The costs and benefits of e-roads versus battery-only trucks when costs are uncertain

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Abstract

This paper compares the cost of diesel trucks, battery electric trucks, and trucks that rely on overhead lines in a decision context where the developments of battery costs and overhead line investment and maintenance costs are uncertain. The user costs contain the truck capital cost and the energy costs, the possible vehicle-to-grid benefits, driver costs, and other distance costs. User costs are compared for optimized battery sizes for trucks with different distance profiles. The possible user cost developments serve as input to an analysis of investment decisions in electric motorways (e-roads). The economics of e-roads are analyzed for two representations of the EU TEN-T network. In the first analysis, average EU truck density and truck trip characteristics are used. In the second representation, we consider domestic and international truck transport between two neighbouring countries with strongly diverging traffic density and the share of international truck trips on their TEN-T network. This allows for the analysis of the non-cooperative and cooperative solutions of the two countries. The installation of e-roads appears to be a robust investment decision for the motorways of large countries that have dense truck traffic but not for less dense counties. Cooperation between large and small countries may increase total benefits depending on future battery costs and overhead line investment and maintenance costs.

Keywords
Electric trucks, battery development, catenary trucks, electric roads, coordination of investments, CBA

JEL Codes
R41, R42, R48

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1. Introduction

Heavy trucks are an important source of carbon emissions. In the EU they account for 25% of road transport emissions (EEA, 2022). Historically the vehicle kilometre travelled by trucks has increased with the GDP in the EU. As vans can be electrified by using technologies and designs developed for cars, the main problem is centred around the heavy goods vehicles (HGV). For large trucks the EU has required manufacturers to decrease the carbon emissions per mile of new trucks by 15% in 2025 (compared to 2019/2020) and by 30% in 2030 (Ovaere & Proost, 2022). These targets will probably mainly be accomplished by more fuel-efficient trucks. However, to reduce emissions more substantially and even down to net zero, HGV must at least partly also use less carbon-intensive fuels, such as biofuels, e-fuels, electricity or hydrogen (Breed et al., 2021). This paper aims to investigate the most cost-effective decarbonization methods for heavy trucks (or HGVs).

We rule out hydrogen trucks because they are a inefficient way of using renewable electricity (OECD/ITF, 2022). Additionally, biofu<els are not considered as a feasible option for the future because of sustainability issues and their limited potential. This leaves us with the electric truck as the main option.

The main issue presently preventing a fast market penetration of electric battery trucks stems from the costs and weight of batteries, assuming daily distances of 700 km or more. Such a long distance would require batteries of up to 1000 TWh, or frequent recharging stops. Even if the cost of the battery were to be reduced, a remaining handicap would be the weight of the batteries (5.5 tons for 1000 TWh), which could make up a noticeable share of the payload. Of course, one can count on technological progress for batteries, but there is no guarantee that future cost decreases will be as significant as in the past. A second cost driver of battery electric trucks would be the risk of queuing at charging stations along the route, which would prove highly expensive for carriers. Consequently, carriers will be willing to pay a substantial amount to ensure queue-free recharging. They will enter contracts with charging station providers, guaranteeing queue-free recharging, necessitating a considerable and costly overcapacity of charging stations along the motorways.

There is one alternative for the battery-only electric truck; this is the battery overhead lines truck (or e-road system) that is connected for part of its trip to an overhead line via a catenary. The advantage of this technology is that it only needs a small battery to make trips to locations not connected to the major motorways. It also eliminates the time cost of recharging or the route.

Therefore, is paper compares the costs of DIEsel trucks, Battery-Only trucks (BAT) and Battery Overhead Line trucks (BOT) relying on overhead lines in a decision context. We assume that the user costs of the trucks contain the truck capital cost and the energy costs, the possible vehicle-to-grid benefits, driver costs, and other distance costs. User costs are then compared for optimized battery sizes for BAT and BOT trucks with different distance profiles. The possible user cost developments serve as input to an analysis of investment decisions in electric motorways (e-roads).

Two problems complicate the investment decision. First, the trucks originating from an EU member state equipped with overhead lines will be lost when they must use the infrastructure of a neighbouring member state that prefers battery-only electric trucks. For this reason, we analyze the non-cooperative and cooperative solutions of two countries with strongly diverging size, traffic density, and the share of international truck trips on their TEN-T network. The economics of the e-roads are therefore analyzed for two representations of the EU TEN-T network. In the first analysis, average EU truck density and truck trip characteristics are used. In the second analysis, we investigate the non-cooperative and cooperative solutions of the two countries by considering domestic and international truck transport between two neighbouring countries.

Second, there is uncertainty about future battery and e-road investment costs and battery weights. This means that there is a large uncertainty in the user cost of BAT and BOT trucks. We approach uncertainty using a two-period game where firms decide on the type of trucks to use for different distances, and where governments decide on the support for recharging infrastructure. In both periods, we assume that there are three truck types: BAT, BOT, and DIEsel trucks. However, the BOT truck can only be used if the government has invested in this infrastructure. In the first period, only proven technologies can be used, implying presently known costs and energy density of batteries, and investment costs of electric roads. The information on the cost and energy density of technologies available in the second period will only be revealed at the end of the first period. Governments must decide on their investments in the first period, considering the uncertainty in the battery cost developments. In the second period, they make follow-up decisions knowing the revealed cost information.

We define these research questions. What is the cheapest alternative fuel technology for large domestic and international trucks in the EU: battery-only trucks or overhead line trucks? How important is coordination of governments within the EU for the social costs and benefits of decarbonizing this sector more quickly? What is the impact of uncertainty on the battery cost developments and the investment and maintenance cost of the e-road for the answers to these questions?

Compared to the literature, we add three important policy features to the assessment of BAT and BOT trucks. The first is to acknowledge the potential role of vehicle-to-grid possibilities of large truck batteries in a world where the electricity supply is increasingly renewable and in need of storage options. The second is the decision under battery cost uncertainty that only unfolds over time. The third is the regional and international coordination of e-road investments.

