GLAECONOMICS

Current Issues Note 24

Reviewing the evidence on carbon emissions from rail and air travel

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Transport for London

LONDON DEVELOPMENT AGENCY

MAYOR OF LONDON

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Greater London Authority
March 2010

Published by
Greater London Authority
City Hall
The Queen's Walk
London SE1 2AA
www.london.gov.uk
enquiries **020 7983 4000**
minicom **020 7983 4458**

ISBN: **978-1-84781-348-0**

Cover photograph
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GLA Economics provides expert advice and analysis on London's economy and the economic issues facing the capital. Data and analysis from GLA Economics form a basis for the policy and investment decisions facing the Mayor of London and the GLA group. The unit is funded by the Greater London Authority, Transport for London and the London Development Agency.

Contents

Key findings

This paper analyses the existing literature on calculating the carbon emissions from high-speed rail and short-haul aviation. By evaluating the methods and assumptions used it is possible to make sense of the results of the literature, revealing a more narrow and robust estimate. This analysis finds that high-speed rail produces 40-100g of CO_2 per passenger kilometre and aviation 150-350g of CO_2 per passenger kilometre over distances up to 500 kilometres. This suggests high-speed rail produces around one-third the CO_2 emissions of short-haul aviation during operation.

Introduction

In recent years aviation has been criticised as a considerable generator of carbon emissions. It is thought that many trips made by plane could be better made by high-speed rail and lead to a reduction in carbon emissions from travel; many studies have been conducted and in general this view is accepted. However, the range of findings is great and the results depend considerably upon the method used and the assumptions made to conduct the calculations. It is understandable that the policy debate may be muddled by imperfect information.

The purpose of this paper is to analyse the existing literature on the subject to assist policymakers in understanding how carbon emissions from high-speed rail and short-haul aviation are calculated and how to interpret the findings and develop an understanding of the key issues involved with emissions estimates.

This note reviews a broad selection of reports and studies by a range of organisations to explain the methods and assumptions used in the literature. It begins with a review of the different methods used to quantify the CO_2 emissions of these two transport modes. It then questions the underlying assumptions, assesses their relative robustness and identifies areas of potential weakness. Finally, it suggests a range of estimates that appear robust and identifies what additional factors need to be considered when devising a high-speed rail strategy.

