Can high speed rail offset its embedded emissions?

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ABSTRACT

This paper analyzes the climate implications of investments in high speed railway lines given uncertainty in future transport demand, technology and power production. To capture the uncertainty of estimated parameters, distributions for the annual traffic emissions reduction required to compensate for the embedded emissions from the construction of infrastructure are calculated using Monte Carlo simulation. In order to balance the annualized emissions from the railway construction, traffic volumes of more than 10 million annual one-way trips are usually required. Most of the traffic diverted from other modes must come from aviation and the project cannot involve the extensive use of tunnels.

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1. Introduction

Although high speed in all modes of transport comes at the price of negative environmental impact, many environmentalists, and the companies and interest organizations of the rail sector, claim that high-speed rail is environmentally beneficial and should be allowed to form an important part of climate change mitigation. Independent research, on the other hand, concludes that these benefits may not be that large.[1]

The embedded CO_2 emissions from constructing and maintaining a high speed link is often substantial, partly because of the extensive use of steel and concrete, which are highly energy intensive in their production (Network Rail, 2009). For a new investment in high-speed rail to make sense from a climate perspective, these embedded emissions must be offset by the reduction in greenhouse gases that is the result of traffic shifting from high-emitting modes to rail when the new link is opened.

This paper determines the amount of annual passenger trips and the magnitude of shift from other modes that are required for compensating for the embedded emissions from the construction of a reference high-speed rail project, when depreciated over the lifetime of the infrastructure. Since the expected lifetime of the components in the railway differ, the embedded emissions are calculated using a steady-state approach where all components are assumed to be continuously replaced and recycled at the end of their lifetime.

The objective of the United Nations Framework Convention on Climate Change's is to prevent greenhouse gases from exceeding a concentration in the atmosphere that would raise the global mean temperature by more than 2 °C above its pre-industrial level. As the atmosphere under current trends will approach this critical concentration of greenhouse gases within a few decades, the payback time for emissions caused in the near term by large projects must be sufficiently short to prevent them from contributing to an overdraft. We have therefore chosen to calculate the carbon annuity based on a 50-year analysis period starting in 2010. This affects the assumptions with regard to available technologies and energy use.

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[1] Including, de Rus and Nash (2007), de Rus (2008), Kågeson (2009), and Nilsson and Pyddoke (2009).

A potential side-effect of building a new line for high speed trains is that the capacity is increased for the movement of freight trains and regional or local passenger trains on the pre-existing rail infrastructure. An indirect effect of this may be a growing shift from road to track that reduces the overall environmental impact of passenger and freight transport. However, for this to happen there must be a latent demand for transport by rail that could previously not be met for lack of capacity.

2. Methodology

The size of the net carbon benefit from a future high-speed train link depends on a number of parameters, among them: the energy per seat kilometer needed for moving different vehicles; the carbon dioxide emitted from the combustion of fossil fuels used for vehicle propulsion; the origin of the electricity; the average rate of occupancy for different transport modes; and the division of generated traffic on diverted traffic from other modes of transport, generated new traffic and pre-existing train passengers. The future values of all these parameters are associated with uncertainty.

In this paper a parametric model is used to calculate the change in CO_2 emissions per passenger kilometer from a person shifting to high-speed rail from another travel mode. The calculations are based on assumptions concerning the amount of energy per seat kilometer needed for moving different new vehicles/vessels in intercity traffic in 2025. These values are then translated into CO_2 emissions using figures for the carbon content of different fuel types and assumptions regarding the average load factors for each vehicle type. To evaluate the total environmental effect of building a new high-speed link, five scenarios are specified to capture different sources of the generated traffic.

To capture the uncertainty of the estimates, Monte Carlo simulation is used. This is a method for transforming a deterministic model into a stochastic model. To capture uncertainties in the input parameters, a probability distribution over likely future values of each parameter is assigned. Using simulation, the distribution of the net CO_2 emissions are calculated. In the simulation, the change in emissions per passenger kilometer and the resulting net emissions for all five scenarios are calculated using random draws from the parameter distributions. The process is repeated a million times until stable simulated distributions for the resulting net emissions are obtained for all transport modes.

