it will take considerable time for the most modern aircraft to completely replace the existing fleet. Similarly it is likely to be very challenging to deliver new aircraft that meet these demanding targets within the 2025 timeframe. However, as a conservative assumption, in our analysis we have assumed that high speed rail will compete with the best new aircraft. In practice, we would expect short haul carriers to operate a mix of aircraft of different vintages as they do today so that average aviation emissions would in practice be somewhat higher than these levels. However, since it is hard to forecast what the fleet mix of different aircraft ages might be over the timescale to 2055 we have focussed the analysis on the most modern aircraft for simplicity.

- Aviation fuel sources

Aviation does not face the same opportunities for fuel decarbonisation open to rail and road. Given the critical importance of fuel that has a very high energy density and that can operate in a wide range of temperatures, kerosene is likely to remain the staple aviation fuel for the foreseeable future.

While there may be some opportunities for biofuel blending, it is expected that much more advanced biofuels, e.g. 3rd generation biofuels optimised for aviation use, would be required in order to meet energy density/temperature requirements. In the more immediate term, there is interest in using the Jatropha plant for this purpose. The timescales for these types of fuel deployment are uncertain and although a number of airlines (such as Air New Zealand and Virgin) are undertaking trials of blends of biofuel with kerosene at present it is likely to be some time before the technical and safety issues associated with this kind of substitution are fully analysed.

- Implications

Nonetheless, the following scenario assumes that the CCC projections are broadly delivered but in stages and that, by 2025, new aircraft are 35% more efficient than their 2006 counterparts. This reflects reaching the lower end of the QinetiQ projections for efficiency improvements from engine/airframe changes.

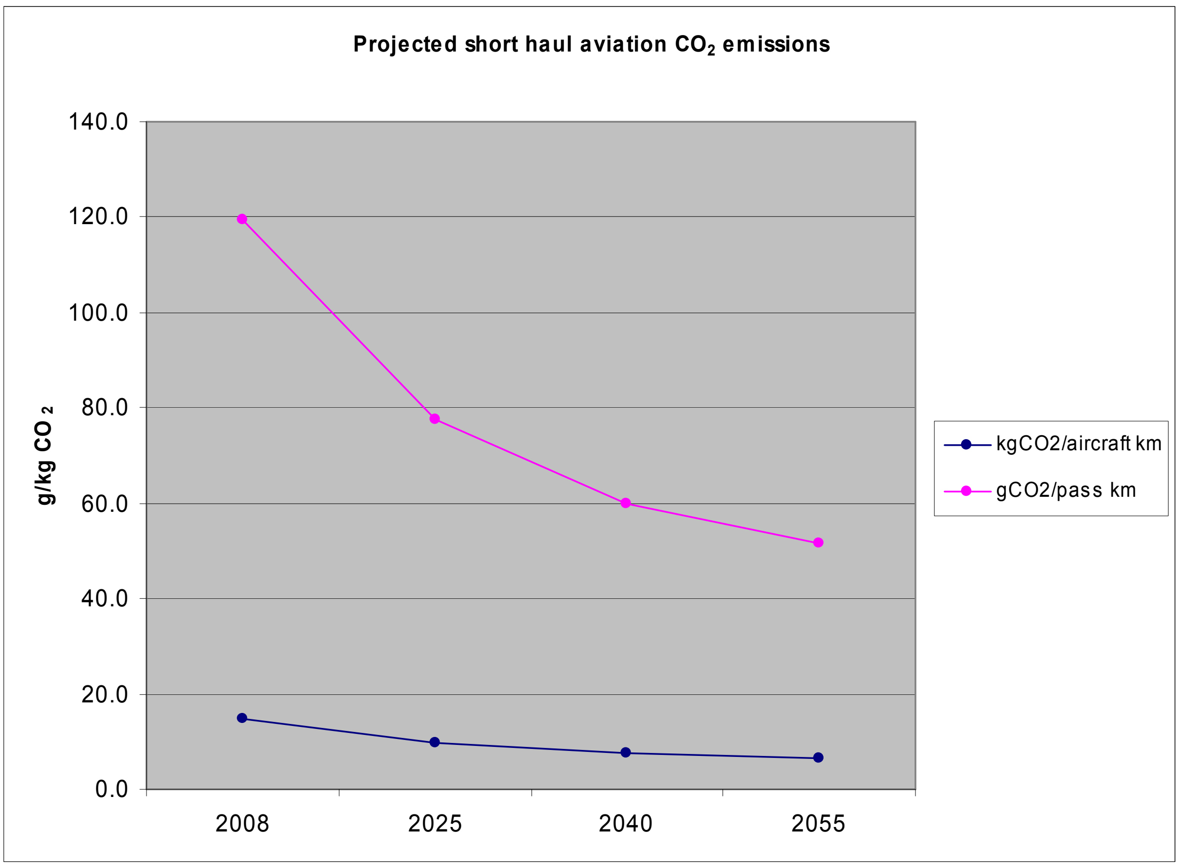
Looking further ahead to 2040, it is assumed all planes in service are 2025 and later vintage (i.e. incorporating the full range of engine and airframe improvements) and that further operational efficiencies could deliver additional improvement such that aircraft are 50% more efficient than 2006.