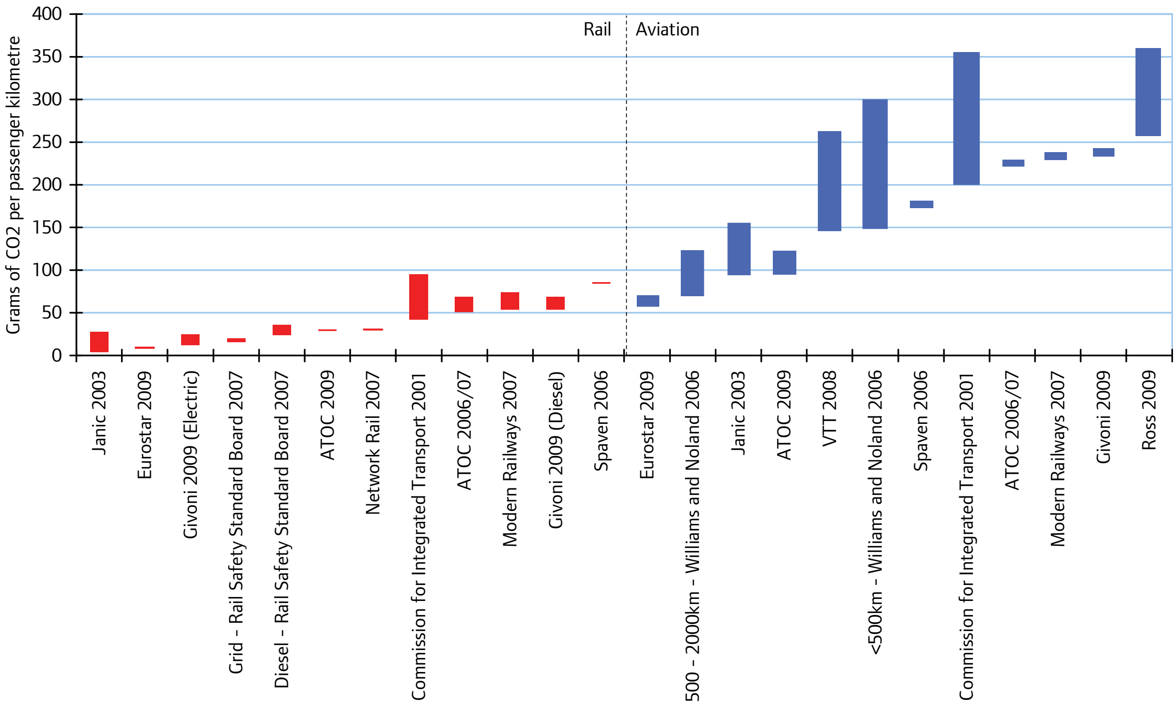
Review of the literature

A number of studies have been completed estimating CO_2 emissions from rail and aviation and the range of findings is very large. Figure 1 shows the findings from these studies, measuring the CO_2 emissions per passenger kilometre for rail and short-haul aviation. The bars in Figure 1 represent the range of emissions estimates calculated in each study. The studies suggest that the carbon emissions from aviation may be as much as 35 times higher than the emissions from rail travel. For example Ross found that air travel may emit more than 350g of CO_2 per passenger kilometre while Eurostar says its trains emits only 8.9g of CO_2 per passenger kilometre. Even within modes a very great range exists between the highest and lowest estimate, as seen in Figure 1.

A range of organisations and individuals have conducted the studies, including companies involved in operating the rail network and train stock, research institues, campaign and pressure groups, magazines and peer-reviewed scientific journals. It is important to understand the type of organisation that commissioned the research, as their agenda may partially determine the assumptions used in making the calculations. These underlying assumptions have a direct effect on the outcome of the study and may be used to view a mode of transport in a more or less favourable fashion.

There are several key methods used to calculate the CO_2 emissions of these different modes of transport. The next section discusses the most commonly used methods and the comparative strengths and weaknesses of each.

Figure 1: Range of estimates of grams of CO_2 per passenger kilometre for rail and short-haul aviation from a selection of research papers



Source: GLA Economics

Review of the methods

There are three key methods used to estimate emissions from aviation and from high-speed rail. Each of these methods is examined below.

1. Route analysis

First is an anaylsis of a route or group of routes. This can be done using either a single vehicle or group of vehicles and it is often employed to determine the CO_2 emissions per passenger kilometre. This method is effective for both aviation and high-speed rail and is suitable for inter-modal comparisons.

The route analysis method allows an actual load factor to be selected using an official measure of that route or a route being considered. It requires a vehicle, or a group of vehicles, to be selected and this selection should be representative of the stock that operates on the route to allow accurate estimates to be produced.

The emissions are calculated based on industry data of vehicle efficiency. Sources such as the International Civil Aviation Organization are conventionally used to produce the aircraft emission levels whilst the CO_2/kWh of UK energy is used in determining the emissions of high-speed rail[1].

One strength of this method is the ease in selecting an appropriate load factor. It also takes into account the nature of specific routes. Because the rolling stock is inserted in the model it is possible to select one that is most representative of the stock operating on the route.

Route analysis is effective at comparing alternative modes of transport to develop an understanding of the CO_2 emissions, on a particular route being considered. But, because it relies on selecting the appropriate vehicle, the method can be easily used to produce an inaccurate estimate.

2. Distance-based analysis

The second method is to develop a non-linear relationship between emissions and journey distance for a vehicle. This allows emissions to be estimated for an unknown stage of a specific distance. A single vehicle is used to develop this relationship and as such the vehicle and load factor are important and have significant influence on the results. Like the route analysis method, industry sources are used to supply vehicle efficiency data.

