The economics of electric roads

Maria Börjesson, VTI Swedish National Road and Transport Research Institute and KTH Royal Institute of Technology, Stockholm, Sweden

Magnus Johansson, VTI Swedish National Road and Transport Research Institute, Stockholm, Sweden

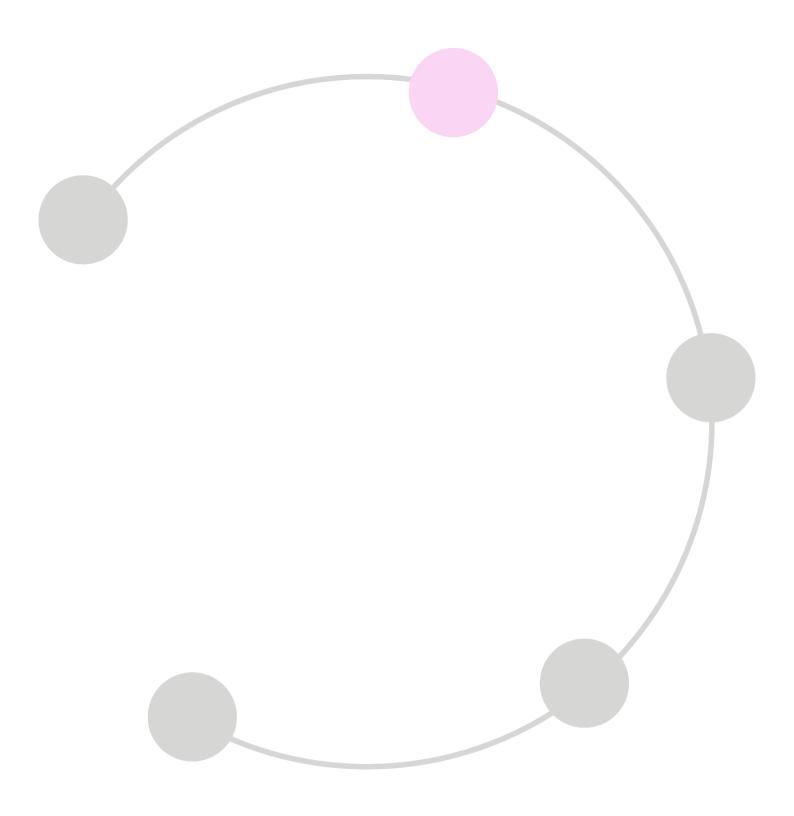Per Kågeson, Nature Associates, Stockholm, Sweden

Abstract

In this paper we present a method for evaluating social benefits of electric roads and apply it to the Swedish highway network. Together with estimated investments costs this can be used to produce a cost benefit analysis. An electric road is characterized by high 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. We model the behaviour of the carriers using the Swedish national freight model system, SAMGODS, determining the optimal shipment sizes and optimal transport chains, including mode and vehicle type. We find that if the user charge is set as to optimize social welfare, the revenue will not fully cover the investment cost of the electric road. If they are instead set to optimize profit for the operator of the electric road operator, we find that the revenue will cover the costs if the electric road network is large enough. Electric roads appear to provide a cost-effective means to significantly reduce carbon emissions from heavy trucks. In a scenario where the expansion connects the three biggest cities in Sweden, emissions will be cut by one-third of the overall emissions from heavy trucks in Sweden. 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 such roads.

Keywords

JEL Codes

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.

---

[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.

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, 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.

When assessing the cost of the electric road we assume the technology for overhead power lines because this is presently the most mature technology (there are other technologies using conduction or electromagnetic induction from below). In future years, electric roads using other technologies might also be relevant to analyze. Moreover, we assume that no electric roads exist outside of Sweden, which would likely increase the benefit of them in Sweden due to economies of scope and scale. Economies of scope and scale across Europe would be relevant to evaluate if countries choose to collaborate on the implementation of electric highways. The methodology of this paper could, however, still be used if extending the analysis or changing cost assumptions in this way.

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), CO_2 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

$$\tau = Kn - (\theta_d - \theta_e)V_e. \tag{1}$$

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

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

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 $\beta<1$. 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 $\alpha>1$. 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 $\alpha<1$.