We organize the paper as follows. The second section provides background information and delves into the findings of the literature. In the third section we study the user cost structure of electric trucks. We define total cost functions of the three types of trucks. The total cost by truck type will depend on a host of variables, including the daily truck distance and available recharging infrastructure. As the battery cost is an important cost element of the electric trucks, the battery size is explicitly optimized for different driving profiles.

In the fourth section we describe our input assumptions for two time periods. In the fifth section we present the results regarding what type of trucks and what development of infrastructure allows to optimize welfare, in the presence of uncertain battery cost development. We use average EU density and truck trip characteristics and assume that the EU decides on this basis on the investments for the whole TEN-T road network of the EU. In the sixth section we drop the assumption of a perfectly coordinated EU government. Instead, we assume that each country makes its own investment decisions regarding the e-road. We compare the welfare optimal choice of a small country (with a high share of international traffic) with a low flow of heavy-duty trucks and a large country (with a lower share of international traffic) with a high flow of heavy-duty trucks. We analyse how the non-cooperative equilibrium of the two countries impacts the welfare and investment decisions and what solutions cooperative bargaining can offer.

2. Background

2.1 Freight growth and the share of road freight

In the EU different mitigation policies have been used to address the growth of CO2 emissions for freight transport. Figure 1 represents a decomposition analysis of the evolution of CO2 emissions over the period 2000-2019. This analysis shows the growth in truck transport activity as the main driving force of the growth as well as the role of different mitigation measures. Hence, as the EU-economy is integrating, further growth of freight activity is expected. The shift to other modes (inland navigation and rail) has not been very successful. One reason for this is that the transport mode is mainly determined by the freight distance and value of the commodity.

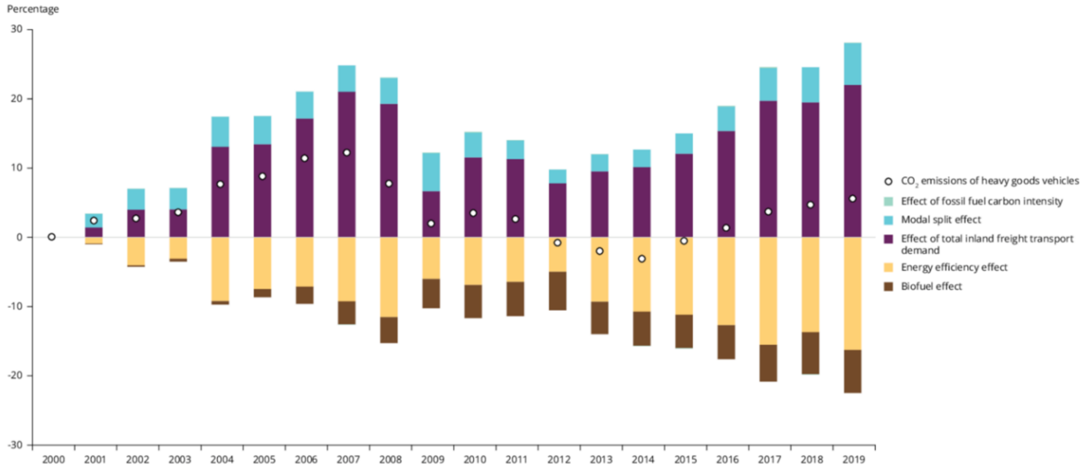

FIGURE 1 Decomposition of the evolution of CO2 emission in the EU (source EEA 2022)

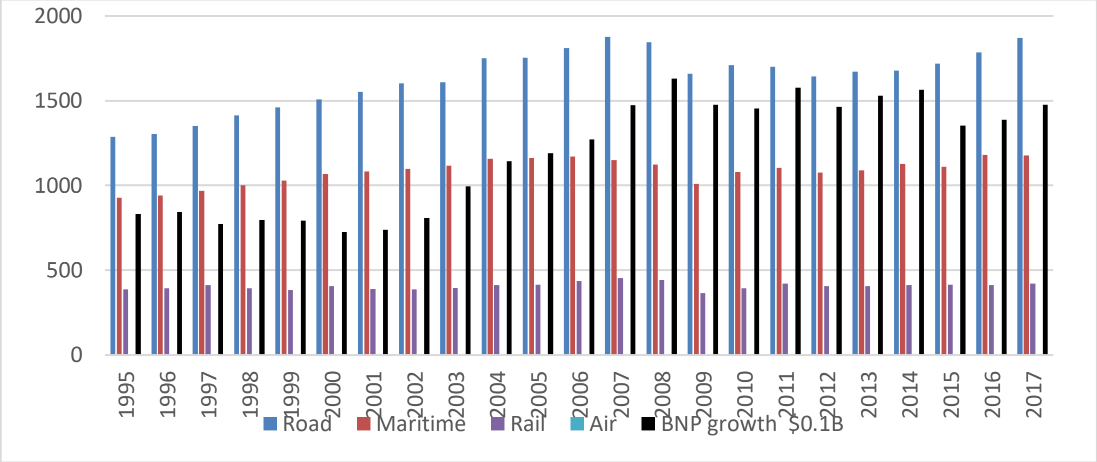

FIGURE 2 The freight transport volume by mode in the EU 1995-2017 and the GDP in the EU.[1] Billion tonne-kilometres (tkm) and $0.1B

2.2 Alternative truck fuels

Figure 1 shows that, blending diesel with biofuels was a first policy to reduce carbon emissions from trucks. In the past, when biofuels were counted as carbon free in the EU, they did reduce carbon emissions to a small extent (cfr. lowest part of the bars in Fig 1). But the use of biofuels led to other sustainability problems and EU will only allow biofuels that are deemed sustainable. The assessment of the maximum supply of sustainable biofuels are uncertain. According to Transport & Environment (2021), the maximum amount of sustaina/ble biofuels that can be used in the EU is limited to 5.8 Mtoe per year. Even if others assess that this is much larger, it is unlikely that large amounts of biofuels are available for trucks.