This method produces a good estimate of emissions over a specific distance for a certain vehicle type. However it relies heavily on assumptions of the vehicle type and the vehicle load factor. It also will not be representative of routes in which multiple vehicle types are used.

3. Network analysis

The third method looks at total journeys using a combination of the total passenger kilometres travelled, total vehicle kilometres travelled or using a large sample of data. This data can be analysed for only routes of a certain distance to make the information more relative to a route being considered. This information is combined with the overall energy consumed to determine the CO_2 emissions produced per passenger kilometre.

This method delivers a very broad analysis based on observed data but is not an examination of a specific route or vehicle. It gives an overview of the average emissions for the mode of transport.

The method's weakness is that it reviews a full network where there are likely to be some routes that are more efficient than others. The overall average is used in the calculation which may not be representative of the route under consideration. For example, consider a route which is normally fully booked and included in this analysis with many that are only half full. These unrepresentative journeys will distort the emissions estimates. Factors that may not be representative include the vehicles, route length and load factor.

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[1] High speed rail is powered by overhead lines and so sources energy from the national grid. The energy used to power the trains is best represented by the general mix of power produced in the UK. Therefore, the average mix of energy produced in the UK should be used to reflect likely energy consumption.

Comment on methods

Each of the above methods has distinct advantages and disadvantages when used to estimate carbon emissions. Route analysis is the most suited to analysing individual routes. Network analysis gives a highly accurate average figure for current emissions over the entire network but is not great on specific routes. Distance-based analysis is the most suitable method where data is unavailable and allows a rough estimate of emissions when needed.

But behind each of these methods are a number of assumptions that can have a significant influence on the results. The assumptions driving the results need to be carefully considered before being able to assess the relative robustness of a particular study. The following section discusses the assumptions that drive these methods.

Key assumptions affecting findings

This section discusses the key assumptions used in the methods discussed previously. It will look at how these assumptions can affect the results of a study. The most influential assumptions are the vehicle used in the analysis, the CO_2 emissions of the energy source, the route selected for analysis, and the load factor of the vehicle.

1. Vehicle type

The vehicle selected when performing the emissions analysis has a large impact on the result. Modern aircraft and trains have better designs and are more fuel-efficient than older models and produce less CO_2 emissions. Figure 2 illustrates the development of fuel efficiency in aircraft and how it has improved over time. Since the 1960s there has been a sharp decrease in emissions which continues today, though at a slower rate. Recent work suggests technological improvements in production of the airframe may reduce CO_2 emissions produced by aircraft 20 per cent by 2025. Improvements in engine technology may yield a further 15 per cent reduction in CO_2 emissions over the same period and improvements to air traffic management and ground operations could lead to another 10 per cent reduction in CO_2 emissions[2].

Rail technology has advanced similarly over time[3]. For example, the class 390, introduced in 2003, is 20 per cent more efficient than the class 373 produced a decade earlier[4].

When selecting a vehicle, it is important for it to be representative of the future stock or the results will not reflect the true emissions level.

There are two main methods of selecting vehicles. The first is using a single vehicle; this can be appropriate when using the route analysis or the distance-based method. This assumption can be improved when employing the route analysis method by taking the average emissions of a selection of vehicles better representing the stock operating upon a certain route[5].

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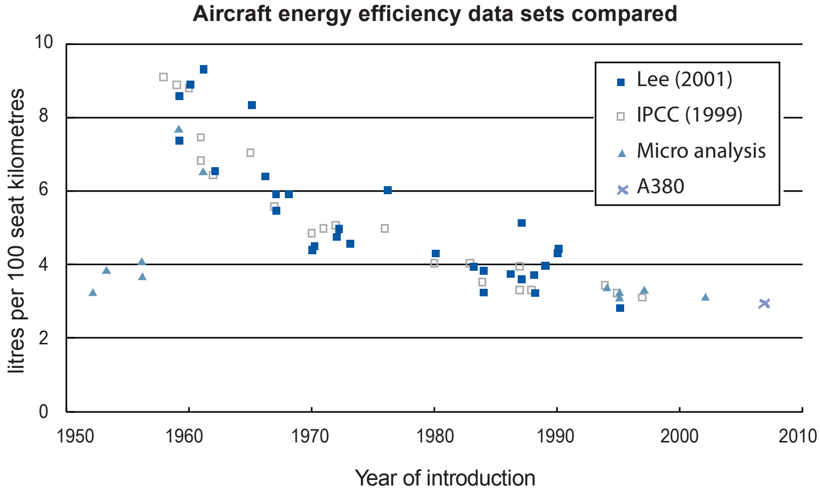
[2] Farries, P. & Eyers, C. (2008).
[3] Rail Standard Safety Board (2007).
[4] ATOC (2009).
[5] Givoni (2009) & ATOC (2009).