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

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

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 direct carbon emissions. Moreover, the EU-ETS system implies that no electricity used in transport in any EU country generates carbon emissions. In this paper we rule out other positive externalities of building electric roads than network externalities, such as learning by doing for electric roads and vehicles, simply because it is difficult to assess them.

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

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

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 increases.

We assume $\beta = 0.5$ we have thus
$$\theta_e = (\theta_d + c) / 2. \qquad (11)$$

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.

---

[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.

3 Input data

3.1 CBA parameters and traffic growth

The cost-benefit analysis is based on the forecast year 2030. For this year a main scenario with electric roads is compared to a base scenario, without the electric road. In the base scenario we assume that all heavy traffic is fuelled by diesel.

Based on the comparison between the two 2030 scenarios, the total benefit of the investment is derived by assuming that the benefits and costs for the forecast year increase linearly with demand during the appraisal period 2025-2040. We assume that demand increases linearly with the Swedish Transport Administration's forecast of traffic growth, given in the leftmost column in Table 1. In a sensitivity analysis, we assume a significantly lower growth rate based on an average annual growth rate over the period 2000 to 2018, given in the rightmost column of the table.

Table 1. Estimated annual growth rate over the full appraisal period for traffic on road for different truck categories

Vehicle weight	Annual growth (%) Forecast, main analysis	Annual growth (%) Trend, sensitivity analysis
60-tonnes	1.65	1.33
40-tonnes	1.84	0.13
Lighter heavy trucks (<=25 tonnes)	1.10	-0.52

Source: The Swedish Transport Administration (2018).

We assume the relatively short appraisal period of 15 years mainly because the technical development of batteries and fuel cells after 2040 is difficult to predict. If the electric road is not in place until 2030, the appraisal period extends to 2045. Note that the choice of opening year has a marginal effect on the resulting NBCR, since both costs and benefits are discounted if the opening year changes.

All prices are given in the price level of 2018 and using the currency exchange rate of €1=SEK 10.

The demand for rail and sea transport is reduced by electric roads, as lower road transport costs induce a transfer of freight demand from rail and sea to road. The annual growth rate of 1.4 per cent per year is assumed for rail traffic based on the Swedish Transport Administration's forecast (2018). For shipping, the annual growth rate of 1.9 per cent per year is assumed, also based on the Swedish Transport Administration's forecast (2018).

The marginal cost of using public funds is taken to be 1.3 (Sørensen, 2010). Carbon emissions are valued at 0.114 €/kg in 2017, according to the Swedish appraisal guidelines ASEK 6 from 2019 (Swedish Transport Administration, 2018). This is approximately four-five times the price of EU emission allowances in 2019. The price of carbon emissions equals the carbon tax on fuel, so that the tax perfectly internalizes the cost of carbon emissions. Now, the fuel tax consists of two parts, energy tax and carbon tax. Only the former equals (and internalizes) the carbon emissions. The energy tax had initially mainly

fiscal motives, but is now rather viewed as internalizing other external effect of motor vehicles, such as noise, accidents and wear and tear of the road infrastructure. Both the value of carbon emissions and the carbon tax (and the energy tax) is assumed to increase annually by on average 1.5 percent in real terms over our appraisal period, so that in 2030 the value of carbon emissions is are 0.136 € /kg.

The marginal cost of wear and tear on the electric road system of the electric road, mainly the contact wire, is taken to be € 0.088 per kilometre based on estimates of wear and tear on the electrical system for trains (Odolinski, 2018). All input parameters are summarized in Table 1. Since one of the main effects of electric roads is reduced carbon emissions, the value of carbon emissions has a considerable impact on their social benefit.

The external costs of truck traffic in terms of accidents, noise and wear and tear on the road infrastructure are taken from Johansson and Johansson (2018). The external cost of health-hazardous emissions is taken from the Swedish appraisal guidelines.

