The economics of electric roads

Maria Börjesson, Magnus Johansson, Per Kågeson

VTI & KTH, Sweden

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1 Introduction

There has been a surge of interest in reducing carbon emissions from heavy trucks in recent years, largely due to ambitious emission targets for transport in many countries as well as in the European Union. While light traffic and probably also regional freight distribution trucks can be electrified using batteries, this is a bigger challenge for long range heavy trucks. The latter would need heavy batteries or frequent recharging incurring delays. For this reason, electric roads, with continuous electricity transmission, has been developed and tested in Sweden and in Germany. In this paper we present a method for evaluating social benefits of electric roads and apply it to the Swedish highway network. Together with the investment cost this can be used to produce a cost benefit analysis.

The electric road is characterized by economies of scale (high investment cost and low marginal cost) and considerable economies of scope (the benefit per kilometre electric road depends on the size of the network), implying that the market will produce a smaller network of electric roads, or charge higher prices for its use, than what is welfare optimal. For this reason, it is relevant for governments to consider investing in electric roads, making the cost-benefit analysis a key decision support. There is, however, prior to this paper, no literature developing methods for assessing the economic rationale of electric roads.

We assume that all trucks that can receive electric power while in motion are hybrids, such that they also have a diesel engine to be used on non-electrified parts of the road network. This makes the hybrids more expensive to buy than a conventional diesel truck. The user charge of the electric road can either be set as to optimize welfare or to optimize the profit for the operator of the road. We calculate the net benefit cost ratio (NBCR) and cost recovery in both cases. We also outline arguments for private and publicly owned electric roads.

The benefit of the electric roads depends on the number of trucks using them. The use depends on the total volume of trucks and the number of these that are (electric-diesel) hybrids. The number of diesel trucks that haulage companies would eventually replace by hybrids will be determined by the profit that they can make from such replacements, assuming that they behave to optimize their profits. The carriers' optimal number of hybrids depend on a) the spatial distribution of freight flows by commodity, b) the spatial distribution of the electric road network c) the difference in driving cost per kilometre between using diesel and electric power received from the electric road, and d) the difference in capital cost between the diesel and the hybrid truck.

We model the behaviour of the carriers using the Swedish national freight model system, SAMGODS, determining the optimal shipment sizes, transport chain and route, including the mode (road, rail, sea) and vehicle type (Diesel60, Hybrid60, Diesel40, Hybrid40, Diesel24)[1] choices of the carriers for a given electric road network. Hence, we take into account that freight transport can divert also from rail and sea to road, if electric roads make freight transport by road cheaper. We make extensive sensitivity analyses with regard to factors b)-d) above.

The impact of the spatial distribution of the electric road network is analyzed by assuming three different network scenarios: small, medium and large. The difference in driving cost per kilometre of using diesel or the electric road depends on the prices of diesel and electricity,

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[1] Heavy goods vehicles, diesel vehicles and hybrids, respectively, having total weight 60-ton, 40-ton and 24-ton. We assume that the 24-ton vehicle are diesel only trucks.

respectively, and on the energy consumption of diesel trucks versus trucks powered by electricity. The operation cost will also be determined by the user charge on the electric roads. We will therefore vary future electricity prices, diesel prices and analyze the difference between welfare optimal and profit maximizing user charges.

We find that the size (and location) of the network is of key importance for the use (and therefore the benefits) of the electric roads, hence we find economics of scope up to a threshold size. A key reason for the larger network being more profitable per kilometre (below a threshold size) is that the carrier's optimal number of hybrids increases with the size of the electric road network. However, when the most heavily used roads are already electrified, the marginal benefit per kilometre of electric road extensions declines with the size of the network.

We find that electric roads will result in a significant reduction in carbon emissions from heavy traffic. In a scenario where the electric road system covers the highways connecting the three largest cities (Stockholm, Gothenburg and Malmö), carbon emissions is estimated to decline by approximately 1.2 million tonnes in 2030, corresponding to one third of all carbon emissions from heavy trucks in Sweden.

We find that if the user charge is set as to optimize social welfare, the revenue will not cover the investment cost of the electric road. However, if they are instead set to optimize profit, the revenue will cover the costs if the electric road network is large enough. Finally, we investigate if intermittent operation of the electric road (gaps in the electric transmission) can increase the net benefit cost ratio. On the one hand the investment cost can then be reduced, but on the other hand this would require the hybrids to have larger batteries to bridge the gaps of the electric roads. We find that intermittent operation is likely to increase the cost benefit ratio.

2 Method

To understand how the carriers will respond, we assume that the total demand for freight truck kilometres are V. Assume further that out of V, V_d kilometres are fuelled by diesel (using a hybrid or a diesel truck) with the kilometre cost θ_d and that V_e kilometres are fuelled by electricity received from an electric road with a kilometre cost θ_e.