To facilitate the specification of the model, all parameters are assumed to be triangle distributed. By using triangle distributions only a lowest, a highest and a central or most likely value for each parameter need to be specified. When creating the model, several correlation structures were tried, but the effects on the final results were found to be small. To simplify the model specification, all random parameters are therefore assumed to be independent.

2.1. Parameters

The sensitivity analysis clearly indicates that for most parameters the choice of value (within reasonable limits) does not significantly affect the depreciation of the embedded emissions. Therefore, the paper focus on the few parameters for which the choice of value is highly influential. These are: the marginal electricity production; the total radiative forcing factor of short-haul aircraft; and the assumed occupancy rate of the various vehicles and vessels. Assumptions on how generated traffic is divided on shifts from different modes and on new generated traffic are also important. The central values for all other parameters have been taken from Kågeson (2009). The highest and lowest values in the distributions have been selected as to provide estimates that significantly differ from the central value without being completely unrealistic. The distributions for all parameters are summarized in Table 1.

2.1.1. CO_2 emission from marginal electricity production

On average, current European power plants emit between 410 and 443 g of CO_2 per kW h produced (Hacker et al., 2009). More than 50% of the power production in Europe is based on the combustion of fossil fuels. Even in Scandinavia where the average CO_2 emissions from power production is less than 100 g, the average effect on emissions from marginal demand is between 660 and 700 g of CO_2 per kW h (Vessia and Byskov Lindberg, 2008; Sköldberg and Unger, 2008). All else equal, rising demand for electricity will make it more difficult to phase out power plants that burn hard coal or lignite.

When investment in high-speed rail results in modal shift and newly generated traffic – it is a matter of change. Under dynamic circumstances, average figures cannot be used for calculating the climate effect. Instead the marginal effect on emissions of greenhouse gases of rising demand for electricity is what matters. The marginal power production may differ somewhat over the months of the year as well as between day and night. The differences between national markets, however, are gradually diminishing as a result of the emerging common European electricity market and the improved transmission of electricity. According to the European Network of Transmission System Operators for Electricity (2010), European integration will require more than 35,000 km of new high-voltage transmission lines to be built before 2020.

Kampman et al. (2010) have analyzed the effect on the grids in Germany, France and the United Kingdom from a partial electrification of road transport. They conclude that increasing demand in Germany would result in more night-time use of lignite and hard coal and more day-time use of natural gas and/or lignite. France uses nuclear power and gas for balancing demand, while the UK relies heavily on gas for this purpose, which may partly be replaced by coal depending on future relative prices.

An effect of higher demand is that it will take longer to replace existing fossil-fueled power production with renewable sources or longer to equip them with carbon capture and storage (CCS). France and Norway are examples of large

Table 1
Parameter distributions for all model parameters.

	Low	Central	High
Parameter distribution for CO_2 emissions from marginal electricity production			
Emission from marginal electricity production (g CO_2/kW h)	225	530	700
Parameter distribution for CO_2 emissions from aircrafts			
Energy requirement for short range aircrafts (kW h/seat km)	0.216	0.245	0.274
Emissions per seat kilometer (without forcing factor) for aircraft (g CO_2/seat km)	55.4	63	70.6
Radiative forcing factor of short-haul aviation (factor of CO_2)	1.0	1.3	1.5
Parameter distribution for CO_2 emissions from buses			
Energy requirement for long-distance buses (kW h/seat km)	0.036	0.042	0.048
Emissions per seat kilometer for bus (g CO_2/seat km)	9.58	11.17	12.77
Parameter distribution for CO_2 emissions from cars			
Energy requirement for cars with internal combustion engines (kW h/seat km)	0.068	0.079	0.090
Emissions per seat kilometer for car with internal combustion engine run on 50/50 diesel/gasoline (g CO_2/seat km)	18	21	24
Estimated average blend of biofuel in diesel and gasoline for car (%)	10	20	30
Climate efficiency biofuel reduction factor for car (%)	55	65	75
Energy requirement for all electric cars (kW h/seat km)	0.032	0.040	0.048
Share of intercity car traffic running on electricity (%)	5	10	20
Parameter distribution for energy requirement of trains			
Energy requirement for high speed trains (kW h/seat km)	0.026	0.029	0.033
Energy requirement for conventional trains (kW h/seat km)	0.016	0.018	0.022
Parameter distribution for average load factors			
Short range aircrafts	0.70	0.80	0.90
Long-distance buses	0.40	0.55	0.70
Cars	0.30	0.40	0.50
High speed trains	0.65	0.75	0.85
Conventional trains	0.55	0.65	0.75