Table 2. Input parameters to the CBA

Input parameters	
Discount rate	3,5 %
Marginal cost of public funds (MCPF)	1.3
Start of construction	2020
Opening of construction	2025
Appraisal period	2025- 2040
Annual economic growth (increase of valuation non-market valuations)	2 %
External cost of carbon emissions diesel truck 2030	0.136 € /kg 0.106 € /vehicle km (40-tonne truck) 0.137 € /vehicle km (60-tonne truck)
The external cost of health-hazardous emissions 2030	0.001 € / vehicle km (40- and 60- tonne truck)
External cost of noise 2030	0.006 € /vehicle km (40- and 60- tonne truck)
External cost of accidents 2030	0.03 € / vehicle km (40- and 60- tonne truck)
The external cost of wear and tear in road infrastructure 2030	0.084 € /vehicle km (40-tonne truck) 0.128 € /vehicle km (60-tonne truck)
The external cost of the wear and tear of the electric road system, mainly the contact wire 2030	0.088 € / vehicle km (40- and 60- tonne truck)

All external effects from rail traffic are not internalized in the track charges. The non-internalized external cost of rail traffic is on average 0.17 k€ per tonne kilometre (Nilsson and Haraldsson, 2018). Hence, society benefits from less rail transport. This is considered in the cost-benefit analysis. The non-internalized external cost of shipping is only on average 0.042 k€ per tonne kilometre, because they are nearly internalized by port and fairway fees (Vierth and Lindé, 2018).

3.2 Price of driving

The demand for using the electric road in the forecast year 2030 depends on the cost of diesel and the cost of driving on electricity, respectively. This is determined by energy consumption per kilometre, the user charge of the electric road, and the price of diesel and electricity, respectively, including taxes.

In 2019, the spot price of electricity was 0.035 €/kWh in Sweden. The Swedish Energy Agency (2019) forecasts that the price will increase to 0.038 €/kWh in 2030 (partly due to that the price of emission permits is assumed to increase as the cap in the EU's trading system ETS is gradually lowered). These assumptions give a total electricity price of 0.079 k€/ kWh in 2030, including electricity tax, grid tariff and the spot price. In the main analysis we also assume that the diesel price, including fuel tax but not VAT, is 1.53 €/litre in 2030.

The future electricity and diesel prices are uncertain. For this reason, we undertake sensitivity analyses. In the first sensitivity analysis we assume a doubled spot price of electricity 2030, i.e. 0.07 k€/kWh, yielding an electricity price in total of 0.11 k€/kWh (including tax and the electricity grid tariff). In the second sensitivity analysis we assume that the price of diesel is € 1.88 per litre in 2030 (including fuel tax but not VAT).

Driving costs also include the costs of vehicle wear, maintenance, tires, value reduction etc. We assume that these costs are the same for electric and diesel trucks.

According to Kühnel et al. (2018), a 40-tonne vehicle using the electric road will consume 1.51 kWh/km in 2030. A diesel truck consumes twice as much energy, 3 kWh/km, implying 3.1 litres of diesel per kilometre.[4] 60-tonne trucks consume 30 percent more fuel than 40-tonne trucks according to the Swedish Association for Road Transport Companies.

We compute the second-best user charge as $e_e - e_d$. Hence, the difference in external costs per kilometre between driving on diesel and using the electric road should equal the corresponding difference in tax and user charge. According to table 3, the difference in marginal external cost between diesel and the electric road truck is 0.017 and 0.049 €/km, respectively (we assume that other marginal external costs are equal for diesel trucks and trucks using the electric road such that they cancel out). The difference in tax is 0.111 and 0.145 €/km, respectively. Note that the energy tax on electricity is not a user charge that covers infrastructure cost and such (this is covered by the grid charge). The energy tax on electricity is mainly fiscal but could just as well internalize external cost of wear and tear of the road infrastructure and accidents. These numbers imply that the welfare optimal user charge for the electric road is 0.094 €/km for 40 tonne trucks and 0.096 €/km for 60 tonne trucks (in 2030). Then the difference in external costs per kilometre between driving on diesel and using the electric road equals the corresponding difference in the sum of tax and user charge.

