Comparison of the environmental impact from aircraft and high-speed train operation

Moshe Givoni
The Bartlett School of Planning
University College London
Wates House, 22 Gordon Street
London WC1H 0QB, England
m.givoni@ucl.ac.uk

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Abstract

Many studies consider the shift of air services from the aircraft to the High-Speed Train (HST) on short haul routes as a way to reduce the negative impact of aircraft operation on the environment. The purpose of this paper is to test the above statement by performing an empirical comparison between the two modes of transport. The analysis compares two options of travel on the London to Paris route. One option is to use the HST from central London to central Paris, and the other is to travel by aircraft, which includes the journey from (to) the city centre to (from) the airport. The comparison of the two options of travel is made in terms of emission of gases, the environmental impact from the emission, and the social cost of the environmental impact. Two categories will be looked at: the effect on air pollution and on climate change. The results do not point out a clear advantage to one mode over the other in terms of the effect on air pollution, but there is advantage to operating HST in terms of the effect on climate change. The main conclusion from the analysis is that there is still insufficient scientific understanding and certainty to allow for a robust and full environmental comparison between the modes, especially when the comparison is in monetary values. This means that substituting trains for planes on environmental grounds cannot be automatically justified.

Introduction

It is apparent that the air transport industry has an adverse effect on the environment. Its operation is associated with different kinds of health problems according to research and the World Health Organisation (RCEP, 2002; Whitelegg et al, 2001; Grayling, 2001; DETR, 2000a and others). This argument is reinforced with the rise in environmental awareness and as more research is carried out. The main environmental effects of the air transport industry can be divided into three groups. These are: local air pollution, global warming (also referred to as climate change), and noise. Except for climate change the effect is of local magnitude, but since most major airports are located in or close to densely populated areas, it means many people are affected. Despite technological improvements that resulted in reduction of the environmental impact of a given flight (for example, the estimated environmental cost of 1 000 passenger/km of a Boeing-777 is £2.78 while the figure for the older Airbus A310 is £3.17 (DETR, 2000b)), the increase in the number of flights and the number of km flown have resulted in increased environmental degradation from the air transport industry operation. This trend is likely to continue in the future; "the air transport industry is growing faster than we are currently producing and introducing technological and operational advances which reduce the environmental impact at source" (Commission of the European Communities, 2001: 1).

Many studies consider substitution of trains for planes to result in reduced environmental impact from aircraft operation. Often environmental benefits from changing the mode used are the main reason for supporting the shift of services from the air to the rail. For example, the Aviation Environment Federation (AEF, 2000) claims that their study called

From Planes to Trains "shows that there is potential for significant environmental benefits from transferring short haul flights to rail" (AEF, 2000: 3). The study by Whitelegg et al (2001) accepts that High Speed Train (HST) is better than aircraft in terms of the impact on the environment. The IPCC report states that "substitution [of aircraft] by rail and coach could result in the reduction of carbon dioxide emission per passenger-km" (IPCC, 1999: 12). The recent study by the Royal Commission on Environmental Pollution (RCEP) also supports a shift from air to rail, which could "reap considerable environmental benefits" (RCEP, 2002: 33). Therefore, benefits in terms of reduced environmental impact are expected as a result of shifting services from the aircraft to the HST.

The aim of this paper is to investigate whether the above assumption, that substitution of aircraft with HST will result in reduced environmental damage, is correct and to what extent. Against the impact of the air industry on the environment the rail industry impact must be measured. There is no doubt that the operation of any rail services is harming the environment on exactly the same groups identified above. Therefore the question is to try and find which mode's operation causes less impact on the environment. If this is found to be the HST, when compared to the aircraft, then substitution of aircraft by HST should be encouraged, at least on environmental grounds.

Since the opening of the Channel Tunnel rail link between the UK and France it became possible to travel from London to Paris using HST services, and with comparable travel times city-centre to city centre. The distance between the cities as well as high demand for services between the cities makes it a good route for mode change. The effect on the environment if mode change will occur on this route is at the centre of the paper.

Previous analysis showed that it is almost impossible to compare the two modes in terms of noise pollution, and to quantify the noise generated and the noise nuisance caused by one flight in comparison with one HST service (Givoni, 2002a). When comparisons are made between the two modes it is usually in regard to the overall operations, not a single flight or a single train service. The units used are usually the number of people around airports, and under the aircraft flight path exposed to aircraft noise compared with the number of people along the rail route exposed to train noise. Since not all aircraft services are expected to be transferred to the HST the noise impact of one flight needs to be compared with the noise impact from one HST service. Evaluating the difference in noise pollution around an airport if one flight is transferred to the HST is almost impossible and it is outside the scope of this paper. Therefore the analysis in this paper will look on the differences in environmental damage caused by HST and aircraft operation in terms of air pollution and climate change only.

The next part of the paper describes the methodology to evaluate the impact of transport operation on the environment, and the special aspects that need to be considered when evaluating aircraft operation. Then the methodology used in this paper, and the case study used will be described. After that the results will be presented and discussed. Finally implications for other routes and conclusions will be drawn.

Evaluating the impact of HST and aircraft operation on the environment

In order to evaluate the impact of transport operation on the environment a certain pathway (outlined in Figure 1) should be followed. The first step/requirement is to know and measure the level of transport activity (mode used, types of vehicles, frequency, energy consumption, passenger and/or freight carried, etc.). This is the only precise step in the sequence shown in Figure 1, from this point as we proceed down the pathways we lose scientific understanding and we add subjectivity into the analysis as a result of the different assumptions we make. The next step is to measure the emission emitted during the journey. This task depends on the scientific knowledge of the relationship between energy sources used, amount of energy consumed, and the resulting emission. In the case of fossil fuels the temperature at which combustion occurs is an important factor determining the emission profile, which adds another obstacle for accurate estimation of emission. Measuring just emission is not enough because of the differences in the effect each pollutant inflicts on the environment, which depends on the pollutant character, its source and its ambient concentration (Colvile et al, 2001).

The next step therefore, measuring ambient conditions, is vital for accurate estimation of environmental impact. To be able to screen the effect of transport emission on the environment from the overall existing environmental conditions (the natural existence of gases in the air plus gases resulting from other human activities) the ambient conditions of the pollutant in question must be considered. If the ambient concentration of a specific pollutant is very high then emission of this pollutant from transport is not likely to increase the environmental impact. Ambient conditions are changing constantly due to weather conditions (mainly wind and precipitation), making it almost impossible to determine the ambient conditions when emission occurs. Indeed, most empirical studies trying to measure the impact of emission on the environment skip this step.