The second method, network analysis, considers a large data set[6]. It has an implicit average of vehicles incorporated in the method. This method gives an overview of the current levels of CO_2 emissions but will capture older vehicles that will not be in the future stock and therefore produce a higher estimate.

Figure 2: Development of fuel efficiency of new aircraft plotted against the first year of production.



Source: European Federation for Transport and Environment (2006)

2. CO_2 emissions of energy production

The CO_2 emissions of the sources of energy have a direct impact on electric high-speed rail. This is because trains get energy from the mains. All methods discussed above will include CO_2 emissions of the energy produced when discussing the emissions of trains.

Most papers[7] will use a formula similar to:

$$\frac{\text{GWh}}{\text{passenger-kilometre}} \times \frac{CO_2}{\text{GWh}} = \frac{CO_2}{\text{passenger-kilometre}}$$

Changing the CO_2 emissions per GWh will have a direct effect on emission levels and the results of the study. It is important to look at how the study selects the CO_2 level and only view studies using an appropriate UK energy mix. Table 1 displays the carbon dioxide emission per GWh from a selection of UK energy sources and the average carbon dioxide emission per GWh produced in the UK.

[6] Finnish VTT (2009) & ATOC (2007).
[7] ATOC (2007), Modern Railways (2007), Givoni (2009) & Rail Safety Standard Board (2007).

Table 1: UK Government estimate of carbon dioxide emissions from electricity generation in Britain

Fuel	Tonnes of carbon dioxide per GWh electricity supplied	
	2007	2008
Coal	915	910
Oil	620	711
Gas	397	393
All fossil fuels	626	605
All fuels (including nuclear and renewables)	496	497

Source: DUKES (2009)

Most papers use CO_2 per GWh generated of approximately 450 to 550 tonnes. This is consistent with the official measures, displayed above, which rates UK at 497 tonnes per GWh. The 2007 UK Energy White paper suggests the CO_2 per GWh may fall 20 to 25 per cent by 2020[8] to around 400 tones per GWH but this is dependent on future investment.

Some studies looking at high-speed rail use the CO_2 emissions per GWh of energy produced in other countries, particularly France. Because much energy in France is produced from nuclear fuel, these studies do not give accurate figures for considering a British high-speed rail system[9]. Though travel from London to the Continent does indeed use French power, the bulk of any new journeys on UK rail will take place wholly within the UK and using domestic power.

Studies looking at aviation generally use CO_2 emissions of 3,100g per litre of jet fuel[10], which is consistent with the International Panel on Climate Change's measure. Studies looking at diesel trains and diesel high-speed trains use standard industry figures for CO_2 emissions of 2,600g per litre of diesel.

3. Load factor

The load factor is a measure of the total utilisation of the available capacity of the vehicle. The load factor of the vehicle has a direct impact on its efficiency. Increasing the load factor will reduce the CO_2 emissions per passenger kilometre. The load factor does not include standing and on some routes may be above 100 per cent[11].

The load factor only gives a partial picture. The total seating capacity also has an effect on vehicle efficiency. For example the Japanese Shinkansen has 1,323 seats whereas the French TGV Reseau has 545 seats. If CO_2 per/GWh and load factor are the same the Shinkansen will

[8] ATOC (2007).
[9] Givoni (2007), Eurostar (2009) & Janic (2003).
[10] IPPC (1999).
[11] Network Rail (2007a).