---

[4] We do account the EU fuel efficiency regulation for trucks (-30% emissions in 2030). Partly this is reflected in the fuel consumtion of the diesel trucks that we assume. It is however also reflected in our study by the assumption of 25 percent lower carbon emissions due to bio-mixing in diesel (also increasing the production cost and price of diesel).

Table 3. Deriving the socially optimal user charge on the electric road: $e_e - e_d$, €/km

	40-tonne truck	60-tonne truck
External cost of carbon emissions diesel truck 2030	0.106	0.137
The external cost of the wear and tear of the electric road system, mainly the contact wire 2030	0.088	0.088
Difference in external marginal cost	0.017	0.049
Fuel tax (sum of energy tax and carbon tax) 2030	0.164	0.213
Energy tax on electricity 2030	0.052	0.068
Difference in tax	0.111	0.145
User charge internalizing the marginal external cost of electric road	0.111-0.017= 0.094	0.145-0.049=0.096

We use figures from Kühnel m. fl. (2018) to compute the extra capital cost of the hybrid. They estimate the incremental cost of a hybrid with a 350-kW diesel engine and an electric engine of the same power to be € 50 000. They include a battery with a range of only 10 to 20 kilometres. The pantograph constitutes roughly half of the additional cost of the hybrid. But the electric engine is cheap and makes up only approximately one tenth of the additional cost. It is likely that the incremental capital cost of the hybrid declines over time as the price of the internal combustion engine is likely to increase due to more stringent exhaust requirements. But since the latter is more uncertain, we adopt the additional cost mentioned above in our analysis. Assuming a depreciation period of 7 years and interest 4 percent, this gives an incremental vehicle cost of €8 300 per year (roughly 7 percent). We disregard transaction and transition costs when the carriers replace their trucks, because all trucks will not be replaced at the same time allowing for a gradual transition to electric hybrids. However, one cannot rule out that such costs could reduce the speed of the transition to hybrids and therefore the optimal user charge the first years after the opening.

In the third and fifth sensitivity analysis we assume intermittent electric power transmission, with gaps in the electric road. In these scenarios we assume that the hybrid trucks must be equipped with a battery with a range of 100 km. Kühnel et al. indicate that a battery of 175 kWh would allow a range of 100 km. The cost of such a battery is stated to be € 19 000 in 2030. The entire additional cost for the truck will then be € 19 000 + 50 000 = 69 000, yielding an extra yearly capital cost of €11 000.

The operation costs used in the main analysis are summarized in Table 4.

Table 4 Operation costs 2030. The main analysis.

	40 ton	60 ton
Driving cost electric road €/km	*0.214*	*0.252*
Of which electricity cost €/km	0.069	0.089
Of which electricity tax cost €/km	0.052	0.068
Of which user charge €/km	0.093	0.095
Driving cost diesel €/km	*0.472*	*0.613*
Of which fuel cost €/km	0.308	0.400
Of which fuel tax cost €/km	0.164	0.213
Wear, service, tires, depreciation etc. All trucks €/km	*0.275*	*0.457*
Total distance cost €/km, electric road	0.489	0.709
Total distance cost €/km, diesel	0.747	0.107
Capital cost all trucks k€/year	111	111
Extra capital cost hybrid truck k€/year	8	8
Extra capital cost hybrid truck with 175 kWh battery k€/year	11	11

3.3 Sensitivity analyses

Here we outline our sensitivity analyses, exploring the robustness of the social benefit of the electric road. The input data in the form of operation cost for the sensitivity analyses is summarized in Table 5.

As mentioned above, in the first sensitivity analysis we increase the price of electricity by 0.0315 €/kWh. Hence, we reduce the cost difference between diesel and electric road operation. In the second sensitivity analysis we increase the price of diesel by € 0.210 per litre. In this case we increase the cost difference between diesel and electric road operation. Since it is mainly the relative difference in driving cost between diesel and electricity that impacts the use of the electric road, these two sensitivity analyses can be interpreted as analysing the sensitivity of any change in the variables impacting the price of driving on diesel and electric driving (taxes, grid tariffs, user charge, electricity and diesel price and fuel consumption).