In terms of alternative power technologies, QinetiQ's assessment for CCC indicates that radical switching to forms of power such as hydrogen fuel cells, solar or even nuclear can be ruled out before 2050 at the earliest. Beyond 2040 to 2055 it is therefore assumed that, in the absence of 'game-changing' technologies (e.g. blended wing aircraft), further efficiency improvements are limited to 1% per annum. This would ultimately suggest that, by 2055, short haul aircraft could be up to 57% more efficient than 2006:

Year	Assumptions
2008	• Short haul domestic jet aircraft fuel consumption and CO_2 performance as per 2006 A319 (assumed average fuel consumption on 300-600km sector)
2025	• New aircraft 35% more fuel efficient than 2006 due to engine, airframe improvements • Assumed new aircraft are 'like-for-like' replacement for A319 i.e. same carrying capacity etc.
2040	• All aircraft 2025 vintage or later • Assumed 50% more efficient than 2006 due to additional engine, airframe and ATM improvements
2055	• Further 1% p.a. efficiencies assumed from 2040 onwards • Aircraft 57% more fuel efficient than 2006

From this, indicative short haul domestic aircraft CO_2 is as follows. Again, it should be stressed that aviation emissions would be expected to higher than this once the fleet mix of different ages of aircraft in the short haul fleets is allowed for.

	2008	2025	2040	2055
kgCO_2 per aircraft km	14.9	9.7	7.5	6.4
gCO_2 per seat km	95.7	62.2	47.8	41.1
gCO2 per pass km (80% loading)	119.6	77.7	59.8	51.4



This scenario, which leads to a more than halving of emissions per seat km by 2055, could be regarded as very optimistic since it assumes the full potential of the efficiencies identified by QinetiQ for CCC is ultimately realised and in a timely fashion. Similarly it takes no account of the likely costs of doing so in higher capital and operating costs, which would of course feed through to airfares and demand levels.

As an illustration of the challenges involved, Boeing's new generation 787 'Dreamliner' employs radical, lightweight composite materials in construction designed to improve fuel efficiency. However, while delivery of the first Dreamliners was originally scheduled for mid-2008, this has now been put back to 2010 at the earliest due to a series of major production delays.

Carbon intensity of UK electricity generation

Key to the environmental impact of high speed rail is the carbon intensity of the electricity used to power the train. Two legislative proposals will drive the decarbonisation of the UK electricity generation mix:

- The EU's commitment to a 20% reduction in GHGs by 2020 (rising to 30% if an international agreement can be reached beyond 2012) together with the EU Renewable Energy Directive target of 20% of EU energy consumption to come from renewable sources by 2020 and;
- The UK's domestic Climate Change Act target of an 80% reduction in GHGs by 2050 on a 1990 baseline.

EU 20/20/20 target

The EU's recent Climate and Energy Package includes agreement to deliver an overall reduction in EU GHGs of 20% by 2020 alongside a target for 20% of all EU energy to come from renewable source by 2020 (hence '20/20/20').

The package relies on an effort-sharing approach amongst member states under which the UK must ensure at least 15% of energy consumption is from renewable sources.

As far as electricity generation is concerned, this implies the share of renewables in UK electricity generation will need to be increased from around 5% currently to approximately 30-37% i.e. a seven or eight-fold increase, on the assumption that the bulk of the 15% will need to come from electricity rather than other energy carriers.