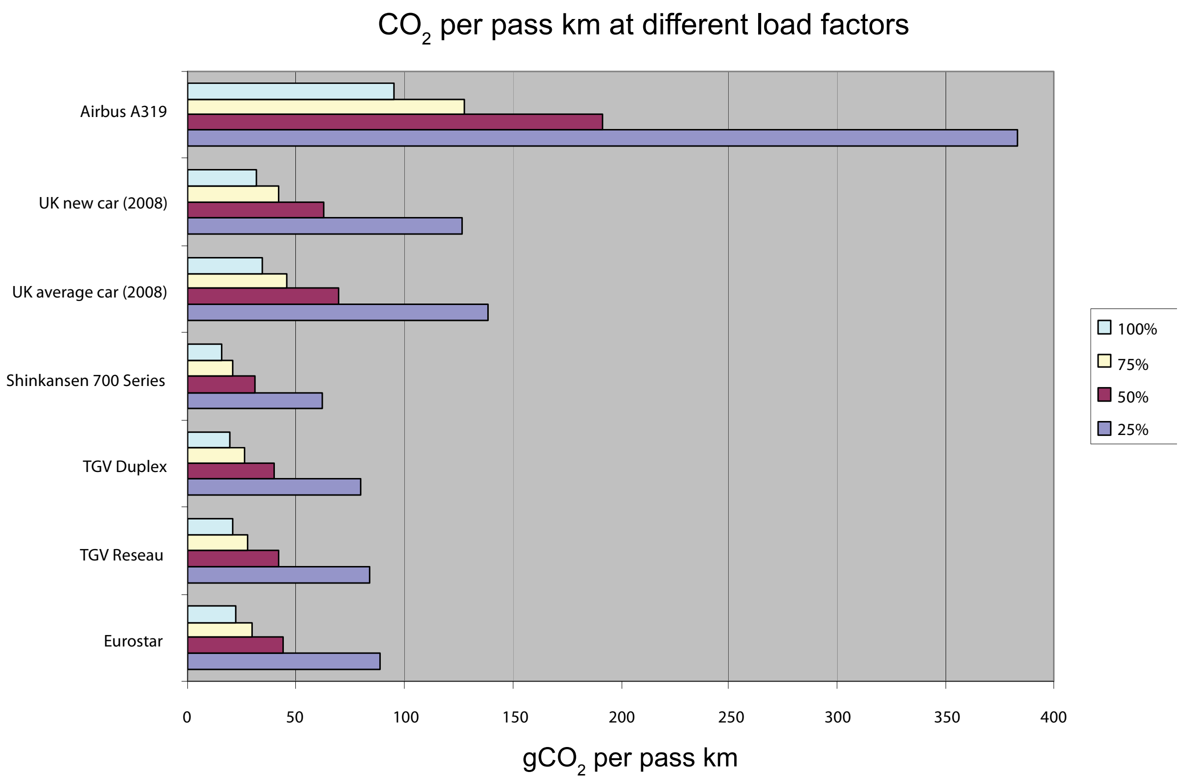
have a significantly lower CO_2 per passeneger-km due to its higher capacity. Increasing the capacity of a vehicle will reduce CO_2 emissions per passenger.

When performing a route analysis it is possible to use the average load factor for that that route[12], from either a single carrier or carriers. This gives an accurate representation of the use on that route.

When using the route analysis method on a collection of routes, or a network analysis that separates data by stage lengths, an independent authority's measure of average load can be used. This method is suited to larger studies involving multiple routes and carriers[13]. This produces a less accurate, but still representative figure, due to the dilutions of the information.

Network analysis has an implicit load factor included in the method and allows for variations between individual routes. This produces a less rigorous figure for examining an individual route but gives an accurate average figure for the mode of transport.

Figure 3: Effect of load factors on $C0_2$ per passenger kilometre



Source: ATOC (2009)

Figure 3 illustrates the effect on $C0_2$ per passenger kilometre of varying the load factor. In per passenger terms, the load factor has a highly significant effect on the $C0_2$ emissions. It is therefore important to employ a realistic load factor assumption when calculating emissions estimates.