This leaves us with two alternative fuels in the EU: hydrogen-fuel cell trucks or electric trucks. The hydrogen option is at present considered as inefficient (OECD/ITF, 2022). Overall efficiency of using renewable electricity for a fuel-cell truck is less than 40% because the production of hydrogen via electrolysis has a limited efficiency (70%) as well as the conversion of hydrogen into electricity via the fuel cell (50%). While the efficiency of using renewable electricity in a battery electric truck is close to 90%. Another problem is the substantial investment cost for hydrogen fuel stations and distribution infrastructure (Rout et al., 2022).

In the literature, one can distinguish two types of contributions on electric trucks. There are the papers focusing on the competition between the BAT trucks and the diesel and fuel cell trucks and there are the papers that focus more on cost-efficiency of e-roads investments.

Cunanan et al. (2021) review the developments for the BAT trucks and hydrogen fuel cell vehicles (HFCVs) and discuss the advantages and disadvantages of both technologies but the relative costs are not included in the comparison. Kluschke

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[1] Sources https://www.macrotrends.net/countries/EUU/european-union/gdp-gross-domestic-product
https://www.eea.europa.eu/data-and-maps/daviz/freight-transport-volume-6#tab-chart_1

et al. (2019) review a large number of studies on more efficient carbon technologies for HGV's, including BAT and BOT. They go beyond Europe and include different parts of the world. They point to the large technological uncertainty. Only partial comparison of technologies are made Siskos and Moysoglou (2019) assess different freight transport options for the EU, including modal shift, fuel efficiency and alternative power trains and find a role for more fuel efficiency and LNG as alternative fuel. Nykvist and Olsson (2021) compare the BAT with the diesel truck and point to the importance of the decreasing weight and increasing lifetime of the battery to become competitive with diesel trucks. Feng and Figliozzi (2013) compare the costs of BAT trucks to those of diesel trucks for the USA market. Speth et al. (2022) focus on the optimal charging infrastructure for the BAT's in Germany, the costs of the BAT's and the charging are not discussed. Ibarra and Saphores (2023) go one step further and point to the traffic flow advantages of electric trucks that appear in a microscopic traffic analysis.

Börjesson et al. (2021) analyze the economics of e-roads for Sweden. They find that e-roads are a cost-effective way to significantly reduce carbon emissions from heavy trucks. In a scenario where the expansion connects the three biggest cities in Sweden, emissions from heavy trucks will be cut by one-third. The main argument against a commitment to e-roads is that investment and maintenance costs are uncertain and that due to large economies of scale and scope, the e-road system must be large for the benefit to be realized. In the long run, battery development can reduce the benefit of such roads. Deshpande et al. (2023) review several studies on the economics of e-roads. Their breakeven cost analysis of e-roads for UK, France, South-Africa and India, finds that e-roads could be an interesting investment for the densest road networks.

Compared with Börjesson et al. (2021) and Deshpande et al. (2023), we integrate the potential advantage of vehicle to grid sales for BAT trucks, we include the decreasing uncertainty over time on battery costs. Finally, we go beyond an analysis on a regional or country by country basis and assess the role of coordination and cooperation for the e-road investments.[2]

There is also literature optimizing the deployment of dynamic e-roads (Liu & Song, 2018), but, of course, this will depend on the costs. Çabukoglu et al. (2018) point out that the electrification of all trucks puts a high demand on the electric grid, which we assume is in place in both electric truck options in this study. Ghandriz et al. (2020) find that the total cost of ownership of an electric truck will change with automated driving systems due to lower costs for the driver, which is beyond the time scale we focus on.

3. Cost structure of trucks

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[2] Littlejohn and Proost (2022) looked into the coordination issues of electric roads in a two-country context where one country is more eager to introduce electric trucks than the other country. This may lead to strategic pricing of diesel by the climate friendly country and even lead to the change of tractors at the border. These are costly strategies that need to be avoided by better coordination

In this section we set up an analytical structure to compare the user costs of the three alternative technologies for long distance heavy trucks: diesel, battery electric trucks (BAT) and battery overhead line trucks (BOT). The analysis of user costs of electric trucks is made difficult by two issues.

First, this type of trucks tends to make long trips and then the range becomes a crucial issue. A long range is possible but requires either a costly and heavy battery capacity or stops underway that are costly too.

Second, a large battery capacity also allows Vehicle To Grid (V2G) services. In this case a large truck battery that is not immediately needed, is made available for helping the electric grid in case of scarcity. This type of ancillary storage is becoming more important because the renewable electricity production is relying more and more on intermittent solar and wind power production (Greaker et al., 2022). In the technical literature there is a belief in the significant potential of this battery function but some fear of battery degradation under frequent charging and discharging. Uddin et al. (2018) conclude that V2G can be economically viable, but demands a smart control algorithm, which takes into consideration the impact of V2G cycling on the battery life. This smart control algorithm limits the effective capacity to some 80% of its nominal capacity.

3.1 Model assumptions

For the specification of the cost function for diesel, BAT and BOT trucks, we use five assumptions. The first assumption is that the net battery capacity B (used in our calculations) equals the gross battery capacity divided by (1+ reserve margin). The reserve margin is necessary to allow the batteries to be used for many charging cycles. As k_e is the electricity consumption per truck kilometre (in kWh/km) the truck can cover the maximum distance B/k_e without recharging. We assume that the reserve margin is 20%.