net-exporters of carbon-free electricity. However, rising demand in such countries means that less capacity can be used for export purposes to replace lignite and hard coal in, for instance, Germany and Poland.

The European Environmental Agency (2009) expects the EU's RED-directive and a gradual lowering of the cap of the European Emission Trading Scheme (EU ETS) to result in emissions from European power production being reduced to on average 130 g of CO_2 per kW h in 2030, whilst International Energy Agency (2009) presents a forecast of 312 g in the World Energy Outlook's reference scenario for 2030. Emissions from marginal production will, of course, be higher.

The estimated parameter distribution for the average CO_2 emissions of marginal electricity production in Europe, during the entire depreciation period, is assumed to range from 100 to 700 g/kW h with 400 as a central estimate. In the case when the marginal electricity production takes place in coal-fired condensing stations, which use carbon capture and storage, the emissions would be around 120 g/kW h – as CCS is not able to capture more than 83–89% of the emissions (Golombek et al., 2011). However, commercial application of CCS is not expected to happen until sometime after 2020, and will therefore affect the second half of the 50-year analysis period much more than the first.

2.1.2. CO_2 emission from short range aircrafts

Assuming all planes run on kerosene, the estimated CO_2 emissions from a short range aircraft can be calculated using the estimated energy requirement and the carbon content of the fuel. To take account of the fact that airplanes emit several other gases and substances that contribute to global warming, the estimated CO_2 emissions per seat kilometer from the aircraft is multiplied by a radiative forcing factor to get a total estimate of the emitted greenhouse gases from aviation. The total effect varies with time horizon and altitude. The factor is significantly smaller for short-hauls than for long-distance flights. For a distance of 500 km it was assumed that the true value falls within the range of factor 1.0–1.5 of the radiative forcing of the CO_2 emitted with 1.3 as a central value.

Table 2
Share of traffic on a new high speed link divided on sub-categories for the scenarios.

Scenario	Traffic diverted from other modes (%)			Generated new traffic (%)	Pre-existing train passengers (%)
	Aviation	Car	Bus		
Central estimate	20	20	5	25	30
High diversion from aviation	32	14	4	25	25
High diversion from cars and buses	12	32	6	25	25
High share of new generated traffic	18	18	4	40	20
High share of pre-existing train passengers	18	18	4	20	40

2.1.3. Traffic scenarios

In this analysis, the simulated emissions per passenger kilometer are applied to five different scenarios. Each scenario gives one example of how traffic generated by the investment in a new high speed line may be divided percentagewise on diverted traffic from other modes of transport, generated new traffic and pre-existing train passengers. Table 2 shows the assumptions made concerning how traffic is divided in the five scenarios.

3. Resulting emission per million one-way trips

For each scenario the simulated distributions for the resulting change in emissions per million 500 km one-way trips is calculated. The distributions are shown in Fig. 1.

From the figure it can be seen that on average all scenarios reduce total CO_2 emissions. The effect is strongest with a high diversion from aviation. However, if the share of newly generated traffic is high, in combination with high emissions from marginal electricity production, there is a small risk that total CO_2 emissions will increase instead of decrease. This highlights the importance of evaluating the share of newly generated traffic when estimating the environmental impact of investment in transport infrastructure. If the new line generates a large number of new trips, which would otherwise not take place, at least from a CO_2 reduction perspective, the project may be unfavorable.