Now, if the extra capital cost of the hybrids, that can receive electric power from the electric road, compared to a standard diesel truck is K. The carriers will determine the number of hybrids, n, they will buy by minimizing their transport cost

$$\tau = Kn - (\theta_d - \theta_e)V_e. \qquad (1)$$

I.e. the carriers will only invest in an additional hybrid if lower driving cost can compensate for the additional capital cost. The number of kilometres fuelled by electric power received from the road, given a positive kilometre cost difference $\theta_d - \theta_e$, is ruled by the function

$$V_e(S, N) = A\, S^{\alpha}\, n^{\beta}, \qquad (2)$$

where S is the length of the total electric road network, n is the number of hybrids that the carrier owns, and A is a constant. Carriers with few hybrids can reduce cost by letting the hybrids operate on routes having large overlaps with the electric roads. However, the more hybrids a carrier has, the more it will use the hybrids also on routes with less overlap. For this reason, the parameter β<1. Moreover, the larger the electric road network is, the larger part of total routes will be covered by the electric roads. For this reason, we will have economics of scope implying α> 1. However, when the full length of the most heavily used parts of the road network is already electrified, we expect that V_e increases slower than linearly, i.e. that α< 1.

Carriers optimizing the number of trucks yields the first order condition of

$$\frac{d\tau}{dn} = K - (\theta_d - \theta_e)A\,S^{\alpha}\,\beta n^{\beta-1} = 0, \tag{3}$$

giving the optimum number of trucks

$$n^{1-\beta} = \frac{(\theta_d-\theta_e)A\beta\ \ ^{\alpha}}{K}. \tag{5}$$

Hence, the lower additional capital cost of the hybrid, the larger the kilometre cost difference $\theta_d - \theta_e$, and the more extensive the electric road system is, the more electric trucks will the carriers buy.

Plugging (5) into (2) gives the resulting number of electric road kilometres

$$V_e = A\,S^{\alpha}\left((\theta_d - \theta_e)\,\frac{\beta A\,S^{\alpha}}{K}\right)^{\frac{\beta}{1-\beta}}. \tag{5}$$

2.1 A public operator maximizing welfare

So how would the user charge of the electric road be set? Assuming a public operator, optimizing welfare, the first best optimal user charge should be set so that the user pays the full marginal external cost of use. The external costs of electric trucks include wear and tear of the road infrastructure and of the electric infrastructure, noise and accidents. These costs are partly internalized by the tax on electricity since we assume that the electricity production as such has no external cost (in Sweden the marginal electricity production does normally not cause any carbon emissions).

However, heavy diesel trucks are not charged for all external costs. In fact, both freight trains and heavy trucks pay less through taxes or rail fees than the external costs they incur on society. We therefore assume the second-best user charge, i.e. the optimal charge for using electric roads given the present tax on diesel fuel.

Suppose again that the total number of truck kilometres is $V = V_e + V_d$. Assume further that the non-internalized external cost of the electric road use is e_e (taking only the tax on electricity into account) and that the non-internalized external cost of the diesel trucks is e_d (taking the tax on diesel into account). Assuming inelastic demand V, the second-best user charge is $e_e - e_d$.

2.2 An operator maximizing profit

The electric road operator is a monopolist who will set the price so as to maximize the profit

$$\pi = (\theta_e - c)V_e(d). \tag{6}$$

The first order condition becomes

$$\frac{d\pi}{d\theta_e} = V_e(\theta_e) + (\theta_e - c)\frac{dV_e}{d\theta_e} = 0, \tag{7}$$

where c is the marginal cost of production per truck kilometre. Note that c includes the cost of electricity (spot price, energy tax and grid fees) as well as the marginal cost of wear and tear on the electric road system. As before θ_e reflects the fuel cost per kilometre for the electric truck when it is fuelled by electric power received from road. The optimal price θ_e that the operator will charge is hence

$$\theta_e = -V_e(\theta_e)/\frac{dV_e}{d\theta_e} + c. \tag{8}$$

$V_e(\theta_e)$ is determined by (5) and taking the derivative of $V_e(\theta_e)$ with respect to θ_e we have

$$\frac{dV_e}{d\theta_e} = -A\,S^{\alpha}\left(\frac{\beta A\,S^{\alpha}}{K}\right)^{\frac{\beta}{1-\beta}}\frac{\beta}{1-\beta}(\theta_d - \theta_e)^{\frac{2\beta-1}{1-\beta}}. \tag{9}$$

Plugging (9) and (5) into (8) we find that

$$\theta_e = (\theta_d + c\frac{\beta}{1-\beta})/\left(1 + \frac{\beta}{1-\beta}\right). \tag{10}$$

Note that the optimal price, or the user fee, does not depend on the extra capital cost *K* for the electric trucks. On the one hand, the number of electric trucks and therefore V_e decreases if the extra capital cost *K* increases, on the other hand the derivative $\frac{dV_e}{d\theta_e}$ decreases (in absolute amount) as *K* increase.