[12] Commission for Integrated Transport (2001).
[13] Williams, V. (2006).

4. Route length

The route being analysed has an impact on the relative CO_2 emissions per passenger kilometre. The longer an aircraft's route the more fuel efficient it will be, to a point. This is due to the lower portion of the flight time spent in the more fuel intensive take-off and landing cycle and a larger portion of time spent in the fuel-efficient cruise altitude.

A similar relationship exists with rail, as more energy is required to accelerate the vehicle to maximum speed than to maintain its speed. This is an important point when considering long-distance rail travel, as additional stops will require multiple periods of acceleration and may lead to a significant difference in emissions than the results a direct city-to-city analysis will suggest[14].

These factors imply that a route analysis or distance-based analysis of short routes will produce estimates that will not be representative of longer routes and vice versa.

A review of selected papers

The route analysis method may be considered most appropriate when comparing high-speed rail and aviation as it allows a direct comparison of individual routes on which the two modes of transport would compete. The distance-based analysis is the least appropriate, as it requires the largest number of assumptions and therefore produces least credible emissions estimate. The network analysis produces a very accurate estimate, but care must be taken to make sure the aircraft and stage lengths used in it represent the route being considered.

Considering the strengths and weaknesses of the methods and viewing the assumptions used, a group of papers were selected as being the most representative, robust and having the most accurate measures of carbon emissions. These papers are displayed in Table 2 and the results are highlighted in Figure 4.

These papers were selected because they use the most appropriate assumptions and methods and therefore produce reasonable CO_2 estimates. These studies use the route analysis (Commission for Integrated Transport, Network Rail, Williams, and ATOC) or network analysis (VTT) method.

These reports use vehicles representative of the most commonly used aircraft and high-speed trains in operation, giving an appropriate estimate for emissions levels for the future stock of vehicles.

The reports employing route analysis techniques select their vehicles in different ways. The Commission for Integrated Transport views four high-speed rail routes and the average electricity consumed on each of these. The Williams study uses the ten most travelled short-haul routes and aircraft operating on them. ATOC and Network Rail use a single vehicle type, the French TGV Reseau and Eurostar respectively, which are relatively old technology.

[14] For example a 500km journey with a stop in the middle is equivalent to two 250km journeys due to acceleration time and energy. This will have higher emissions per passenger-km than the single 500km route with no stops.

All the route analysis reports, except ATOC, also use a weighted average of individual route load factors. This generates a good estimation of the average load factor operating on that route. ATOC employs a static load factor of 70 per cent, a reasonable figure in line with current high-speed rail lines usages.

The VTT network analysis uses a very large sample of aircraft flights. VTT studies 160,000 flights, separating them in categories by stage length. This produces rigorous results and gives an idea of the current CO_2 emissions per passenger kilometre for that stage length. The average age of the Finnair fleet, the largest used in the study, is 4.7 years, which represents a reasonably new selection of aircraft. The weakness with this method is that it will produce higher estimates due to capturing some older vehicles currently in use and perhaps less popular routes.

When estimating high-speed rail emissions, the CO_2 emissions of energy produced needs to be reasonable. The Commission for Integrated Transport uses figures from the National Atmospheric Emissions Inventory. Network Rail uses the figure of 612g CO_2/kWh and ATOC uses 560g CO_2/kWh. These are all reasonable assumptions, if slightly high.

Overall findings

The rail results from the selected studies suggest high-speed rail in the UK may emit between 40-100g of CO_2 per passenger kilometre. The lower estimates in the broad literature have been removed as many use a mix of French and British energy, which would not be appropriate to understand the trips made on a new British high-speed rail line. These studies CO_2 suggest short-haul aviation produces 150-350g of CO_2 per passenger kilometre.

The results of these selected studies lie roughly in the middle of the estimates of the original collection of studies. This highlights how employing unrealistic assumptions can alter the estimates, producing higher or lower approximations.