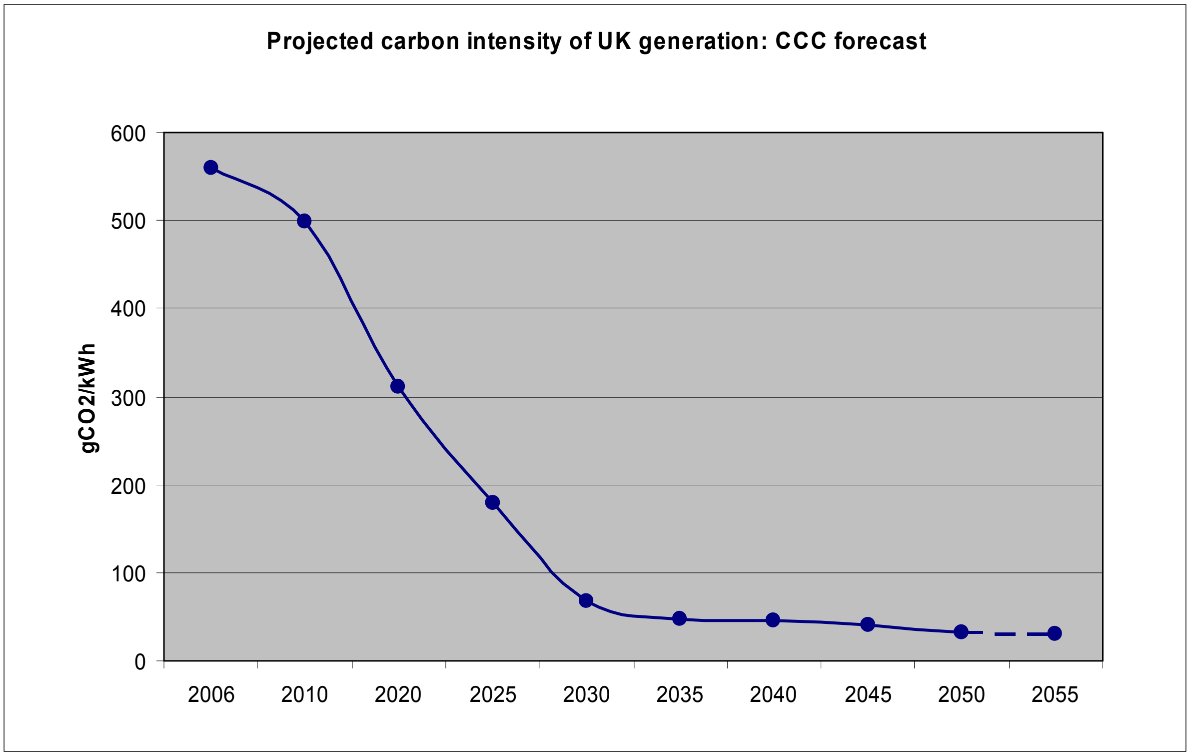
UK 80% target

The recently enacted Climate Change Act commits the UK to an 80% cut in GHGs by 2050 (on a 1990 base). The target will apply across all sectors but, to the extent that some sectors will be unable to deliver 80% reductions (e.g. aviation, shipping), other sectors will be required to pick up the 'slack'. To this extent, aviation is therefore included (it was excluded from the original Kyoto agreement).

In support of this, the CCC report sets out the means of reaching the 80% goal along with carbon budgets for the period 2008-2022. These require interim cuts of 31% (on a 1990 base) by 2022, rising to 42% if a global deal on emissions cuts is reached.

Changes to the UK generation mix

CCC identified the progressive decarbonisation of electricity generation as one of the key mechanisms for reaching the 80% goal. Indeed, because of the relative ease of decarbonisation of electricity generation compared to other sectors, electricity generation is expected to reduce its emissions by over 90% compared with today.[15] Heavy deployment of renewables (especially wind) as well as some nuclear and coal with CCS is envisaged as the means to drive the carbon intensity of UK generation down from around 560gCO_2/kWh in 2006 to around 310gCO_2/kWh by 2020 and, ultimately, well below 100gCO_2/kWh by 2030:



Source: CCC to 2050 with ATOC estimate for 2055 value. Estimates are for carbon intensity at point of consumption i.e. including losses in transmission and distribution. The estimates are of the average mix during the year rather than those derived from the fuel sources used to generate electricity at the times during the year that high speed rail would be drawing load from the grid system. These may be higher or lower than the average.