We assume β = 0.5 we have thus

$$\theta_e = (\theta_d + c)\,/\,2. \tag{11}$$

2.3 Model

To simulate the non-linear effect of the network size, we study the likely response of the carriers given three different electric road networks:

- A small network consisting of E4 between Stockholm and Norrköping with a length of 31.5 km (sum of both directions)

- A medium-sized network consisting of E4 between Stockholm and Malmö with a length of 121.1 km (both directions)
- A large network consisting of the European roads between Stockholm and Malmö (E4), and Malmö and Gothenburg (E6) and the national road between Gothenburg and Jönköping (Rv 40). Total length 191.4 miles (both directions).

The Swedish national freight model system, SAMGODS, builds on the basic assumption that the carriers minimize the transport cost. The transport cost functions include shipment time, varying by commodity, and pecuniary cost. The model uses freight demand for 34 commodity groups by production and consumption zones as input. Zones are on the municipality level in Sweden. In neighbouring countries zones correspond to the NUTS-2 level[2], and in countries further away the zones are on the country (groups of countries) level. The model takes into account domestic freight transport demand, as well as international freight transport demand. The freight demand is disaggregated into demand between three size class levels of firms (small, medium and large) giving nine demand types. The optimal shipment sizes and optimal transport chains, including the choice of mode and vehicle type[3] are computed assuming that the carriers minimize transport cost. The 60-ton trucks are only allowed to operate in Sweden and Finland. Besides trucks, the model includes 7 train sets and 20 ships of varying types and sizes.

Implementing electric hybrid truck in Samgods is done by changing distance transport costs and capital costs of the hybrid trucks. The hybrid truck has a higher capital cost K (cost per year) than the standard diesel truck. On the other hand, the hybrid truck has a lower distance cost $\theta_d - \theta_e$, but only on road segments where electricity is used.

3 Results

3.1 Effects on carbon emissions

The table 1 shows that the smallest electric road network has modest effects. The effect is substantially higher for the medium-sized electric road network. In fact, the number of vehicle kilometres using the electric road per kilometre of the electric road network is twice as large for the medium-sized network compared to the smallest network. (For 40 tonne trucks the number of vehicle kilometres using the electric road per kilometre of electric road increases from 133 000 to 276 000). Hence it illustrates (as predicted in section 2) the existence of economics of scope, i.e. that the number of vehicle kilometres using the electric road increases faster than linearly with the length of the electric road network (implying $\alpha > 1$). However, the economies of scope only exist up to a threshold size of the network. When the size of electric road network increases further to the largest network, the number of vehicle kilometres per kilometre on the electric road increases slower than linearly with the length of the electric road network (implying $\alpha < 1$).

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[2] NUTS (Nomenclature of Territorial Units for Statistics) is a hierarchical classification system for a spatial division the EU territory. The spatial resolution of the NUTS 2 level distinguishes basic regions, meant to be used in evaluations of regional policies.

If connecting the electric road network between the three biggest cities in Sweden, just below one third of the totally involved vehicle kilometres could be fuelled by electricity.

3.2 CBA

Table 7 shows that in the main scenario, the social benefits of the electric roads are larger than their social cost in the three electric road network scenarios that we analyse. The largest benefit stems from operation cost savings for carriers because it is cheaper to operate trucks on electricity compared to diesel. The second largest benefit is the savings in carbon emissions.

The net of the (negative) marginal cost of wear and tear on the electric road system and the (positive) value of the reduced (carbon and health-hazardous) emissions are as expected slightly larger than zero (following from to the marginal costs per kilometres given in 3.2). The net of the tax revenue (diesel and electricity) and user charge is mildly positive. If demand had stayed constant, the change in revenue (slightly negative) and externalities (slightly positive) should exactly have balanced since we set the user charge to $e_e - e_d$, and as the externality per vehicle kilometre is lower for hybrids. However, because new road traffic is generated the revenue is positive. The generated road traffic also increases other external (negative) effects (wear and tear of the road infrastructure, noise and accidents)

The new road traffic is generated as an effect of diversion of freight transport from sea and rail. Reduced rail traffic generates a positive socio-economic effect as the external effect of rail traffic is not fully internalized by the track charges. However, there might be negative effects in the form of increased transport cost for rail, due to scale economies when demand is shrinking. On the other hand, there might be positive effects of reduced congestion on the rail tracks. Since these two effects are not known we chose to omit them.