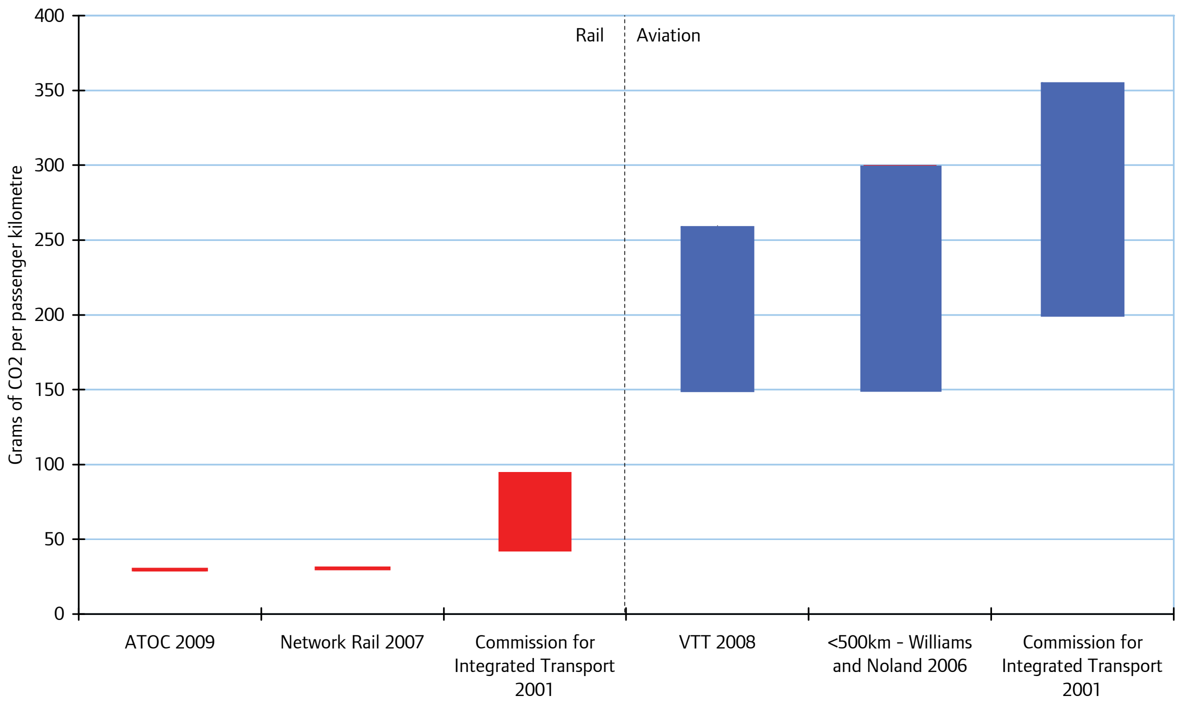
The studies viewing aviation have a far greater range than those examining high-speed rail. The aviation studies display a much higher range in their estimates as the studies view a range of route lengths, and shorter routes generate a far higher emissions estimate. In addition the aviation studies also include different flight paths and models of aircraft, which causes a further degree of variability within the results when viewing specific routes.

The findings of the selected papers confirm that rail travel produces less CO_2 emissions per passenger kilometre than short-haul air travel. But the range of results is far narrower than in the overall spread of literature which suggested air travel could produce as much as seven-times the carbon emissions as rail. This review of the literature concludes that rail travel produces roughly one third of the emissions per passenger kilometre of air travel.