4. Annual traffic required for offsetting embedded emissions

Large CO_2 emissions are generated from the construction and maintenance of a high speed link. In Network Rail (2009) the embedded greenhouse emissions from a high speed link are analyzed. Since the lifespan differs for different elements, the embedded emissions are annualized over the anticipated lifetime of each element. To calculate the embedded emissions there was also a need to consider the whole lifecycle including maintenance and the degree of material recycling when repairing the infrastructure. The embedded emissions are therefore expressed as CO_2 equivalent emissions per rail-track km per year.
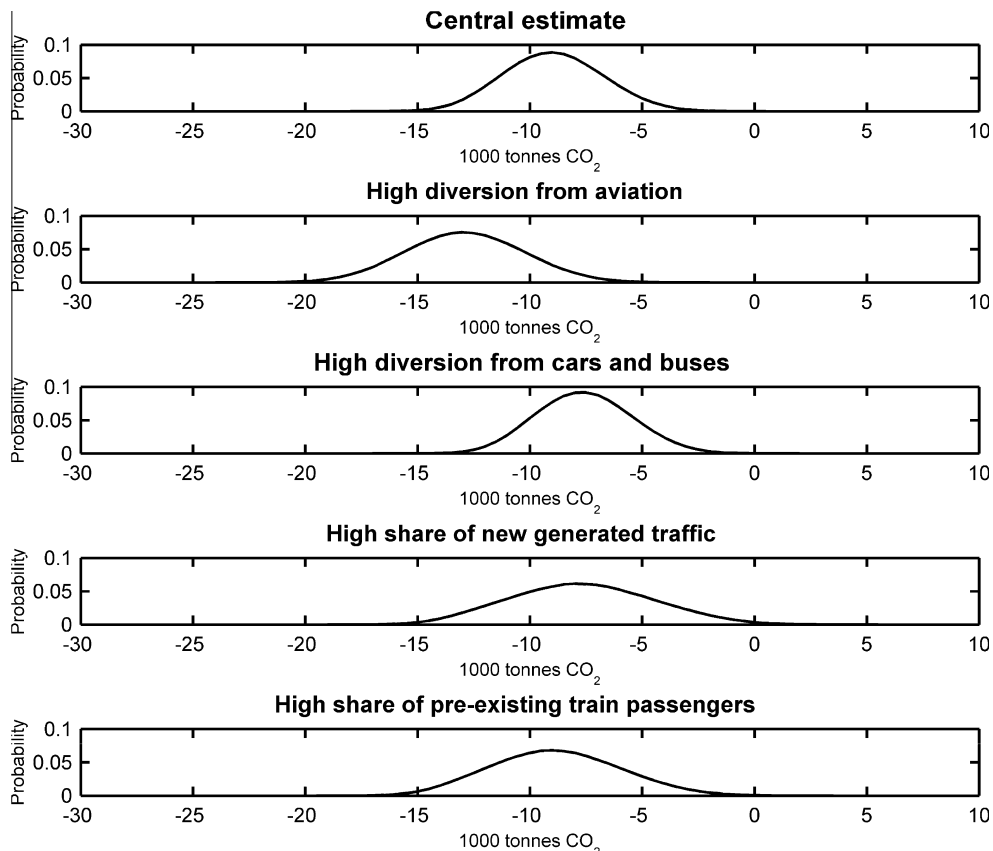

Fig. 1. Simulated distributions of the change in emissions per million 500 km trips for the five different traffic scenarios.