The investment cost is lower than the net benefit and the NBCR is therefore positive. The NBCR is highest for the medium-sized network, 0.89. Given that the medium-sized electric road network was already built, an extension of the electric road system further (according to our third case) would have a NBCR of 0.25. Even for the smallest network the benefits would be larger than the costs.

Table 1. Cost-Benefit Analysis. Social cost of carbon emissions 114 €/tonne. Million €, net present value.

	Large	Medium	Small	Expand Large if Medium is built
Carbon emissions	1 532	1 072	180	460
Other emissions	15	10	1.7	4.4
Other external effects	-241	-222	-43	-19
Government (tax revenue)	-1 366	-919	-148	-447
User Charge	1 449	1 053	182	396
Operation Cost Electric Road	-1 317	-958	-164	-360
Profit for carriers	4 725	3 431	605	1 294

Reduced external cost railway	5.6	4.5	0.7	1.1
Net benefit	4 802	3 471	614	1 331
Investment cost	2 907	1 839	478	1 068
NBCR	0.65	0.89	0.29	0.25

3.3 Sensitivity analyses

We have five sensitivity cases. The reduction of carbon emissions and NBCR is relatively robust in sensitivity analysis one and two, with fairly large variations in diesel and electricity prices. Both the medium-sized and the large electric road network have a positive NBCR even with a sharp increase in the future price of electricity (the small network has however then a NBCR below zero).

Sensitivity analysis three, assuming intermittent electric transmission (gaps in the electric road network) and that the hybrid trucks are equipped with a battery with a range of 100 km, consistently yields higher NBCR than the scenarios with electricity transmission along the entire route. In this analysis, there is also an additional social benefit not included in the calculation: larger batteries can also be used for electric driving on roads that are not electrified (which the Samgod model cannot take into account).

Sensitivity analysis four, assuming a profit maximizing operator of the electric road, shows that for the medium-sized network, the revenue from the user charges almost cover the investment and maintenance costs. The NBCR is higher than in the main scenario, because the investment cost is lower as public funding are replaced by funding from user charges. Public funding causes deadweight losses as reflected by the MCPF. The benefit of reducing carbon emissions decreases by 20-25 percent, as it becomes more costly for carriers to use the electric road. The carriers´ profits shrink substantially in this scenario, as their transport cost is reduced less due to higher user charges.

Sensitivity analysis five assumes intermittent electric transmission in combination with a profit maximizing operator. Since the investment cost is lower in this scenario, the revenue from the user charges amply covers the investment and maintenance costs of the large and medium-sized networks (the revenue from the user charge corresponds to 130 and 140 percent of investment and operating costs, respectively). The NBCR is lower than in sensitivity analysis three, since the lower investment cost due to user financing does not fully outweigh the lower reduction of carbon emissions.

In all sensitivity analysis, the NBCR is highest for the medium-sized electricity network. Increasing the value of carbon emissions increase the NBCR substantially.

4 Conclusions

For all the electric road scenarios that we analyse, the social benefits of the electric road are larger than the social cost. The largest benefit stems from operation cost savings for carriers, simply because it is cheaper to fuel the trucks on electricity than on diesel. The second largest benefit is the reduction of carbon emissions. The NBCR and the reduction in carbon emissions per invested euro is highest for the medium-sized network, indicating economics of scope up to a network size threshold.

The reduction of carbon emissions and NBCR is relatively robust in sensitivity analysis one-two, based on fairly large variations in diesel and electricity prices. Intermittent electric transmission increases the NBCR due to lower investment cost, though this alternative requires larger batteries and thereby increases the costs of hybrid trucks.

If the user charge is set to optimize welfare, the revenues cover the marginal cost of the wear and tear on the electric road. Assuming a profit maximizing operator of the electric road, the revenue from the user charges almost covers the investment and maintenance costs for the medium-sized network. If we assume intermittent electric transmission, the investment and maintenance costs are fully covered in all electric road scenarios. However, if user charges are set by a profit maximizing monopolist, the reduction in carbon emissions decreases by 20-25 percent, as it becomes more costly for carriers to use the electric road.

The main argument against a commitment to electric roads is that investment and maintenance costs are uncertain, and that in the long run, battery development or hydrogen fuel cells can reduce the benefit of electric infrastructure. We have tried to take the latter risk into account by assuming a calculation and depreciation period of only 15 years, until 2040, but it is nonetheless a risk.

It remains an open question as to whether this result can be transferred to other countries. On the one hand, Sweden has low electricity prices increasing the benefits of electric roads. On the other hand, Sweden has also long distances compared toits small population, reducing the benefits. Finally, the large economies of scope indicate the benefit of coordinated expansion of electric roads in Europe.

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