The next step in the pathway is to define the effects any pollutant has on the environment, the dose-response or source-receptor relationship. On top of the scientific limitation in establishing the exact effect each pollutant has on the environment in general, and on human health in particular, there exists the limitation in measuring and quantifying those effects and attributing the effects observed to a specific pollutant. Environment impact is usually measured in terms of the effect on human mortality and morbidity although emission can effect habitats, vegetation and wildlife as well. To determine or measure how many more people will be admitted to hospital because of increase in SO_2 from transport, for example, is neither an easy nor an accurate task. Yet, such estimates and measurements are done constantly and provide estimates of environmental impact from transport operations.

Comparing different impacts of transport operation e.g. noise and NOx emission is like, in economists jargon, 'adding apples and oranges'. Because aircraft can produce noise and emit NOx a common denominator for all affects on the environment needs to be found. This is usually the monetary value of the impact, the cost of damage (real and perceived) caused by transport. It seems sometimes this is the ultimate goal when trying to evaluate the effect human activities has on the environment since it brings all the effects on the environment, together with other outcomes of human activities, to a common basis. But, as noted above, the further we go down the pathway to arrive at monetary quantification of the environmental damage caused, the less accurate and robust our results and analysis become. In the former stage, when considering the impact air pollution has on human health, we had to accept the scientific uncertainty whether the effect described is really the result of the assumed pollutant and the objective difficulties in measuring the effect. Now we are adding to our analysis the subjectivity associated with estimating the value of, for example, air pollution and its effects, which are measured through peoples' perception of the damage caused and their willingness to pay to avoid or repair this damage. Daniels et al (2000) provide a detailed description of environmental evaluation methods.

The methodology described above can be used for any mode of transport, but for aircraft operation attention must be given to the altitude at which emission occur. While emission from any other mode of transport occurs at ground level, emission from aircraft operation occurs mainly at higher altitudes and this has influence on the impact from aircraft emission.

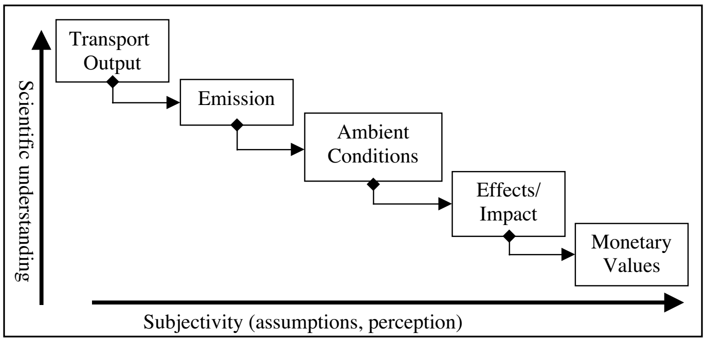

Figure 1: *Steps in evaluating transport impact on the environment*
Source: Based on Schipper (2000).

THE EFFECT OF AIRCRAFT OPERATION ON THE ENVIRONMENT

The difference in the atmosphere elements at different altitudes means that aircraft emission emitted above ground level has different impact on the environment than aircraft and other modes' emission emitted at ground level. When aircraft operation is considered three different parts of the atmosphere are included: ground level, the troposphere (lower atmosphere), and the stratosphere (upper atmosphere) (Figure 2). For the effect of aircraft emission on air pollution, a local phenomenon, only emission occurring within the ground level are considered while for the effect of aircraft emission on climate change the entire sky is considered.

The ground level part of the atmosphere, the one considered for the analysis of air pollution, is up to 915 m. Above that it is assumed that emission cannot affect human health on the ground. Above the ground level, the troposphere is considered up to about 12 km at mid latitudes (8 km at the Polar regions and 16 km in the tropics (Archer, 1993)), and above that is the stratosphere. Most aircraft cruise at an altitude of between 10 to 12 km, i.e. at the boundary between the troposphere and the stratosphere, called the tropopause. Most subsonic aircraft will probably not reach the stratosphere during cruise, and during short haul flights of less than 90 minutes aircraft are unlikely to reach even the troposphere limit.

To evaluate the impact aircraft operation has on air pollution the Landing Take-Off (LTO) cycle is considered. The LTO cycle consists of 5 different stages; it begins when the aircraft descends from cruising altitude and approaches and lands at the airport. The second step in the landing portion of the cycle is taxiing to the gate and subsequent idle. The next three steps are the three operating modes in the take-off portion of the cycle: taxi-out/idle, take-off and climb-out. During each mode the engine operates at different thrust (power), which results in different profile and quantity of emission. The engine power used for each mode and the time the aircraft spend at each mode are considered when measuring emission from aircraft during the LTO cycle. The altitude boundary for the LTO cycle is determined by the height of the 'mixing zone'. "The mixing zone is the layer of the earth's atmosphere where chemical reactions of pollutants can ultimately affect ground level pollutant concentrations. The height of the mixing zone for a given [airport] location varies significantly by season and time of day" (EPA, 1999: 2-8).

The standard, set by the ICAO, is to consider aircraft emission at flight level of under 915 m (3000 ft) (Archer, 1993). With the mixing zone set at a height of 915 m the custom is to assume take-off time of 0.7 minutes, climb-out of 2.2 minutes and approach and landing of 4 minutes (Archer, 1993). The last two depends on the height of the mixing zone and the flight procedure adopted by the pilots. To complete an LTO cycle 19 minutes of taxiing and idling (with engine on) are assumed before take-off and 7 minutes after landing (Archer, 1993), this of course will vary between airports mainly due to the congestion levels at each specific airport.

"The five major air pollutant species which comprise the most significant emission from commercial jet aircraft are Volatile Organic Compounds [VOC], Carbon Monoxide [CO], Oxides of Nitrogen [NOx], Particulates [PM], and Sulfar Dioxide [SO_2]" (EPA, 1999: 2-1). The emission of these pollutants from aircraft during the LTO cycle need to be compared with the emission of these pollutants from the operation of HST services. The literature does not always distinguish between VOC and Hydrocarbons (HC), for example in the EPA study it says "organic chemicals emitted into the atmosphere are typically described as VOCs (or "hydrocarbons")" (EPA, 1999: A-5). Therefore HC and VOC will be treated as the same pollutant in this study.