The second assumption is that only the average cost per day is relevant for the cost function, and that there are only two types of days in a year. *Short trip* days: days with a short trip distance that can be covered in less than 4.5h of driving as this avoids a drivers' rest stop of 30 min that is mandatory in the EU. *Long trip* days: days with a long trip that requires 9h of driving, this is the maximum driving time for one driver per day and includes one compulsory rest stop of 30 min where the battery can be at least partly charged.

These assumptions allow to distinguish trucks by the number of days per year that the truck operates long trips. We assume as average speed 65 km/h and consider that the EU legislation stipulates that the driver may drive maximum 4.5 hours before a 30-minute break is required. We assume that the short trips are short enough to avoid a break for the driver, thus 4.5 h. We further assume that the long trips are no longer that 9 h, since this is the maximum travel time in the EU. Assuming 250 days per year, the annual distance of trucks making only short or only long trips are then:

- Short trips only: 4.5h x 65 km/h= 293 km/day x 250 days= 73,125 km/year

- Long trips only: (9h x 75 km/h=675 km/day x 250 days= 168,750 km/year

We assume that proportion of days per year that the truck makes long/short trips is x, and that this is distributed in the truck fleet. So, the daily distance for trucks with share x of long-distance days are $L(x) = l_s(1-x) + l_l x$. In this way we represent all trucks with annual distances between 73,125 and 168,750 km. This type of formulation (used for cars in Greaker et al. (2022)) allows to optimize the battery capacity in function of the expected number of short and long trips. We allow for V2G benefits, during days when the total battery capacity is not needed to cover the trip of the day. This may increase the optimal truck battery size in an electricity market with strongly fluctuating availability of renewables.

The third assumption regards the minimum and maximum size of the battery of the BAT truck. First, we can assume that for short trips, it is probably never cost efficient to make a recharging stop, so the minimum battery capacity B is larger or equal to the length of a short trip $(\frac{B}{k_e} - l_s) \geq 0$. Hence, for short trip days, the battery truck will fully charge its battery in the depot and use the remaining battery capacity for V2G sales.

For long trip days, the battery will again be fully loaded at the depot and will be recharged on route. But we can assume that B is never larger than the full length of a long trip $(l_s - \frac{B}{k_e}) \geq 0$, for two reasons. First the truck will have to stop anyway to respect drivers' time restrictions in the EU (9h per day). Second, as the only function of batteries larger than what is needed for a long trip is to sell off peak electricity in peak periods, it is cheaper to use dedicated batteries for electric storage than to use truck batteries that are never needed for a day trip.

A truck that makes a long trip, can either have returned to the depot or make a stop after the maximum driving time per day (9h). We assume that the recharging at the depot or on road at the end of the journey, can be done at the same electricity cost.

The fourth assumption is that the price of electricity depends on the type of charging. We distinguish four types of charging with associated electricity prices per Kwh: Home charging f^h, vehicle to grid Sales f^s, stationary recharging on route f^0 and charging via the overhead line on the e-road f^e .The choice of the battery capacity and its use is guided by the difference in these four electricity prices.

We assume that the unit electricity value of V2G sales is larger or equal to the unit cost of home charging because home charging can be at least partly in the off-peak, while V2G mainly makes sense in the peak period or in the case of balancing problems: $f^h \leq f^s$. We also expect that the unit cost of stationary on route charging is higher than the cost of home charging and higher than the vehicle to grid sales price $f^h \leq f^s \leq f^0$. The main reason for the higher cost of en route charging is that the carriers will be willing to pay a lot for access to the private charging stations without too much queuing. They will enter costly contracts with charging station providers guaranteeing queue-free recharging. The assumptions on the types of electricity costs are summarized in Table 1.

This brings us to the fifth and last assumption, that the investment cost of the electric road is covered by the government, while the maintenance cost will be split among the users. In each country, there will be only one regulated monopolistic supplier of e-roads. We assume that the marginal external cost of electric trucks (congestion, accidents, and wear and tear on the road infrastructure) is the same as for diesel trucks and is thus disregarded. Disregarding cost recovery of the e-road, the users of the e-road should ideally pay the marginal maintenance costs. However, since there are no assessments of the marginal maintenance cost, but there are assessments of the yearly maintenance costs, we assume that the users pay the yearly maintenance cost. This yearly cost is estimated to be 2% of the investment cost of the e-road (Ainalis et al., 2020; Oeko Institute, 2020). Moreover, it may also be more efficient to let the users, rather than the government, pay the full maintenance cost to finance part of the e-road. We still assume that the government pays the investment in the e-road due to high risks and network effects, and because the dead-weight loss induced by even financing charging would probably be greater than the marginal cost of public funds, at least if the e-road is competing with diesel trucks.

f	average cost of electricity		Including energy supply, network cost, fees, and charges (not taxes)	
f^{h}	home charging			
f^s	vehicle to grid sales	$f^{\mathrm{h}} \le f^s$		
f^0	stationary recharging on route	$f^{\mathrm{h}} \le f^s \le f^0$		
f^e	via the overhead line	$f^e = M_p \cdot F$	F is the average daily flow of heavy trucks	M_p daily maintenance cost
w	weight of battery			

TABLE 1 Different types of electricity costs

We assume that the yearly maintenance cost is split between the users and added to the price electricity charged from the e-road. This means that the electricity price for using the e-road is calculated as $f_p^e = \frac{M_p}{F_p}/k_e + f$, where M_p is the daily maintenance cost per kilometre of e-road in period $p \in \{1,2\}$, F is the average daily flow of heavy trucks multiplied by their average electricity consumption per km and f is the average electricity cost. The investment cost of the private charging stations on route is covered by the electricity price on route. With these assumptions we can formulate user cost functions by truck type.

3.2 The cost functions

The average daily cost per payload V (tonnes) with a diesel truck is defined as

$$u_D(x) = \{P_d + T_d) + \big((1-x)l_s + xl_l\big)\,\big(k_d(d+b) + v_d\big)\}\frac{1}{V} \qquad (1)$$

where the first term is the daily annuity of the purchase cost and purchase tax $P_d + T_d$. The second term represents the variable costs, including the fuel cost (d) and the fuel tax (b) per litre times the unit fuel consumption k_d (liter diesel/truck km) plus the other variable costs v_d per truck km. The operation cost per truck km is then multiplied by the average daily distance.