In the third sensitivity analysis, we assume intermittent electric power transmission, with gaps in the electric road infrastructure being equally long as the distance covered. We are reducing the investment and operation cost of the electric road by half. We assume that the hybrid trucks must therefore be equipped with a battery with a range of 100 km, increasing the additional yearly capital cost of the hybrids (see section 2.2). We double the user charge assumed in main analysis but assume also that distance travelled on the electric road is halved. Hence, the average user charge per vehicle kilometre along the electric road routes (including the gaps) will be the same as in the main analysis. Keeping the average user charge constant in this way (and therefore the total operation cost per kilometre) might be justified if the marginal cost of the wear and tear on the remaining electric road infrastructure increases.

The fourth sensitivity analysis reflects a scenario where a profit maximizing monopolist operates the electric road. The operator will set the user charge to maximize profit according to equation (11). Using this equation in combination with the input parameters of the main analysis we find that the user charge increases by € 0.128 per km (40 tonne trucks) and € 0.178 per km (60 tonne trucks), respectively, compared to the main scenario where the user charge is based on the short-term marginal cost.

Sensitivity analysis five assumes again the situation where a profit maximizing monopolist owns and operates the road´s electric infrastructure. In this analysis we assume intermittent electric power transmission, as in sensitivity analysis three, and assume that the hybrid trucks must be equipped with a battery allowing a range of 100 km, thus increasing the extra annual capital cost of the hybrid. The capital cost of hybrids and the investment and operating costs of the electric road are the same as in sensitivity analysis three. Again, we double the user charge assumed in main analysis and assume that distance travelled on the electric road is halved. Hence, the average user charge per vehicle kilometre along the electric road routes (including the gaps) will be the same as in the main analysis. This assumption is justified by equation (11), showing that the user charge will depend on the price of diesel and electricity, which both remain unchanged. The user charge also depends on the marginal cost of wear and tear on the electric road infrastructure, and we assume thus, as in sensitivity analysis three, that the wear and tear on the remaining electric road increase. Equation (11) also shows that the optimal user charge stays unaffected by the increase in the extra capital cost of the required hybrids with larger batteries.

Table 5. Operation costs per kilometre 2030. Main analysis and sensitivity analysis

	Fuel cost electric road: fuel, tax, user charge €/10 km		Fuel cost diesel fuel, tax €/10 km		Operation cost all trucks: Wear, service, tires, depreciation €/10 km		Operation cost of electricity in proportion to diesel.	
	40-tonne	60-tonne	40-tonne	60-tonne	40-tonne	60-tonne	40-tonne	60-tonne
Main scenario	2.14	2.52	4.72	6.13	2.75	4.57	0.65	0.66
Sensitivity analysis 1	2.62	3.14	4.72	6.13	2.75	4.57	0.72	0.72
Sensitivity analysis 2	1.52	1.72	4.72	6.13	2.75	4.57	0.57	0.59
Sensitivity analysis 3	2.14	2.52	4.72	6.13	2.75	4.57	0.65	0.66
Sensitivity analysis 4	3.42	4.30	4.72	6.13	2.75	4.57	0.83	0.83
Sensitivity analysis 5	3.42	4.30	4.72	6.13	2.75	4.57	0.83	0.83

3.4 Investment cost

There is yet no full-scale electric road system in the world and the investment costs of such systems are therefore uncertain. There are two electric road demonstration projects in Sweden using different technologies for transmitting electricity to the vehicle. The Elväg Gävle project has built a two-kilometre track using overhead lines. The E-road Arlanda demonstrates a conductor transfer technology from the road surface on a two-kilometre long test track. There are no cost estimates of a full-scale expansion of the Swedish demonstration projects that we judge to be realistic. There are, however, German assessments of the investment cost of conductive transmission from above. Boston Consulting Group and Prognosis (2019) estimates the cost per kilometre of electric road in both directions to € 2.5 million. The Fraunhofer Institute et al. (2018) and Sundelin et al. (2018) both assess the cost to just over € 1.7 million per kilometer in both directions.