The main effects of the pollutants described above are as follow:

Nitrogen Oxides (NOx): NOx affect human mortality and morbidity through three separate channels: as NO_2 directly, as ammonium nitrate (a component of PM_{10}) and through a secondary reaction with VOCs resulting in the formation of Ozone, which affect climate change (Maddison et al, 1996). NOx affect lung function, and may harm immune system

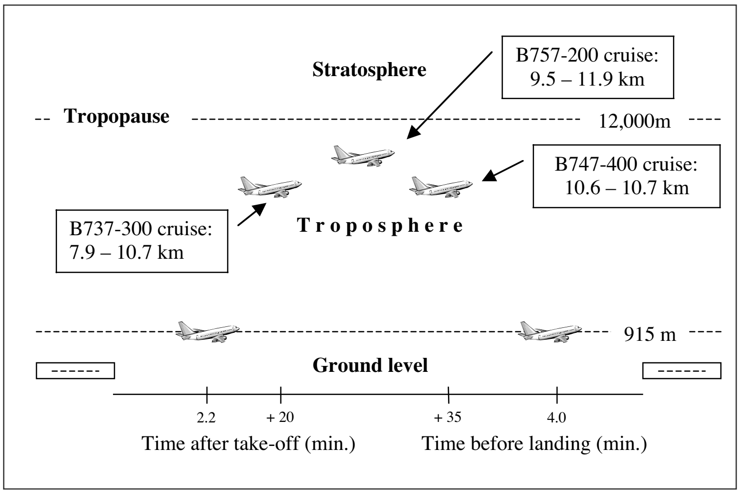

Figure 2: *Illustration of the atmosphere layers and aircraft's flight and cruise altitude. Source: compiled by author.*

cells, increase susceptibility to infection and aggravate asthma (Whitelegg et al, 2001).

Sulphur Oxide (SOx): SO_2 can affect human health through two main channels, directly as SO_2 concentrations and through its oxidation in the atmosphere to form small particulate matter (PM). Emissions of this colourless, although strong smelling, gas can result in bronchitis and other diseases of the respiratory system. Coal fired electricity generation is a major source of this gas as well as diesel fuel (Button, 1993).

Particulate Matter (PM_{10}): Often referred to as small particulate matter these are solid and liquid particles in the air of under 10-micron diameter. Evidence exist that link PM_{10} and premature mortality and morbidity (Maddison et al, 1996). Particulates are associated with a wide range of respiratory symptoms including coughs, colds, phlegm, sinusitis, shortness of breath and more (Whitelegg et al, 2001). In some of the studies discussed in this paper the term aerosols (or Aer.) is used and this will be considered as PM for the analysis.

Carbon Monoxide (CO): CO can have detrimental effects on health because it interferes with the absorption of Oxygen by red blood cells. This may lead to increased morbidity. CO is especially a problem in urban areas where synergistic effects with other pollutants means it contributes to photochemical smog and surface Ozone (O_3). CO emissions result from incomplete combustion and some 90% of all CO emissions originate from the transport sector (Button, 1993).

Hydrocarbon (HC): HC is an organic compound that contains the elements of carbon and hydrogen only. Benzene, the simplest member of the class is a known carcinogen, causing leukaemia (TEST, 1991).

Volatile Organic Compounds (VOC): These comprise a wide variety of hydrocarbons and other substances. They generally result from incomplete combustion of fossil fuel. Besides respiratory problems some of the compounds are suspected of being carcinogenic (Button, 1993).

To evaluate the impact of aircraft operation on climate change the entire flight, from the moment the engines are turned on until they are turned off, needs to be considered. The term 'Climate change' (also called greenhouse effect) refers usually to the increase in ambient concentration of certain gases, the Greenhouse Gases (GHGs), as a consequence of human activities that has lead to an increase in the earth temperature and subsequently climate change. The IPCC Second Assessment Report from 1995 states that "increases in greenhouse gas concentrations since pre-industrial times (i.e., since about 1750) have led to a positive radiative forcing[1] of climate, tending to warm the surface of the Earth and produce other changes of climate" (IPCC, 1999: 4). Climate change is a global phenomenon and there is no direct relation between the location of emission and location of the effect, although emission, especially from aircraft, can have a regional effect on climate. An important distinction relating to location of emission is the altitude at which emission occurs.

The main GHGs emitted from the operation of aircraft and HST are Carbon Dioxide (CO_2), Oxides of Nitrogen (NOx), Water Vapour (H_20), and Sulphate and soot aerosols. Ozone (O_3) is another, very important, GHG but it is not emitted by transport operations. It is created and depleted by other pollutants emitted from transport operations, and it is almost impossible to measure the amount of O_3 created as a result of a flight or HST service. In addition, the direct radiative forcing of Sulphate and soot aerosols from aircraft is small compared to those of other aircraft emission, and the aerosol mass concentrations, in 1992, resulting from aircraft are small relative to those caused by surface sources (IPCC, 1999). These pollutants will not be included in the analysis of climate change.

"Water is the most powerful of the GHGs…[and] is the most plentiful exhaust species to be emitted from jet engines" (Archer, 1993: 71). But, the effect emission of H_2O has on climate change depends on the altitude at which emission occurs. At lower altitudes concentrations and impacts of H_2O are largely determined internally within the climate system and are not significantly affected by human sources. Archer (1993) considers lower altitudes, where the effect of H_2O emission on climate change is negligible, to be up to 9 km. The distinction made by the IPCC (1999) is that water vapour emission in the troposphere, where most subsonic aircraft water vapour emission are released, will be removed by precipitation within 1 to 2 weeks, and the RCEP (2002) states that "in the troposphere the amount of water vapour emitted in aircraft exhaust is negligible compared with the pre-existing concentrations in the atmosphere" (RCEP, 2002: 12). Since aircraft on short haul flight are not expected to reach an altitude where H_2O emission affects climate change, the effect of water vapour emission from aircraft on climate change should not be included in this analysis.

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1. Radiative forcing is "a measure of the importance of a potential climate change mechanism. It expresses the perturbation or change to the energy balance of the Earth-atmosphere system in watts per square meter (Wm-2). Positive values of radiative forcing imply a net warming, while negative values imply cooling" (IPCC, 1999: 3).