For the BAT truck, remember that we assume that the minimum battery is equal to $k_e l_s$, i.e., that they can make short trips without recharging as stated above, and that the maximum battery capacity B is $k_e l_l$. Remember also that we assume that only 80% of the full battery power is used as a reserve margin of 20% is important for the longevity of the battery. The battery capacity B is expressed in net terms in the average daily cost per payload V (tonnes). The equivalent average daily cost of a BAT truck with x long trips per year and net battery capacity B and payload V is in period p

$$u_{BAT}\,(x_l, B, p) = \Big\{P_a^p + (1-x)k_e\Big[\,(l_s\, f^h - (f^s - f^h)\Big(\frac{B}{k_e} - l_s\Big)\Big] + xk_{e1}\Big[\frac{f^h B}{k_e} + f^0\Big(l_l - \frac{B}{k_e}\Big) + v\Big(\,l_l - \frac{B}{k_e}\Big)^{1.2}\Big] + \big((1-x)l_s + xl_l\big)(t + v_a)\Big\}\Big(\frac{1}{(V-wB)}\Big) + aB, \qquad (2)$$

where the first term P_a^p is the daily annuity for the purchase cost (excluding the battery cost aB) of an electric battery truck in period p. The second term $(1-x)k_e\Big[\,(l_s\, f^h - (f^s - f^h)\Big(\frac{B}{k_e} - l_s\Big)\Big]$ represents the average cost that is generated by a short trip day. It consists of the cost of electricity charged at the depot minus the benefits of a V2G sale by using the battery capacity that is not needed for the short trip $(B/k_e - l_s)$, times the difference between the sales price of peak electricity and the home charging electricity cost $(f^s - f^h)$.

The third term $xk_e[f^h B + f^0\,(l_l - B/k_e) + v(\,l_l - B/k_e)^{1.2}]$, represents the average daily cost of a long trip that consists of the costs of charging fully the battery at the depot $f^h B$, plus the fuel cost of charging on route $f^0(l_l - B/k_e)$, plus the scheduling and discomfort costs of refuelling en route $v(\,l_l - B/k_e)^{1.2}$. The scheduling and discomfort cost is assumed to be increasing in the time spend at the stop because the waiting time becomes less useful the longer the truck waits. We chose an exponent of 1.2, representing a slight non-linearity. Finally, there are the taxes proportional to distance t, and variable costs for the average daily trip v_a.

Note that the operation cost per payload here increases with the weight of the battery wB, where w is the battery weight in tonnes/kWh. Finally, there is the cost of the battery itself.

For battery overhead or catenary trucks (BOT) we need additional assumptions on the coverage of the network. For trucks operating domestically, or if all countries coordinate the provision of electric roads, we assume that a share θ_s and θ_l (for short- and long-distance trips) of the distance is on an e-road.

The owner of a BOT truck will connect to the overhead lines whenever they are available, and will fully charge the battery at the depot, drive on battery power, and use the remaining battery power for V2G sales. The average daily cost per payload V for the BOT truck is in period p

$$u_{BOT}(x_l, B, p) = \Big\{ P_p^b + (1-x)k_e\big[\,(\theta_s l_s f_p^e + (1-\theta_s)\,(f^h l_s - (f^s - f^h)(B/k_e - (1-\theta_s)l_s)\big] + xk_e\Big[\theta_l l_l f_p^e + f^h B/k_e + f^0\left(l_l - \frac{B}{k_e} - \theta_l l_l\right) + v\left(\,l_l - \frac{B}{k_e} - \theta_l l_l\right)^{1.2}\Big] + ((1-x)l_s + xl_l)(t + v_a)\Big\}\left(\frac{V}{(V-wB)}\right) + aB \qquad (3)$$

which is fully equivalent to the cost function for BAT trucks for the share of the road network not covered by the electric road (1- θ). For the part , θ, covered by the electric road, it will charge from the overhead power lines. During the short trips, the truck will not have to charge from the public charging station so that the minimum battery size is $(1-\theta_s)l_s k_e$. The maximum battery size is $(1-\theta_l)l_l k_e$, covering the full distance when off the e-road. Hence with maximum battery size, the BOT truck will never have to charge on route.

We also assume that the BAT truck cannot charge its battery when travelling on the e-road because it is not equipped for that. Note that the price of electricity when charging on the e-road, f_p^e, varies between the time periods because the maintenance cost per kilometre road M_p varies between time periods.

3.3 Optimal battery size for the battery only truck (BAT)

In this section, we derive the optimal (net) battery size, B^*, as a function of the proportion of days that the truck makes long and short distance trips. We constrain the battery size between the minimum size required for a short trip $B^{min} = k_p^e l_s$ and the maximum size required for a long trip $B^{max} = k_p^e l_l$.

Neglecting the cost of the extra weight of the battery making up part of the truck's payload, the first order condition for cost minimization w.r.t. B for given x >0 (for B>B^{min}) is derived from (2) as

$$x(\,f_e^h - \,f_e^0) \;-\; 1.2xk_p^e v\left(l_l - \frac{B^*}{k_p^e}\right)^{0.2} - (1-x)\,(f_e^s - f_e^h) + a = 0. \quad (4)$$

If the non-linear charging cost is increased from 1.2 to 2, we can derive a linear function for the optimal battery size from (4) as

$$B^* = k_e l_l + \frac{1}{2vx}[(x(f_e^o - f_e^h) + (1-x)(f_e^s - f_e^h) - a]. \qquad (5)$$

This shows that the optimal battery size is a balance between the marginal benefit of a larger battery for a given x because it decreases the cost of charging en route (first term in the brackets) and increases the benefit of V2G on short trop days (second term in the brackets), and the marginal cost of a larger battery, a (third term in the brackets). Figure 3 depicts the balance within the limits B_{min} and B_{max}. The marginal benefit due to less recharging on route is decreasing linearly in B ($x(f^0 - f^h)$, the blue line in Figure 3), the marginal benefit curve shifts upwards with the V2G term $(1 - x)(f^s - f^h)$ (green line in Figure 3). Increasing the number of long trips per day x shifts the marginal benefit curve upwards (dotted blue and green lines).