In this project, we assume the most mature technology using electricity transmission from overhead lines. PIARC (2018) assess the investment cost of this technology to € 2.2 million per kilometre of electric road in two directions. This figure includes € 0.4 million for increased transmission capacity from the regional road network. In addition, the Swedish

Transport Administration, assess the cost of € 0.3 million per kilometre and direction for installation of railing and other required road equipment. Since we are studying investment in an existing highway, where the level of road equipment is already high, we have chosen to assume only half this cost. In total, we thus estimate the cost € 2.5 million per kilometre electric road in both directions. Since we assume a relatively short appraisal period for the electric road system under which the capital cost is written-off, only 15 years, we disregard the annual maintenance cost of the electric infrastructure. We do however assume a marginal cost of one additional vehicle using the electric road when computing the optimal user charge and operational cost of the electric road as described in section 3.

4 Results

4.1 Effects on carbon emissions

The two leftmost columns of table 6 show the share of all truck vehicle kilometres in Sweden that is fuelled by electricity transmitted from the electric road in the main scenario. The next two columns show the total vehicle kilometres where the trucks are fuelled by the electric road. The subsequent column shows the total length of the electric road network (S). The final three columns show the total vehicle kilometres (thousands) by trucks fuelled from the electric road in relation to the total length of the electric road network $V/(S \cdot 10^3)$.

In summary, the table 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 $\alpha < 1$).

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.

Table 6. Vehicle kilometres by trucks fuelled from the electric road

	Vehicle kilometres (VK) by trucks in Sweden fuelled by the electric road As share of total VK (%)		VK by trucks in Sweden fuelled by the electric road V [million km]			Length of the electric road network S [km]	VK (thousands) by trucks on the electric road per kilometre electric road $V/(S \cdot 10^3)$		
Electric road scenario	40-tonnes	60-tonnes	40-tonnes	60-tonnes	Tot		40-tonnes	60-tonnes	Tot
Small	2.9	4.01	42	129	171	315	133	409	542
Medium	23.4	20.6	334	662	997	1 211	276	547	823
Large	31.8	28.6	454	916	1371	1 914	237	479	716

The reduced cost of road transport implies that freight transport diverts from rail and sea to road, increasing the vehicle kilometres by truck. The electric road impacts the vehicle kilometres of trucks in Sweden as shown in the first four columns of Table 7. The effect is again modest for the smallest electric road network, and larger for the medium-sized and large networks. In the latter, the vehicle kilometres produced by 40 and 60 tonne trucks, respectively would increase by a little less than 4 percent. However, the vehicle kilometres produced by light trucks declines such that, in total, the truck kilometres increase by only 2.5-3 percent. The final three columns of the table show how freight transport measured in tonne kilometres change by mode: as expected it increases for road transport and is reduced for rail and sea transport.

Table 7. Change in VK by trucks. Change in tonnes kilometres by transport mode; percent

	Change in VK for freight transport road %				Change in freight transport, tonnes-kilometres, %		
Electric road scenario	40-tonnes	60-tonnes	Lighter heavy trucks	Total	Road	Rail	Sea
Small	0.43	0.75	-0.85	0.45	0.29	-0.17	-0.08
Medium	4.08	3.04	-2.78	2.53	2.68	-1.16	-1.62
Large	3.97	3.66	-4.28	2.68	3.19	-1.45	-1.85

4.2   CBA

Table 8 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. These cost savings are substantially larger than the reduction in carbon tax revenue for the government because it is cheaper to operate the trucks on electricity than on diesel even if disregarding the carbon tax. 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, 1.02. 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 0.34. Even for the smallest network the benefits would be larger than the costs.

Table 8. Cost-Benefit Analysis. Social cost of carbon emissions 114 €/tonne (2017). Million €, net present value.