Table 2: Summary of findings of selected papers

Study	Assumptions	Results
VTT - Air Traffic Emissions	Uses 160,000 flights from mainly Finnair, with an average fleet age of 4.7 years. Data from the airlines are based on route-specific observed fuel consumption.	178-259g CO_2/passenger-km <463km - aviation
Commision for Intergated Transport	Average load factor of routes analysed. Uses a weighted average aircraft operating along each route to determine emission levels.	200-355g CO_2/passenger-km - aviation
Victoria Williams	Uses Association of European Airline Traffic report load factor of 65.2%. Twelve aircraft used in the report represents a broad range of modern operating aircraft. Uses CAA top destinations for European, non-European and scheduled domestic flights.	$C0_2$ Per passenger-km <500km ranges from 300g $C0_2$/km to 150g $C0_2$/km - aviation
Network Rail	Load factors weighted average of four different HS routes. Assumes energy produced at 612g $C0_2$/kWh. Uses Class 373 Eurostar as vehicle for the analysis.	30.3g CO_2/passenger-km - high-speed Rail
ATOC analysis for Greengauge 21	Uses a Load factor of 70%. Assumes energy produced at 560g CO_2/kWh. Uses TGV Reseau train as vehicle for the analysis.	29.5 g CO_2/passenger-km - high-speed Rail
Commision for Intergated Transport	Average load factor of routes. Weighted average of types of aircraft along each route to determine emission levels.	42-95g CO_2/passenger-km - high-speed Rail

Figure 4: Range of findings of selected papers, grams of CO_2 per passenger kilometre for rail and short-haul aviation



Source: GLA Economics

Other considerations: infrastructure and emissions at altitude

There are two other factors that affect the carbon emissions of these transport modes but are not currently well quantified and will affect the CO_2 emissions of these modes of transport. These are generally not included in the studies examined. These are the effect of emissions at altitude and the embedded carbon cost of construction of the infrastructure.

The effect of emissions at altitude

Although the effects of emissions are relatively well understood at surface level, there is a lack of understanding of their effects when released higher in the atmosphere but it is thought the impact is higher at altitude. The most common method of accounting for the effects of altitude on the relative effect of CO_2 emissions is the IPCC's radiative forcing index (RFI). This figure multiples the calculated emissions by 2.5 determining a level that is comparable with emissions produced at ground level. Other papers have determined that the RFI may lie between 1.9 - 4.7[15]. This wide range highlights the uncertainty about the exact effects of emissions when released at altitude.

Literature exists discussing the shortcomings of applying such a method to determine CO_2 emissions[16]. There are also discussions on what altitude short-haul flights attain and how this

[15] Grassl, H. & Brockhagen, D. (2007).
[16] Foster, P. M. (2006).

may affect the radiative forcing. More research is required before the environmental effect can be accurately quantified.

Carbon embedded in the construction of infrastructure

Aviation has a relatively small infrastructural cost, whereas high-speed rail has a relatively large one. Constructing a rail network is a very carbon-intensive process and although some papers try to examine the cost of this, there is no conclusive concensus about the environmental impact[17]. These papers suggest that when the cost of the infrastructure is included, the cost of rail may be significantly higher than suggested by its operation emissions alone.

Chester (2009) suggests that including all the construction and regular operations, the CO_2 emissions from rail are increased by 80 to 150 per cent but only by 20 to 30 per cent for aviation. This would significantly reduce the difference in CO_2 emissions between these competing modes of transport. Further research is needed to understand this and to allow the additional costs to be included in the valuation of these modes of transport.

Conclusion

There exists a large body of literature discussing emissions from aviation and high-speed rail. This literature, using a variety of methods, produces a very broad range of results and this paper has analysed the strengths and weaknesses of each. Focusing on papers using a combination of the most appropriate methods and assumptions it is possible to provide a better range of estimates: 40-100g/passenger-km for high-speed rail and 150-350g/passenger-km for aviation. These estimates fall into the middle of the initial sample of studies. This estimate does not take into account two additional factors that could influence the relative CO_2 efficiency; the carbon cost of the infrastructure and the effects of emissions produced at altitude. More research is needed into these areas to enable their inclusion into the estimates.

This paper has shown there is a significant difference between the CO_2 emissions from high-speed rail and aviation. High-speed rail likely produces only around one-third the CO_2 emissions of aviation from operation. The original sample of studies estimated high-speed rail to produce one-seventh the emissions of aviation. It is important policymakers take into account the methods and assumptions used in future reports calculating emissions estimates when devising transport policy.

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