In some circumstances emission of water vapour from aircraft at the troposphere can lead to the creation of condensation trails (contrails) and sometime, as a result, to the formation of cirrus clouds. This phenomenon is believed to contribute to climate change (RCEP, 2002; IPCC 1999). Considering the short flying times and even shorter time at high altitudes, and that the warmest possible temperature at which a given aircraft will produce a contrail is in the region of -40^{0}C at cruise altitudes (Williams et. al. 2002), the formation of contrails if they exist are not likely to significantly contribute to climate change during short haul flights.

The above means that the analysis of aircraft and HST operation impact on climate change will focus on emission of CO_2 and NOx. In the next section the methodology used to evaluate and compare the environmental impact of HST and aircraft operation on the case study route will be outlined.

Evaluating the environmental impact of HST and aircraft operation on the Paris-London route

The methodology adopted in this paper will be to compare the modes in terms of air pollution and climate change by measuring and comparing emission, the impact on the environment, and the cost of the impact on the route from London to Paris.

Because of the different seat capacity offered by each mode they cannot be compared in terms of emission per one trip. Instead, units of emission per passenger on the route or emission per seat offered on the route should be used. Whether the units chosen are seats or passengers assumptions must be made concerning the services' passenger load factor (LF). When considering the operation of transport services the amount of emission is directly related to the capacity (seats) offered. The amount of capacity offered is related to passengers' demand for services but the relationship is not straightforward and it depends on many factors. Therefore, it is considered more appropriate to use units of emission per seat offered on the route by each mode rather than units of emission per passenger. It is acknowledged that given the lower LF usually achieved by HST compared to aircraft services together with the higher capacity offered on board the HST choosing units of seat rather than passenger will give advantage to the HST. But, by using these units the potential of the HST in reducing the environmental impact from aircraft operation is represented.

The comparison in this paper is between two options of travel on the route London city centre to Paris city centre. One option is using the aircraft, the other is using the HST. While the HST stations, Waterloo (and St. Pancras in the future) in London and Gare de Nord in Paris, are located in the city centre the airports, Heathrow (LHR) in London and Charles de Gaulle (CDG) in Paris are located in the city outskirts. Therefore the journey by air must also include the journey from the city centre to the airport (London to LHR), the access journey, and the journey from the destination airport to the destination city centre (CDG to Paris), the egress journey.

The emission that occurs during the journey to the airport and from the airport will be added to the emission from the flight to arrive at the total emission when choosing to travel by air. To keep the analysis in consistent the same units, emission per seat, were used for the access and egress journeys. The majority of journeys to and from the airport are made by car, 65% at LHR (Watkiss et al, 2001), and 69% at CDG (TCRP, 2000). For this mode a capacity of four seats is considered (representing the vehicle potential, although sensitivity tests will be made assuming the car offers one seat and not four). The rest of the journeys to and from the airport are made by public transport. Emission from bus was measured for that mode, assuming seat capacity of 70. Considering the modal split between the car and public transport at LHR and CDG and each mode emission, the emission per seat was calculated for the access journey to LHR and egress journey from CDG. Including in the analysis also metro, light rail, and rail services to get to/from the airport would probably result in lower emission (mainly due to higher capacities of these modes), but considering the dominance of the car on these journeys it was unlikely to significantly effect the results.

The first basis for comparison between the two options of journey is in emission per seat supplied on the route. Because of the different affect each gas has on air pollution and climate change summing the total emission across the different gases has no meaning; so the impact of each gas must be considered, and this will be the second basis for comparison. For the analysis of air pollution the toxicity factor of the gases, used by Quinet (1994), is considered as the common denominator that allows to sum together the effect of the different pollutant emitted during the journey, and allows a meaningful comparison between the modes. For the climate change analysis units of CO_2 equivalent are considered as the common denominator. The third basis of comparison is the cost of the damage caused by emission, which occur during the journey. Lu and Morrell (2001) collected and compared monetary values assigned to the damage caused by emission of pollutants from different studies, and since "the monetary evaluation of the damages is still uncertain (reflected in the wide range of monetary impacts), the unit social cost estimates for each pollutant have been averaged across all the studies" (Lu and Morrell, 2001: 382). This average social cost will be used to evaluate air pollution. Because there is no information to determine which of the studies is better or more robust using the average across the studies seems the least unfavourable option. For the cost of climate change caused through emission of HST and aircraft two different cost estimates were used.

Before moving to present the results it is important to remember the decreasing scientific understanding and increasing subjectivity as we move from comparing the modes in terms of emission to comparison in terms of impact, and finally in terms of cost.

Results

AIR POLLUTION

A study by the EPA (1999) provides emission rates of HC, CO, NOx and SO_2 during the different LTO stages for dif-

Table 1: Emission of pollutants by different modes on the Paris-London route (gram/seat).

	HC	CO	NOx	SO_2	PM_{10}
Aircraft (B737)	5.27	93.57	65.82	3.55	0.013
Access/Egress (Car = 4 seats)	14.47	87.84	10.82	0.16	0.34
Total Air journey	19.75	181.40	76.65	3.72	0.35
HST journey (40% LF)	0.40	0.99	14.03	24.50	8.69*

*Source: based on EPA (1999), Watkiss et al (2001), Quinet (1994). *Aerosols*

Table 2: The impact from air pollution caused by HST and aircraft journeys (toxicity factor)

	HC (CxHx)	CO	NOx	SO_2	PM_{10}	Total
Toxicity factor	100	1	125	100	100	
Aircraft	527	94	8 228	355	1	9 205
Access/Egress	1 447	88	1 353	16	34	2 938
Total Air journey	1 975	182	9 581	372	35	12 144
HST journey	40	1	1 754	2 450	869	5 114

Source: based on Quinet (1994) and Table 1.

ferent types of aircraft, and these are used in this analysis. For aircraft PM_{10} emission[2] and the access/egress journey emission, estimates given by Watkiss et al (2001) are used. For the HST mode emission, estimates given by Quinet (1994) are used. The estimates for the HST are given in units of gram per passenger km, and since this study uses units of seats the HST LF had to be assumed to allow conversion of passenger units to seat units. The amount of pollutants emitted during a journey from London to Paris when choosing the aircraft and when choosing the HST as the main mode of travel is shown in Table 1.