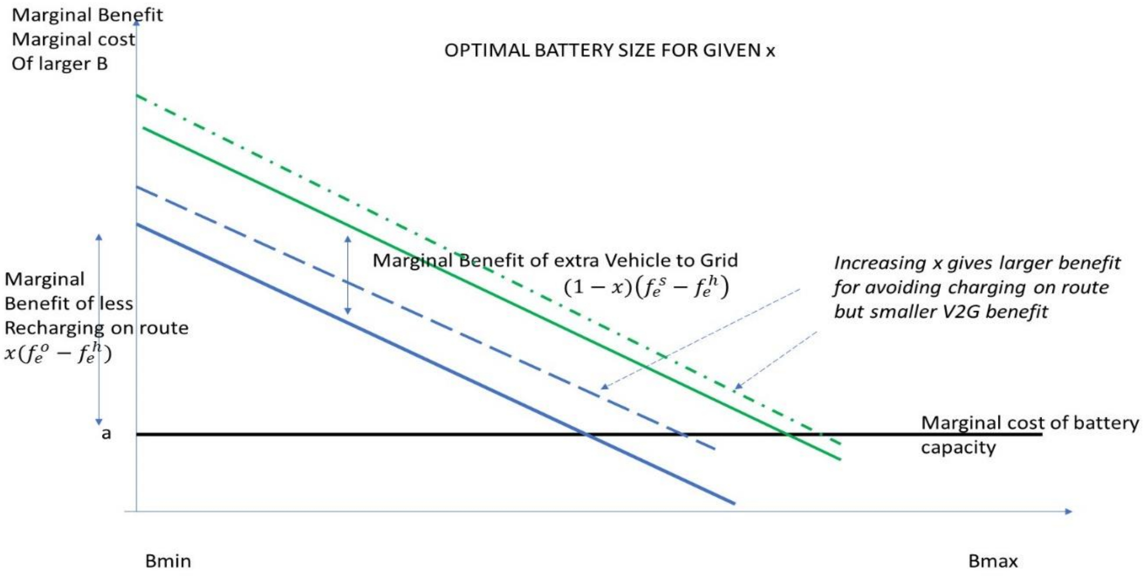

FIGURE 3 Optimal battery size for a Battery Only Truck (BAT)

3.4 The Battery size for Catenary trucks

Catenary trucks only need a battery when they are not on the e-road. When the e-road only serves a share θ of the distance, the optimal battery is decreasing in this share θ. The battery size has now a lower minimum and maximum: the minimum needed for a short trip $B^{min} = (1 - \theta_s)\, k_e l_s$ and the maximum needed for a long trip $B^{max} = (1 - \theta_l) k_e l_l$.

As the marginal benefit of extra battery capacity is lower than for a BOT and the marginal cost of extra battery power is the same, the optimal battery size will be smaller The marginal benefit curve will be shifted downwards relative to the functions in Figure 3 (and since the electricity is charged from the e-road the slope will differ).

3.5 Total cost function for different technologies

The cost of different truck technologies depends on the resource costs as well as on the infrastructure supply. Figure 4 illustrates the relative costs under simplified assumptions. A diesel truck has the highest variable cost but a relatively low vehicle cost because it does not need a battery. So, for short distances, the diesel truck is competitive. If the motorways have an e-road, the catenary truck also has a low vehicle cost because only a small battery is needed (and no combustion engine). The variable cost is also low. So, disregarding the installation and maintenance costs of the e-road equipment, it is the cheapest option for all numbers of long trips per day or yearly distance classes.

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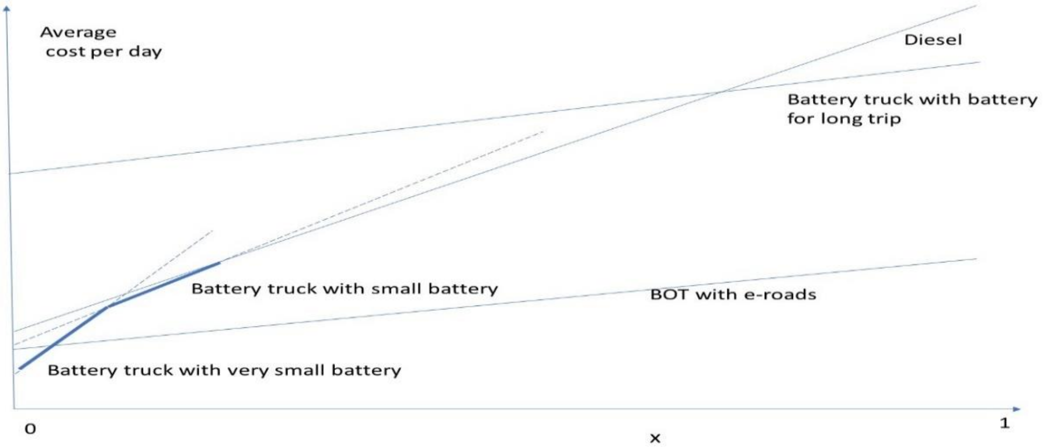

FIGURE 4 Total cost of using trucks under different assumptions

The BAT truck also has a low variable cost (comparable to the e-truck) but needs a bigger battery and thus has a higher fixed cost. Therefore, it is likely to be only an option for trucks with a large share of long trips.