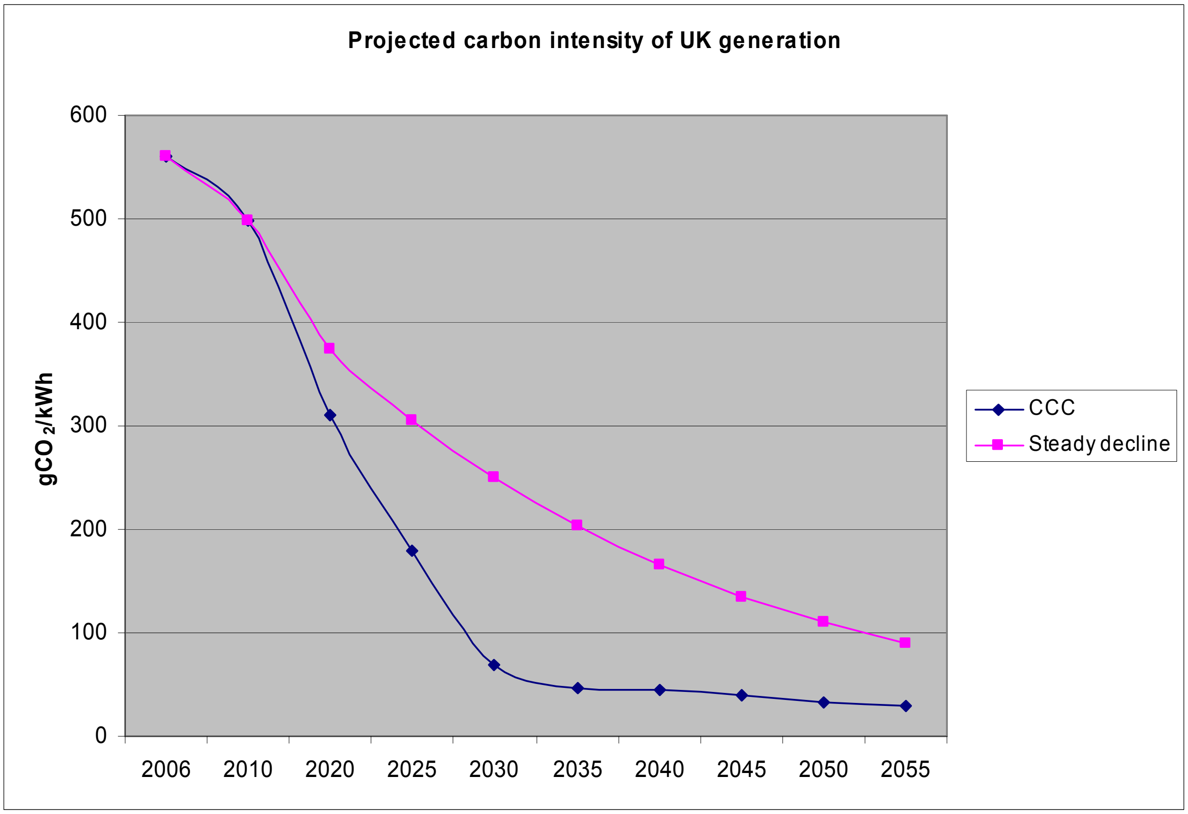
From 2020-2030 the pace of electricity decarbonisation is very rapid i.e. approximately a 75% reduction in carbon intensity, compared to 38% in the previous decade.

It should be emphasised that the CCC work is not a forecast for the UK's grid mix but rather a scenario to illustrate the action that will need to be taken to decarbonise generation to meet the national 80% target. It therefore supposes substantial measures to stimulate renewables, nuclear and carbon capture and storage, which might be achieved through a combination of the current policies, i.e. emissions trading (carbon pricing) and a requirement on suppliers to achieve designated amounts of renewable energy.

For comparison, we have created an alternative scenario in which electricity is decarbonised less rapidly than the CCC envisage but somewhat more rapidly than recent

[15] Strictly, these percentages are not directly comparable since the 80% goal is from the base of 1990 rather than today.

trends. In this alternative scenario, decarbonisation occurs at a steady pace of 4% p.a. after 2020 to reach an 80% reduction by 2050 and an 84% cut in total by 2055.