Considering the aircraft option alone the results show that the access/egress part of the journey is important and in some pollutants contribute more emission than the flight alone. Considering the two options of travel, offering a seat on board the HST results in less emission across all gases except for emission of SO_2. Although the total amount of emission emitted by each mode can be calculated, this is avoided since it does not mean anything and it will be misleading due to the different affect on air pollution each gas has.

Instead, the impact on the environment from the emission of these gases is considered in Table 2 using the gases toxicity factor. Looking on the aircraft option of travel first, the results show that the actual flight is potentially more damaging to the environment than the access/egress journey considering the amount and mix of gases emitted and their toxicity. The higher emission rate of NOx is the main contributor to aircraft operation impact on air pollution. When comparing the two options of travel in terms of impact on air pollution the journey by HST causes less air pollution mainly due to lower emission rates of HC and NOx. But, the HST is responsible for more air pollution caused by SO_2 and Aerosols emission. Even when considering the aircraft alone, in comparison to the HST's impact on air pollution, the latter has a clear advantage.

The results for the aircraft depends on the type of aircraft used, this was the B737-300 the most common narrow body aircraft in the world (IATA, 2001). During Autumn 2001 the most common aircraft on the route LHR-CDG was the A320 (BAA, 2001). Using this type of aircraft reduces the air pollution caused by the flight by about 10%, to 8 209 units of toxicity; not a substantial difference. When considering that most car journeys are with one passenger or in the case of journeys to/from airports with a driver plus a passenger considering the car capacity to be four seats might be misleading. If assuming that the car offers only one seat and accounting for the modal split at LHR and CDG airports the impact on air pollution from the access/egress journey increases by over 250% to 10 506 units of toxicity. This further increases the HST advantage. If assuming a 50% LF for the HST, instead of 40%[3], the toxicity factor of the HST journey rise by almost 25% to 6 392 units of toxicity, but this does not change the overall conclusion from Table 2.

The last comparison between the two options of travel is in terms of the cost of damage caused by air pollution from the journey. Table 3 shows that when considering the social costs caused by air pollution the aircraft is actually a better option of travelling. This is a surprising result since it was expected that the higher toxicity of emission from the aircraft journey will be translated into higher cost of damage. The reason for the difference is the high cost estimate for

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[2] The Watkiss et al (2001) study provides surface emission rates (i.e. emission during the LTO) for different domestic routes in the UK, together with the mix of aircraft types operating on the route and their seat capacity. Considering the London-Leeds route (where 89% of the aircraft were B737 and the other 11% were Fokker 100) and the distance between the cities the given estimate of emission/km was converted into emission/LTO and then emission/seat.

[3] Emission from the HST are not assumed to change with the load factor. But because the calculations are based on an estimate of emission per passenger-kilometre, load factor had to be assumed to convert this estimate into emission per seat.

Table 3: The cost of damage caused by air pollution from HST and aircraft journeys (Euro/seat).

	HC	CO	NOx	SO_2	PM_{10}	Total
Euro/kg emission	3.29	0.06	9.12	48.74	106.1*	
Aircraft	0.017	0.006	0.600	0.173	0.001	0.798
Access/Egress	0.048	0.005	0.099	0.008	0.036	0.196
Total Air journey	0.065	0.011	0.699	0.181	0.037	0.993
HST journey	0.001	< 0.001	0.128	1.194	0.922	2.246

*Source: based on Lu and Morrell (2001), Table 1 and *Mayers et al (1996).*

emission of SO_2, which is much higher than the toxicity factor of SO_2 in relation to other pollutants. Figure 1 suggested that as we go down the path of evaluating environmental impact from transport operation we lose scientific understanding and we increase subjectivity; this suggests that the results in Table 2 have more scientific understanding and less subjectivity than the results in Table 3.

The results in Table 3 show that for every seat offered on board the HST, and not on board the aircraft, the extra damage caused from air pollution is worth 1.25 Euro. The results are not very sensitive to aircraft type (12% reduction in the cost/seat for the A320 to 0.699 Euro) but are sensitive to the assumption on car capacity. When assuming the car offers one seat the cost of access/egress journey increases by more than three times, from 0.196 Euro to 0.663 Euro. This raises the cost of air pollution from the whole air journey to 1.362 Euro. When increasing the HST LF to 50% the cost estimate rises to 2.808 Euro, an increase of 25%.

In conclusion, the above analysis did not indicate any clear advantage to one option of travel over the other. The conclusion mainly depends on the units of comparison chosen. Because of the different affects different pollutants have on air pollution it is not enough to measure the amount of gases emitted by each option of travel. When comparing the modes in terms of the toxicity of the gases, which assumed to indicate the potential level of air pollution they are likely to cause, the journey by HST is a better option. However, when considering the cost of the damage caused by air pollution the results show that the journey by aircraft should be preferred. The conclusion will not change if the access/egress part of the air journey is ignored, but the results actually point out the importance of adding the journey to/from airport to the analysis. This journey contribution to air pollution is significant, and in some pollutants it is responsible for more air pollution than the whole journey by HST.

The results shown above did not allow a conclusion to be reached regarding the preferred option of travel, but they indicated that the focus in attempting to do that should be on two gases: NOx and SO_2 and their effect on air pollution. The evidence is ambiguous and do not always support the much higher cost estimate for SO_2 emission used in Table 3. A study by Calthrop from 1995 cited in Maddison et al (1996) found the number of premature mortalities per year attributed to SOx emission to be 1 880 while the number attributed to NOx emission was 2 000. A study by Pearce from 1994 cited in Perl et al (1997) calculated that the direct damages in the UK from NOx emission are 240 Euro/ton and from SO_2 280 Euro/ton. In Perl et al (1997) a study by Crozet from 1994 was cited which stated that direct estimation of minimal damage cost for NOx and SO_2 in France were: 2 041 and 2 094 Euro/ton respectively which can be considered as almost equal. In addition, Table 2 indicated that NOx emission is more toxic than SO_2 emission. In contrast to the above, all the four studies used to calculate the monetary value of NOx and SO_2 used in Table 3 found the cost of damage caused by SOx emission to be higher than the damage caused by emission of the other pollutants including NOx. It seems more research is required on this matter.