A BOT truck designed for short trips and thus having a small battery is shown as a dotted cost curve in Figure 4. When this truck is used for a long trip, it will have to stop for on-route charging, and this means that the slope of the cost function increases. For trucks making more long trips, one chooses a larger battery, implying a higher fixed cost but lower variable cost. In this way one can construct the minimum cost envelope for the BAT truck (shown as bold solid curve on Figure 4). In the limit, with maximum battery capacity, we are back at the case with no refuelling stops.

Finally, we introduce V2G benefits, coming into play when the battery size exceeds the requirements for a short trip on days with short trips. These increases the optimal battery capacity (see Figure 3).

4. Data

In the initial analysis, we assume that the EU coordinates the installation of e-roads on the core TEN-T network in the EU. The decision is based on the average density and cost conditions for the whole EU. However, in Section 6, we will expand our analysis by considering a scenario where there is no coordinated effort to introduce e-roads in the EU, with the risk that international trips are unable to use the e-road infrastructure in neighbouring countries. We do this for countries with lower and higher densities of the road network and with low and high share of international trips. In this section, we present only the most important input data. More details can be found in Appendix 1.

4.1 Distances

The trips in the EU can be categorized into three main groups: short-haul, medium-haul (50-400 km), and long-haul (>400 km) trips (van Grinsven et al., 2021). In this paper, we will not consider short-haul trips. Our short trips, defined in Section 3, are taken to represent medium-haul trips with average trip distance of $l_s = 293$ km. Similarly, our long trip will represent long-haul trips with average distance $l_l = 675$ km (Figure 8 in T&E (2021)). The total vehicle kilometers travelled by medium and long-haul trips account for 40% and 53% of all truck vehicle kilometers (vkt), respectively. However, the respective shares of trips (rather than vkt) are only 35% and 11%. From these numbers, we arrive at the proportion of trucks in three segments, ρ_x, and their number of long-distance trips $x = \{0.1, 0.5, 0.9\}$, as described in Table 2.

Share of trucks ρ_x	ρ_xf days with long trips, x
75%	10%
10%	50%
15%	90%

TABLE 2 Distribution of the number of trucks with long trip days.

4.2 E-roads investments and user costs

We assume the core TEN-T network is electrified. The length of this network is approximately 30,000 km (Transport & Environment, 2021). The flow of HGVs on the e-road has a significant influence on the user charge, since we assume that the users bear the maintenance cost, which is assumed to be a function of the number of users (while the government covers the investment cost).

The average flow of HGVs is 6,600 trucks/day on the Core TEN-T motorway network. However, there is a large variation in traffic flows of HGVs among countries, where the Netherlands has on average more than 10,000 trucks while Sweden has just over 3,200 trucks/day. We assume that the average flow of HGV stays constant over time, given that it has remained almost constant over the period 2011-2019 (CEDR, 2020).

According to Oeko Institut (2020) the annual maintenance cost amounts to 2% of the investment cost. Using this assumption for period 1 and period 2 and the investment cost and average traffic flow, we can calculate the user charge. Because the transition to e-trucks takes time, we assume that in a representative year in period 1, only half of the trucks utilizing the core TEN-T network use the e-road. It is further assumed that θ_l =73% of the long-distance trips and θ_s = 62% of medium distance trips are made on the TEN-T network (thus on the e-road).[3] Investment costs of the e-road, and other input data is given in Table 4.

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[3] The share of the distance that are driven on the TEN-T network are calculate bas on the following input data: 44% of the long-distance trips (>400 km), travel on the TEN-T network only (Transport & Environment, 2021, Fig 7). Another 44% trips above 400 km, travel to or from locations connected to the TEN-T, so that 80% of their travel distance takes place on the TEN-T network. Together this suggest that 44%+44%x80%=79% of the travel distance by trips >400 km, takes place on the TEN-T network. But we also allow for some additional distance outside the TEN-T network and assume that trucks travelling longer than 400 km per day travel 73 percent of their distance on the TEN-T network. For trucks travelling 150-400 km, the corresponding number is 62 percent.

4.3 Truck costs

We assume that the number of heavy trucks in the EU that are used for long trips and need to be electrified N = 700,000.[4] The fuel and capital costs, which are assumed to remain constant across the two periods, are described in Table 3. The capital cost and weight of the battery, as well as the investment and maintenance costs of the e-road (which determine the price of electricity charged from the e-road), are uncertain in the second period and are shown in Table 3. All capital costs are computed per day, using a discount rate of 4% and an economic lifetime of 7 years and 250 days per year.

	Period 1 and Period 2	Note
Diesel price €/liter	1,08	EU average ICC,T (2021), Table 9
of which diesel tax €/liter	0,45	EU average ICCT (2021), Table 9
Diesel consumption, l/km	0,307	ICCT (2021)
Electricity consumption, Kwh/km	1,1	ICCT (2021)
Electricity cost – overhead €/Kwh, f	0.119	EU average ICCT (2021), Table 10
Electricity cost depot charging €/Kwh, f^h	0,16	ICCT (2021), Table 10
Electricity cost charging en route €/Kwh, f^0	0,41	ICCT (2021), Fig 7
Electricity price for selling to grid €/Kwh, f^s	0,28	
Diesel truck € (€/day)	150,000 (89)	Kunnel 2019 and the ICCT (2021). To calculate cost per day, assume 7 years, 250 days/year and discount rate 4%.
BAT excl battery € (€/day)	100,000 (59)	
BOT excl battery € (€/day)	125,000 (74)	

TABLE 3 Fuel and capital costs

In the first period, the cost of batteries and the investment and maintenance costs of electric roads are by assumption known. In the second period, we introduce uncertainty for the investment costs. This uncertainty is only resolved at the end of the first period. One of the important parameters is the unit battery cost. In two scenarios i) and ii) in period 2, we combine an assumption on the battery cost and an assumption on the cost of the e-roads. In scenario i), the high battery cost and weight is combined with a low investment and maintenance cost of the e-road, (maintenance cost 2% of investment cost), and in scenario ii) the low battery cost and weight is combined with the high investment and maintenance cost of the e-