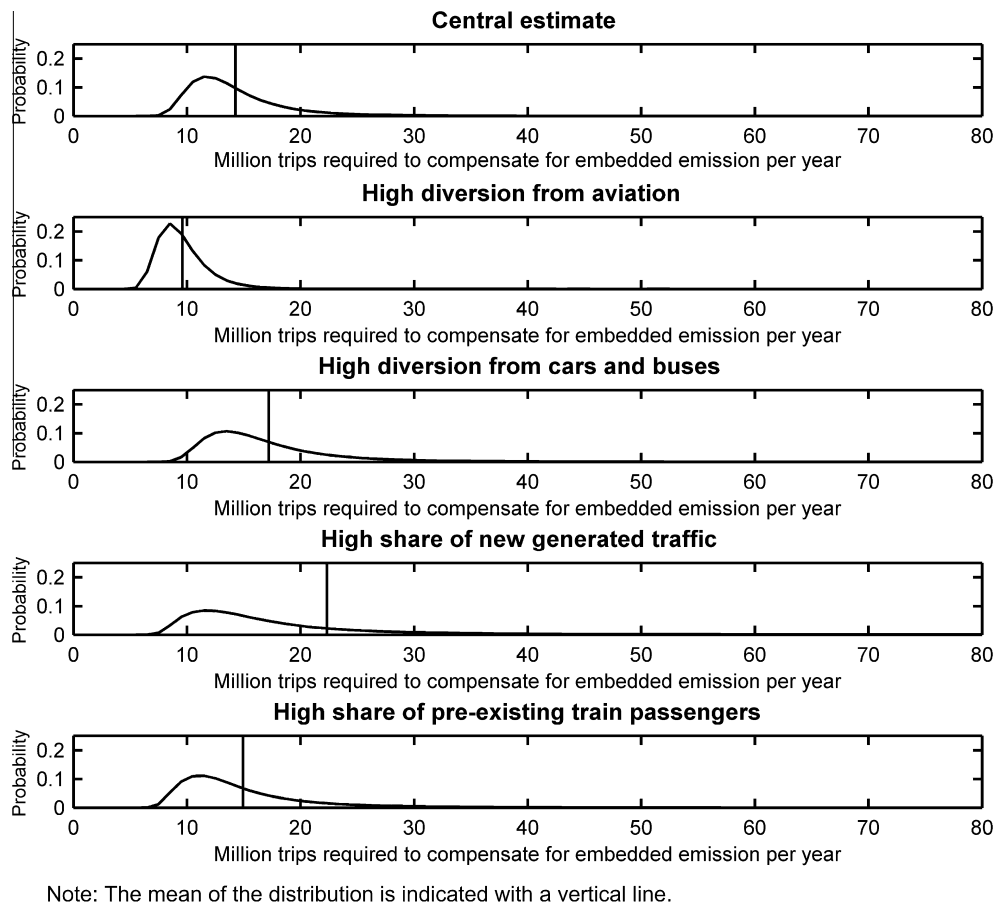Note: The mean of the distribution is indicated with a vertical line.

Fig. 2. Simulated distributions of the annual trips needed to fully compensate for the annualized embedded emissions from constructing and operating the high speed line in the reference project.

An important factor for the size of the embedded emissions is the proportion of tunnels versus open sections. Network Rail (2009) assume that the embedded emissions, for open sections, varies between 140 and 230 tonnes CO_2 eq. per rail-track km per year depending on the type of track and recycling rate. For tunnel sections the embedded emissions varies between 880 and 980 tonnes CO_2 eq. per rail-track km per year. Other studies on the embedded emissions from railway infrastructure come to somewhat different results depending on what factors they include in the analysis and what assumptions they make regarding the design, geographical location and depreciation period of the project (Claro, 2010; International Union of Railways, 2009). The overall magnitude of the embedded emissions is however the same.

To study the overall effect on CO_2 emissions from building a new high speed line, a reference project was used. The project is a 500 km long double track high speed line. Figures for the embedded emissions from the construction are taken from the central estimate in Network Rail (2009) with a recycling rate of 50% and assuming that 10% of the line is tunnels. The estimated annualized embedded emissions from constructing a 500 km long double track line is 118,000 tonnes of CO_2-eq.

Using the reference project, the required number of trips needed to compensate for the embedded emissions could be calculated. The simulated distribution of the required number of trips is shown in Fig. 2.

The figure shows how many annual trips are needed to compensate for the embedded emissions from constructing and operating the new high-speed line, that is, when the emissions reduction, from the induced modal shift, is equal to the embedded emissions from constructing and operating the railway. When comparing the emissions reduction with the embedded emissions from constructing the new railway, the overall positive result in Fig. 1 changes. If the number of annual trips is below the required value, the reduced emissions from traffic diversion cannot compensate for the annualized embedded emissions from the construction. Even with a high diversion from aviation, on average nearly 10 million annual one-way trips are required to compensate for the annualized construction emissions – as indicated by the vertical line in the figure. For the other scenarios, the average number of required annual trips is even higher, between 15 and 20 million.