The air pollution caused by aircraft operation is determined, amongst other things, by the height of the mixing zone. This was set at 915 m according to ICAO estimation, but it might change from one airport to another. If the mixing zone limit is higher or lower it will change the amount of emission included in the climb-out and approach stages of the LTO cycle, but will not change the emission during the other stages. Emission of HC, CO and SO_2 during climb-out and approach stages amounted to 4%, 6% and 45% respectively of the total emission of these gases during the LTO cycle (for a B737). But considering the relatively small impact of these gases on air pollution together with the relatively small change in emission if the mixing height is changed, the results are not likely to be sensitive to changes in the mixing zone height. However, emission of NOx, found to have the most impact on air pollution, during the climb-out and approach stages amount to 62% of NOx emission during the LTO cycle. If the mixing zone will be only half, set at 450 m, NOx emission that affect air pollution will be reduced by more than 20 grams, or 2 550 units of toxicity, or 0.186 Euro per seat. Although this is not enough to change the conclusion, the reduction in the toxicity factor and the cost is almost the same as the impact and cost of the access/egress journey. The above shows that the results are to some extent sensitive to the assumption on the height of the mixing zone.

Air pollution is determined by where emission occurs as much as by how much emission occurs. Therefore for this study a comparison is needed between the number of people exposed to emission around airports and emission that occurs from the journeys to/from the airport, on one hand, and the number of people exposed to emission from power stations (assuming they are the main source of energy supply for HST), on the other hand. Such an analysis is beyond the scope of this paper and such a comparison between the modes was not found. It might be assumed that airports are built closer to populated areas than power plants. Also,

Table 4: Aircraft and HST emission of GHG on the London-Paris route (gram/seat).

	NOx	CO_2
Aircraft (B737)	326.74	35 901
Access/Egress (Car=4 seats)	10.82	1 610
Total Air journey	337.57	37 511
HST journey (40% LF)	14.03	5 711

Source: based on Archer (1993), EPA (1999), Watkiss et al (2001), Quinet (1994).

while most of the emission from aircraft operation (and emission from travelling from the airport to the city centre) is at ground level, emission from power plants is higher in the sky. Power plants' stacks are usually tens of meters high and can reach 200m or even 300m. All this suggests an advantage to the HST that cannot be quantified within the scope of this paper.

CLIMATE CHANGE

To evaluate the impact a flight has on climate change, the whole flight, from the moment the engines are turned on until they are turned off, must be considered. According to the flights timetable (BAA, 2001) it is assumed that a flight from LHR to CDG takes 65 minutes. The LTO cycle is assumed to take 33 minutes, which leaves 32 minutes of flight that are divided between climb mode and descent (approach) mode. On such a short flight the aircraft is not expected to reach cruise height (7.9-10.6 km for the B737 (Archer, 1993)) but will climb until required to start the descent for landing. Based on fuel consumption estimation for each mode, and CO_2 emission rate of 2 950 grams per kg of fuel consumed, given by Archer (1993), the emission rate of CO_2 was calculated. For NOx emission estimates for the B737 given by the EPA (1999) study for climb and approach are used. For the access/egress journey emission estimates in Watkiss et al (2001) are used, and for the HST mode emission estimates given by Quinet (1994) are used.

Table 4 shows the amount of NOx and CO_2 gases emitted during the journey from London to Paris. In both gases the journey by air results in more emission. The emission that occurs during the journey to/from the airport are almost negligible in comparison to the emission during the flight. However, in comparison with the HST journey the amount of emission during the access/egress journey is significant. Table 4 also points out the clear advantage the HST has in terms of GHG emission over the aircraft. Because the HST option results in less emission in both the gases measured, it can be concluded that it is a better option of travel from the aspect of effect on climate change. For a better evaluation of the difference between the two options of travel the impact caused by the gases must be compared. Even when assuming that the car provides only one seat and not four seats, the emission from the journey to/from the airport is small compared to the emission during the flight. But assuming the car provides only one seat results in the journey to/from the airport being responsible to more emission of NOx (34.6 gram/seat) than the whole journey London-Paris by HST, and about the same emission of CO_2 (5 695 gram/seat on the journey to/from the airport). This does not hold when assuming 50% LF for the HST, in that case NOx emission is 17.54 grams and CO_2 7 138 grams.

CO_2 emission have in general the same effect wherever they are emitted, this combined with the fact that the emission of CO_2 is directly related to the amount of fuel consumed makes it easy and accurate to measure compared to other gases. This is not the case with NOx emission. The impact of NOx emission on climate change depends on the altitude at which emission occurs. “The global warming impact of NOx from aircraft is enhanced relative to ground-level emission of NOx. This is due to much of the NOx being injected into the troposphere at the height where it has most impact on global warming. Ground-level emission of NOx and subsequent greenhouse gases are largely removed by chemical reactions before they reach this level” (Archer, 1993: 63).

There are different estimates of the impact of NOx emission on climate change relative to the impact from the same amount emitted at ground level and the same amount of CO_2 emission. Maddison et al (1996) defines the Global Warming Potential (GWP) of a gas which allows us to compare the impact of different gases on climate change. The GWP is the immediate impact of the gas integrated over their lifetime residency in the atmosphere. The immediate impact of a gas is defined as the product of its increase in atmospheric concentrations multiplied by the increase in radiative forcing per unit of concentration. GWPs are expressed relative to that of CO_2, which is given a GWP of unity. NOx GWP is 270. Archer (1993) summarizes different studies that quantify the differences in NOx and CO_2 emission impact on climate change. Egli estimated that at cruising height NOx stays in the atmosphere about one hundred times longer than at ground level. Johnson and Henshaw estimated that aircraft NOx emission produce about thirty times more change in the ozone inventory than an equivalent change in man-made surface NOx emission. Archer (1993) also writes that according to the IPCC and the UK DoE, NO_2, through its production of Ozone (O_3), has on average 150-160 times the global warming effect of CO_2. The only estimates of the impact of NOx emission at altitude compared to NOx emission at ground level and compared to CO_2 emission, is given by an ETSU study which estimates that “one gram of NO_2 has three times as potent a greenhouse effect at ground level as the same amount of CO_2, and in the upper atmosphere 335 times the effect.” (Archer, 1993: 64). This estimate is used in the analysis to compare between the two options of travel in terms of relative impact on climate change; the results are shown in Table 5. Given the range of estimates quoted above and the degree they vary Table 5 should be regarded as an illustration of the dif-

Table 5: NOx and CO_2 emission impact on climate change (CO_2 equivalent units*/seat).