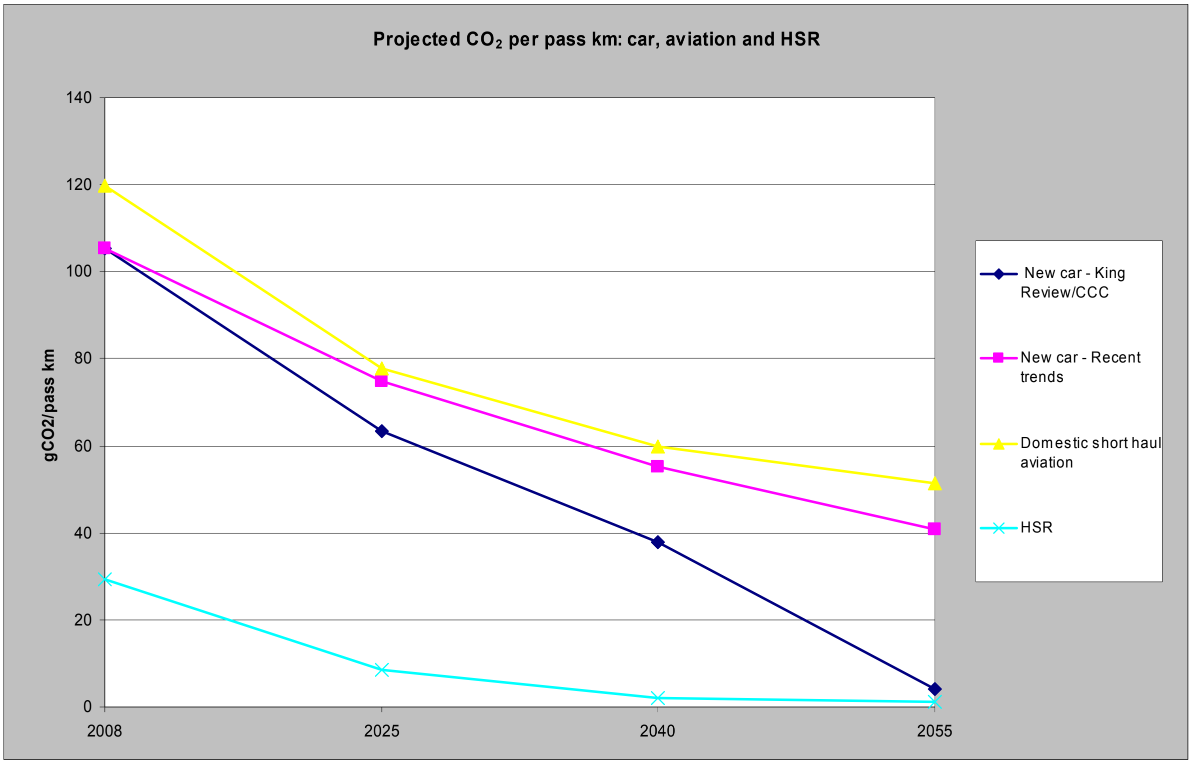


Source: CCC as above and comparison based on CCC (Scenario 3) to 2020 then 4% p.a. reduction to 2055.

This alternative scenario illustrates that, if electricity is not decarbonised in line with the CCC's projections, high speed rail emissions would be correspondingly higher than has been assumed. However they would still remain significantly lower than competing modes.

Future comparison: car, short haul aviation, high speed rail

Taking the earlier projections for technical improvements of each mode, the load factors that they achieve and the forecasts for carbon intensity of electricity generation that the CCC have made, the relative consumption per passenger km emissions of different modes can be compared:



Source: Estimates based on earlier assumptions and CCC forecasts for CO_2 intensity of generation.

This shows that high speed rail emissions per passenger km are lower than other modes to start with and, as a result of decarbonisation of the electricity supply, fall to very low levels indeed by 2055. Rail's advantage over air improves over time but the King Review/CCC scenario for car means that the carbon impact per passenger km falls by over 95%. However, even with a reduction of this scale, high speed rail emissions per passenger km would still be around a third of those from cars.

Importantly, while this illustrates that, by 2055, emissions from electric cars may fall close to zero and aviation emissions could be significantly lower than today, from a climate change perspective it is the intervening period 2025-2040 that is of course of high interest. It is during this period that concerted action to stabilise emissions in the atmosphere is required to minimise the risk of dangerous climate impacts in the very long term. This suggests that the very significant carbon advantage high speed rail would hold over both car and air in this period ought to be fully exploited in policy development.

Richard Davies
Leigh Thompson
ATOC, April 2009