The reference project consists of a relatively low proportion of tunnels. For a railway with a higher proportion of tunnels, even more trips would be required to compensate for the annual embedded emissions of the construction of the project.

5. Discussion

In traditional cost-benefit analysis, future costs and benefits would be calculated year-by-year and discounted into net-present value. As one cannot forecast future technological development post 2025 with any degree of accuracy, assumptions were made concerning the nature of new technologies entering the market in 2025 as a proxy for average specific emissions caused during the entire depreciation period. This makes discounting difficult. However, a drawback of not discounting is that one cannot distinguish between early and late emissions. By refraining from discounting the value of future benefits, this paper overestimates the net present value of investing in a shift to a low-emitting transport mode.

The method used in this paper does not capture all aspects of its subject. As already mentioned, the indirect effect on emissions of greenhouse gases from being able to use existing rail infrastructure for new types of traffic, after opening a new high speed line, is not covered. This aspect is analyzed in Åkerman (2011). However, to be able to make up for any size-able carbon deficit of a new high-speed line that does not attract enough traffic, the indirect climate benefits of making new use of the existing line would have to be significant. If so, it may be better to focus on how to accommodate those types of railway services rather than investing in a new line dedicated to high speed passenger transport.

Another aspect not considered is the possibility that, in the absence of investment in high speed lines, growing demand for rail services would require investment in other kinds of additional capacity where construction would also affect climate change. However, there may also exist other types of response to a growing imbalance between supply and demand that give rise to fewer emissions, e.g. congestion charges and incentives to improve the utilization of inland waterways and/or short sea shipping routes, and the partial replacement of business travel by telecommunication.

A different type of partial coverage is the fact that part of the high speed rail infrastructure, in particular tunnels, may have a lifespan substantially longer than 50 years. Thus, limiting the analysis to a depreciation period of 50 years may be unfair. On the other hand, the benefits of emissions reductions in the distant future may turn out to be much less important than those that take place in the near future, as the world is getting closer and closer to the point where the accumulated concentration of greenhouse gases in the atmosphere will exceed the point where it leads to an increase of the mean average temperature of more than 2 °C.

In the Monte Carlo simulation all random parameters were assumed to be uncorrelated. This simplified the specification of the model as there was no need to define a correlation matrix between the parameters. However, the theoretical foundation for this simplification can be questioned since it, for instance, implies that the future emissions per seat kilometer for conventional and high speed trains are uncorrelated, although being based on similar technologies. To verify the results, the robustness of the model with respect to assumptions regarding the parameter correlation structure has been tested.

This was done by identifying groups of parameters that were likely to be correlated. The simulation was repeated based on the assumption that parameters belonging to the same group were perfectly correlated with each other, but uncorrelated with all parameters outside of the group. The correlation decreased the variance of the distributions for emissions per passenger kilometer slightly. However, this only had a small effect on the number of annual trips needed to balance the annualized embedded emissions from the construction of the infrastructure (the mean of the distributions changed with less than 5% for all traffic diversion scenarios). Since the results did not significantly differ from the results when all parameters were assumed to be uncorrelated, this indicated that the results were robust to changes in the parameter correlation structure.

Another aspect is that the cap of the European Emissions Trading Scheme (EU ETS) may be seen as guaranteeing that CO_2 emissions from power production will not be affected by any increase in demand for electricity. If so, this is equally true for aviation emissions that will become subject to the EU ETS in 2012. Viewed this way, a shift from aviation to trains following investment in high speed rail would, by definition, have zero impact on the overall emission of greenhouse gases. On the other hand, a growing demand for electricity will affect the price of emissions allowances, which may make EU governments hesitant about requiring ambitious future cuts in emissions (WWF Deutschland, 2009).

6. Conclusions

To be able to balance the annualized emissions from the construction of a high-speed rail line, traffic volumes need to be large, and the diverted traffic should primarily come from aviation. The possibility to reduce overall emissions by making new use of the part of the capacity of an existing line, which becomes available as a result of the opening of a high-speed link, is site-specific and depends on future demand for additional rail traffic. High traffic volumes, thus, appear to be the only way both to recover costs and balance construction emissions.

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