	NOx	CO_2	Total
Aircraft LTO	197	9 772	9 969
Aircraft (climb + descent)	87 408	26 130	113 537
Access/Egress	32	1 610	1 642
Total Air journey	87 638	37 511	125 149
HST journey	42	5 711	5 753

** 1 gram NOx at ground level = 3 grams CO_2, 1 gram NOx above ground level = 335 grams CO_2.*
Source: based on Archer (1993) and Table 4.

Table 6: The cost of HST and aircraft journeys impact on climate change (Euro/seat).

Study	Eyre et al			DETR		
	NOx	CO_2	Total	NOx	CO_2	Total
Euro/kg emission	0.97*	0.01		3.9	0.09	
Aircraft	0.317	0.359	0.676	1.274	3.231	4.505
Access/Egress	0.010	0.016	0.027	0.042	0.145	0.187
Total Air journey	0.327	0.375	0.703	1.317	3.376	4.693
HST journey	0.014	0.057	0.071	0.055	0.514	0.569

*Source: based on Lu and Morrell (2001), DETR (2000b), and Table 4. * refers to N_2O.*

ferences between the two options of travel. There is no evidence to suggest that these estimates are better than the other estimates nor is it possible to infer the robustness of the estimated used here. Because of the difference NOx emission at ground level and high altitude has on climate change the emission from aircraft had to be divided to emission during the LTO cycle (emission at ground level) and emission during the rest of the flight.

The results in Table 5 show, as expected, the advantage of the HST option of travel over the aircraft option of travel. The impact on climate change from a journey by air is more than 20 times the impact of a journey by HST. Compared to the aircraft operation impact on climate change the impact on climate change from the HST and from the access/egress journey is negligible. The results also indicate that to reduce the impact of aircraft operation on climate change it is more important to reduce aircraft NOx emission than CO_2 emission.

The cost of the damage caused by climate change as a result of every seat offered on the route London-Paris is presented in Table 6. Two different estimates were used in the analysis; one from a study by Eyre et al quoted in Lu and Morrell (2001) and one from a DETR (2000b) study. The two studies differ greatly in the cost estimates. When using the cost estimate of Eyre et al every seat offered on board the aircraft and not on board the HST results in 0.632 Euro higher costs of damage from climate change. When using the DETR estimates the difference between the two options of travel is more substantial and amounts to 4.124 Euro for every seat offered on the aircraft and not on board the HST. The results in Table 6 suggest, unlike Table 5, that emission of CO_2 causes more damage and is responsible for more impact on climate change.

In conclusion, the analysis on climate change showed that HST is a better option. This was shown in terms of the quantity of GHG emitted, their impact measured in CO_2 equivalent units, and the cost of damage caused by climate change from emission of the GHG. The surface journey to/from the airport was not as significant in contributing to the impact on climate change, as was the case in the analysis of air pollution. Also, assuming that the car seat capacity is one and changing the HST LF would not have affected the results significantly.

Although the analysis quantifies the different impact each mode has on climate change those figures should be considered with caution and are better used for illustration purposes because of the uncertainty concerning not only the cost of the damage caused by climate change but even in the understanding of the way climate is changing by emission of GHG and mainly NOx.

AIR POLLUTION AND CLIMATE CHANGE

To compare between the environmental damage caused by each option of travel the damage caused as a result of air pollution and climate change must be brought together. The only possible way to do this in this analysis is by summing the costs figures given in Tables 3 and 6. The results are shown in Table 7 for the two different cost estimates used to measure the cost of climate change. Even when ignoring the limitations of using monetary values to assess the impact of transport operation on the environment there is no clear answer to the question of which option of travel is environmentally better. Using the HST rather than the aircraft will result in more damage from air pollution but less damage in terms of climate change. Overall, if using the low cost estimate for climate change impact the air option of travel is better, and when using the high estimate for climate change impact the HST is a better option.

In 2001, 21 815 flights were recorded between LHR and CDG airports (CODA, 2002). If all the flights were served by B737 (128 seats) a total of over 2.79 million seats were offered on the route. Providing 2.79 million seats between

Table 7: The cost of environmental damage from travelling on the London-Paris route (Euro/seat).

	Air pollution	Climate change (low)	Total		Air pollution	Climate change (high)	Total
Aircraft	0.80	0.68	1.47		0.80	4.51	5.30
Access/Egress	0.20	0.03	0.22		0.20	0.19	0.38
Total Air journey	0.99	0.70	1.70		0.99	4.69	5.69
HST journey	2.25	0.07	2.32		2.25	0.57	2.81

Source: based on Tables 3 and 6.

Table 8: Environmental cost/benefit from shifting aircraft services between LHR and CDG to the HST in 2001 (Million Euro).

	Air pollution	Climate change (low)	Total		Air pollution	Climate change (high)	Total
Cost difference	+3.5	-1.8	+1.7		+3.5	-11.5	-8.0

Source: based on Tables 3 and 6.

London and Paris on board the HST and not the aircraft will result in an increase in air pollution worth over 3.5 million Euro, and a decrease in damage from climate change worth 1.8 million Euro if using the low cost estimate, and 11.5 million Euro if using the high cost estimate for climate change (Table 8). When considering both air pollution and climate change the change in mode used will result in decreased environmental damage of 8 million Euro when using the higher estimate for climate change. This decrease is unlikely to support or justify the investments required, for example, to provide an HST link to LHR airport. However, adopting the lower cost estimate for climate change will increase the environmental damage from replacing the aircraft by HST by 1.7 millions Euro.

On 3 November 2002 the prices for travelling between London and Paris[4] were 94.4 Euro for using Eurostar's HST services (no taxes included in the price), while flying between the cities with British Airways (BA) (from LHR to CDG) cost 110.1 Euro (65.6 fare plus 44.5 taxes). The cheapest flight available was with Easy-Jet from Luton airport to CDG for 55.6 Euro (26.1 fare plus 29.5 taxes). Dividing the prices above by two, to represent the cost of one-way journey, and comparing them to the air pollution and climate change costs show that the environmental costs represent about 6% of the cost of travelling by HST, 10% of flying with BA, and over 20% of the cost of flying with Easy-Jet. If passengers travelling from London to Paris, by HST or aircraft, would have to pay for the environmental damage they cause their cost of travel would have increased substantially. Financial analysis showed that on those tickets the companies did not cover their operational costs (Givoni, 2002b), and if passengers would pay the environmental costs those companies would have to incur further losses on these tickets to attract passengers.