	Large	Medium	Small	Expand Large if Medium is built
Carbon emissions	1 825	1 277	214	548
Other emissions	15	10	2	4
Other external effects	-241	-223	-43	-19
Government (tax revenue)	-1 297	-869	-139	-428
User Charge	1 419	1 032	177	387
Operation Cost Electric Road	-1 317	-958	-164	-360
Profit for carriers	4 725	3 431	604	1 294
Reduced external cost rail	6	4	1	1
Reduced external cost see	3	3	0	0
Net benefit	5 137	3 708	653	1 429
Investment cost	2 907	1 839	478	1 068
NBCR	0.77	1.02	0.37	0.34

4.3 Sensitivity analyses

Table 9 present the benefit-cost analyses for our 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 Samgods model cannot take into account). Note that it might be more profitable for both the electric road operators and the carriers if the trucks were to be equipped with even larger batteries. It is possible that already 250 KWh battery would allow coverage over most routes outside the motorways, depending on country and route. In that case the trucks might not need a diesel engine, reducing the cost of the trucks and the fuel. A larger battery would also allow longer gaps in the electric road along the motorway, reducing investment and maintenance cost.

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 the sensitivity analysis where we assumed a lower growth rate of truck traffic, based on the past trend instead of the forecast (see Table 1) the NBCR reduces but only slightly, see Table 10. Increasing the value of carbon emissions increases the NBCR substantial. In all sensitivity analysis, the NBCR is highest for the medium-sized electricity network.

5 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.

Several arguments can be made for public operation and ownership of electric roads. First, it is unlikely that private investors would be willing to take the risks of such an investment. There are at least two major investment risks. The first is that investment and maintenance costs become larger than estimated. Costs are uncertain as there is no full-scale electric grid network in operation yet. The second risk is that the battery development may in the longer run enable 100 percent battery operation. The use of fuel cells is another competing technology, currently too expensive but perhaps gaining ground in the long term. However, the solution of applying intermittent electric transmission requiring trucks equipped with larger batteries (of which some might even not even have a diesel motor), would allow some hedging of the risk as reduces the investment cost but still accomplish the same fuel cost and carbon emission reduction. Second, the large economies of scale and scope (i.e. that the electric road network are extensive for the potential benefits to be fully realized) make the investment risky and probably to extensive for a private investor. This is demonstrated by the result that the smallest electric road network is least profitable and cannot be fully financed by user charges.

Third, a private operator would eventually need to be regulated. As long as diesel trucks remain, the user charges set by the monopolist electric road operator are restricted by the competition from them. However, if the diesel trucks are completely outcompeted, the pricing of the electric road needs to be publicly regulated.

Fourth, private ownership of the electric infrastructure on a publicly owned road implies divided ownership and responsibility for maintenance. This can lead to losses in efficiency and raise liability issues and associated risk management.

In summary, electric roads appear to provide a cost-effective means to significantly reduce carbon emissions from heavy trucks. In the scenario where the expansion connects the three biggest cities in Sweden, emissions will be reduced by approximately 1.2 million tonnes in 2030, which corresponds to approximately one-third of emissions from all heavy trucks in

the country. 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.

6   References

Boston Consulting Group och Prognos., 2019. Analyse der Klimaphade Verkehr 2030. Rapport på uppdrag av der Bundesverband der Deutchen Industrie (BDI).

Energimyndigheten, 2019. Scenarier över Sveriges energisystem 2018 (No. 2019:7).

Fraunhofer Institute for Systems and Innovation Research ISI, Oeko-Institut, och Institute for Energy and Environmental Research, 2018. lternative drive trains and fuels in road freight transport – recommendations for action in Germany. Karlsruhe, Berlin och Heidelberg.

Johansson, M., Johansson, O., 2018. Internalisering av godstrafikens externa effekter – konsekvensanalyser med Samgodsmodellen : en delrapport inom SAMKOST 3. Statens väg- och transportforskningsinstitut.

Kühnel, H., Florian, S., Wolf, G., 2018. Oberleitungs-Lkw im Kontext weiterer Antriebs- und Energieversorgungsoptionen für den Straßengüterfernverkehr. Öko-Institut e.V, Freiburg.

Nilsson, J.-E., Haraldsson, M., 2018. Redovisning av regeringsuppdrag kring trafikens samhällsekonomiska kostnader: SAMKOST 3.

Odolinski, K., 2018. Marginalkostnader för järnvägsunderhåll: trafikens påverkan på olika anläggningar.