Conclusions

The background for this paper was the perception that shifting passengers from the aircraft to the HST will result in reduced environmental impact from transport operations. Therefore the aim of this paper was to measure and quantify the reduced environmental impact on one route, the London-Paris route, when aircraft services are replaced with HST services. This was done in two categories where most benefits were likely to occur: air pollution, and climate change. Since the two modes offer different capacities the comparison was made in units of one seat and not one service. The difference between the theoretical methodology to evaluate environmental impact and what is possible in empirical study, and especially within the scope of this paper, meant that the comparison between the modes was in terms of emission of relevant gases per seat on the route; the impact from the emission; and the cost of the damage caused by the emission. Two options of travel were compared. One where the journey is by aircraft, and this includes the journey to the origin airport and from the destination airport to the city centre. The other option of travel was to use the HST from city centre to city centre.

The analysis found that on the London-Paris route the HST has a clear advantage over the aircraft in terms of the impact on climate change. In terms of air pollution it was not possible to conclude which option of travel is better, but the analysis did not consider that probably more people are exposed to air pollution around airports and on the way to airports than the number of people exposed to pollution from the HST's energy source, the power stations. The analysis showed that the access/egress journey from/to the airport is very important and its effect on air pollution is significant in respect to the effect from the HST and aircraft journey. Furthermore, although the cost of environmental damage was calculated the robustness of the analysis is questionable and the suggestion is to avoid, at least at present, the use of monetary evaluation to compare HST and aircraft operation im-

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[4] Cheapest return tickets for travelling between London to Paris during 2-5 December 2002.

pact on the environment. If choosing to accept the monetary evaluation the analysis found that environmental benefits do not always exist, and if they do exist they are limited.

The findings in this paper are very important because they show that it cannot be automatically assumed that shifting services from the plane to the train will result in environmental benefits. In addition the analysis showed the difficulties associated with quantifying the environmental impact, in any terms, and the need for further research to gain better understanding and knowledge of the impact of transport operation (and mainly aircraft operation) on the environment.

On routes such as London-Paris or London-Brussels the HST and the aircraft modes of transport are currently competing. The analysis above showed that at least on environmental grounds there is no obvious reason to encourage transfer of passengers from the aircraft to the HST. But on other routes, for example the Frankfurt-Stuttgart route, the aircraft and the HST services are integrated and co-operation between the modes takes place. Under such a way of operation, as it is done by Lufthansa and Deutsche Bahn, the aircraft service is removed (in theory, since in practice Lufthansa is still operating aircraft on the route) and the emission from the air journey is saved. At the same time no extra emission from the HST service occur since Deutsche Bahn does not add services to cater for the Lufthansa passengers[5] on the route. It is only under such a way of co-operation between the modes that we can expect high environmental benefits from transfer of passengers from the aircraft to the HST.

IMPLICATIONS FOR OTHER ROUTES

The environmental impact of aircraft operation on air pollution and climate change depends mainly on flying time, capacity of the aircraft and the height of the mixing zone, and when considering the journey to or from the airport the modal share and the distance of the airport from the city centre need to be considered. HST operation impact on the air pollution and climate change depends mainly on the mix of sources used to generate electricity, the route distance, and the train capacity.

Taking into consideration those factors and based on the analysis above, what are the implications of the results found here to other routes where substitution of air services by HST services can take place? The characteristics of the routes where air to rail transfer can take place are quite unique in terms of route distance and flying time. Considering the huge difference between HST operation and aircraft operation impact on climate change, on the distances where the modes compete or where substitution between the modes can take place the HST will always be a better option of travel. Even if considering a route distance of 2000 km (and without changing the aircraft emission, assuming 65 minutes of flight) the impact of aircraft operation on climate change is almost double the impact of HST operation.

Taking into account that even on the case study route it was not possible to reach a conclusion on which of the modes has less impact on air pollution, it is not possible to have a general conclusion for other routes. When comparing the modes in terms of toxicity factor, where on the case study route (494 km) the operation of HST service results in less air pollution, the HST remains a better option of travel up to a distance of about 1100 km. Air pollution caused by aircraft operation is not directly related to the flight distance since we consider the LTO cycle only (although for greater distances the aircraft need to carry extra fuel which results in extra emission during the LTO cycle), so when accepting the toxicity factor as the unit of comparison the HST is a better option on routes where the modes can compete or substitution can take place. Comparing between the modes in terms of the cost of air pollution a different conclusion is reached. When assuming no change in emission from the aircraft, the aircraft should be the preferred option of travel on any HST route longer than 200 km. This means that when accepting the monetary value units, aircraft operation will result in less impact on air pollution on any route where aircraft and HST compete or where substitution can take place.

On routes such as Amsterdam–Paris or Madrid–Seville the main factors affecting air pollution and climate change from aircraft and HST operation are very similar. Flying time is not significantly different (70-75 minutes for Amsterdam–Paris and 60 for Madrid–Seville); the aircraft used are relatively similar (all single isle aircraft with dominance to the B737 and A320); with no better information the height of the mixing zone can be assumed as the ICAO estimate of 915m; and it can also be assumed that no major differences are expected in the amount of emission during the surface journey to/from the airport. To estimate the emission from the HST an estimate for the French TGV was used, which means assuming the French mix of energy sources used to generate electricity, and this would have been used if the case study was the route Amsterdam–Paris or even Madrid–Seville since this was the best estimate for HST emission found. The route distance Amsterdam–Paris (about 500 km) and Madrid-Seville (471 km) does not vary much from the London-Paris route (494 km). Although the train capacity varies significantly between the routes[6] the estimate used in the analysis is in emission per passenger units (on the TGV trains) and it does not allow to take account of different train capacities since all the calculations are based on the same train. However it can be assumed that there is some correlation between the train capacity and size to the amount of emission emitted during operation, which means the rate of emission per seat will not vary significantly between trains. The above leads to the conclusion that we cannot expect different results on the routes Amsterdam-Paris and Madrid Seville from the results for the case study route London-Paris.

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[5] See note 3.

[6] Eurostar trains, operating on the London-Paris route, have a capacity of about 750 seats; Thalys trains, operating between Paris and Amsterdam, have a capacity of 377 seats; and the AVE trains, operating between Madrid and Seville, have a capacity of 329 seats (UIC, 2003).

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