PIARC, 2018. Electric road systems: a solution for the future?

Sørensen, P.B., 2010. Swedish tax policy: Recent trends and future challenges. Finansdepartementet, Regeringskansliet.

Sundelin, H., Linder, M., Mellquist, A.-C., Gustavsson, M., Börjesson, C., Pettersson, S., 2018. Business case for electric road. Presented at the 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria.

Swedish Transport Administration, 2018. Swedish Transport CBA Guidelines: ASEK 6.1. Swedish Transport Administration.

Trafikverket, 2018. Prognos för godstransporter 2040 – Trafikverkets Basprognoser 2018, rapport 2018:087 (No. 2018:087).

Vierth, I., Lindé, T., 2018. Internaliseringsgrader för godstransporter med olika trafikslag i Europa. Statens väg- och transportforskningsinstitut.

Table 9. Sensitivity Analyses Cost-Benefit Analysis. Social cost of carbon emissions 114 €/tonne (2017). Million €, net present value. Sensitivity Analysis

	Main Scenario			Sensitivity Analysis 1			Sensitivity Analysis 2			Sensitivity Analysis 3			Sensitivity Analysis 4			Sensitivity Analysis 5		
	Large	Medium	Small	Large	Medium	Small	Large	Medium	Small	Large	Medium	Small	Large	Medium	Small	Large	Medium	Small
Carbon emissions	1 825	1 277	214	1 703	1 188	198	1 940	1 366	243	1 757	1 223	197	1 451	997	162	1 321	895	121
Other emissions	15	10	2	14	10	2	16	11	2	14	10	2	11	8	1	10	7	1
Other external effects	-241	-223	-43	-194	-178	-30	-335	-295	-43	-227	-213	-31	-122	-103	-12	-115	-92	-12
Government (tax revenue)	-1 297	-869	-139	-1 219	-819	-134	-1 353	-907	-162	-1 246	-828	-131	-1 051	-707	-117	-952	-631	-84
User Charge	1 419	1 032	177	1 312	948	156	1 538	1 129	198	1 366	991	156	2 977	2 091	333	2 720	1 879	256
Operation Cost Electric Road	-1 317	-958	-164	-1 218	-880	-145	-1 428	-1 048	-184	-634	-460	-72	-1 017	-718	-111	-925	-643	-86
Profit for carriers	4 725	3 431	604	3 591	2 584	444	6 289	4 610	825	4 499	3 254	534	1 813	1 268	206	1 662	1 142	157
Reduced external cost railway	6	4	1	4	3	0	8	6	1	4	3	0	1	1	0	1	1	0
Reduced external cost see	3	3	0	3	2	0	4	4	0	3	3	0	2	2	0	2	2	0
Net benefit	5 137	3 708	653	3 996	2 857	492	6 679	4 875	882	5 536	3 982	654	4 066	2 838	463	3 726	2 559	353
Investment cost	2 907	1 839	478	2 907	1 839	478	2 907	1 839	478	1 453	919	239	2 236	1 414	367	1 118	707	184
NBCR	0.77	1.02	0.37	0.37	0.55	0.03	1.3	1.7	0.8	2.8	3.3	1.7	0.82	1.01	0.26	2.3	2.6	0.9

Table 10. Cost-Benefit Analysis, growth rate of truck traffic is based on the past trend instead of the forecast. Social cost of carbon emissions 114 €/tonne (2017). Million €, net present value.

	Large	Medium	Small	Expand Large if Medium is built
Carbon emissions	1 727	1 209	203	518
Other emissions	14	10	2	4
Other external effects	-235	-215	-42	-20
Government (tax revenue)	-1 228	-823	-131	-405
User Charge	1 346	978	168	367
Operation Cost Electric Road	-1 249	-908	-156	-341
Profit for carriers	4 486	3 257	576	1 229
Reduced external cost rail	6	4	1	1
Reduced external cost see	3	2	0	0
Net benefit	4 866	3 512	620	1 355
Investment cost	2 907	1 839	478	1 068
NBCR	0.67	0.91	0.30	0.27