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[4] The number of trucks to be electrified matters for the cost calculations as there are important cost differences between the different types of trucks. In the EU, there are 1.3 million long-haul trucks and 1.3 million medium-haul truck. But new trucks are used much more than old trucks. Many of the old trucks have a low annual mileage because they are not used for longer trips. However, given that the road network of 300,000 km has an average flow of 660 trucks per day, with an average milage of 400 km, and travelling 70% of the travel distance on this network, 700,000 trucks are needed. This is the number of trucks that do some long trips and with which we work here.

road (maintenance cost 4% of the investment cost) of the e-road. The investment costs in the second period do not depend on the investment decisions taken in the first period because we assume that the economic lifetime of the investments is smaller than the length of the first period. In addition, we assume that the technical progress in batteries is driven by the e-car production sector.

	Period 1	Period 2 i)	Period 2 ii)	Source/ Comment
Battery cost €/Kwh (€/Kwh/day)	150 (0.089)	LOW battery cost 75 (0.045)	HIGH battery cost 125 (0.074)	ICCT (2021). To calculate cost per day, assume 8 years, 250 days/year and discount rate 4%.
Weight of battery in tonne/Kwh	0,008	LOW 0,004	HIGH 0,005	(Basma et al., 2021)
Investment cost e-road €/km	1,700, 000	HIGH e-road cost 1,000,000	LOW e-road cost 1,500,000	Swedish transport administration, 2023.
Electricity price charging from e-road, €/vkm, $f_p^s = \frac{M_p}{F} + f$	0,042+ 0.119= 0,161	HIGH e-road cost 0.019 + 0.119 = 0.138	LOW e-road cost 0.013 + 0.119 = 0.132	Assume user cost 2%/4% of maintenance cost (Oeko Institute, 2020). Also in TRV UK report (Ainalis et al., 2020).

TABLE 4: Uncertainties in the second period

5. Results

In this section we report results for the TEN-T motorway network. By assumption, one coordinated decision is taken for the whole network based on average truck densities on the network. For each period and each cost scenario, the benefit cost ratio of the e-road investment is assessed.

5.1 Period 1

We report the average user costs of trucks as function of the number of days with long trips given an optimal battery size. Therefore, we start with a numerical optimization of the battery sizes for both the BAT and BOT trucks using equations (2) and (3). The battery size results are presented in Table 6. In period 1, we observe that the optimal battery size for the BAT truck increases with the share of long trips, due to the high cost of recharging en route, implying higher electricity costs and waiting times for the drivers. Selling to the grid on the days when the trucks make short trips helps making up for the high cost and weight of the battery needed for the long trips as indicated by Figure 4. Conversely, the BOT truck is equipped with a smaller battery, designed to primarily cover the distance without e-road infrastructure. The battery size for the BOT truck remains relatively stable across different shares of long trips, even if the truck making mostly short trips, has the smallest battery size.

Given the optimal battery sizes in the first period, the BOT truck proves to be cheaper than both the diesel and the BAT truck, across most shares of long trip days x (only the diesel truck is cheaper for small x). The main driver of this result is the lower fuel cost for the BOT truck. For short trips, where the battery is not fully used, the BOT truck can also reduce the net cost by selling electricity to the grid.

Table 7 reports the welfare analysis of the e-road for period 1, we compare the diesel truck to the BOT truck, since the diesel truck is then the second-best option. Moreover, we assume that the diesel tax only internalizes half of the carbon emissions from the diesel truck, such that the non-internalized carbon cost, φ, corresponds to 4 €-cent per vkt.[5] The daily capital investment cost assuming 4% discount rate 250 days per year and an economic life of 10 years for period 1 is I_1. The Swedish Marginal Cost of Public Funds, π, is taken to be 1.2. This means that the social benefit (here a cost saving) per day of the e-road is calculated as

$$\Omega_1 = N \sum_x \rho_x(u_{BOT}(x, B^{max}, 1) - u_{DIE}(x) + (1-x)\varphi l_s + x\varphi l_l) + \pi I_1 \qquad (6)$$

The net benefit cost ratio, NBCR is calculated as (the cost saving per € of investment) is 0.64 for period 1 indicating a social welfare gain.

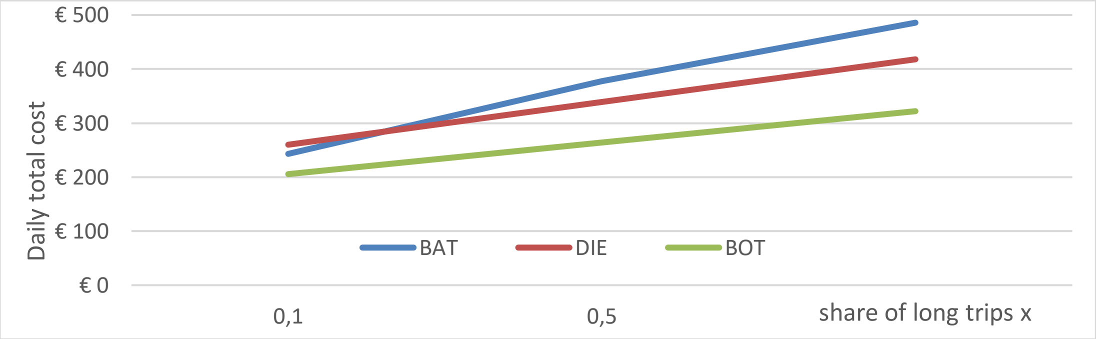

FIGURE 5 Average cost of trucks in function of average number of long trip days

Share of long-distance trips	BAT	BOT
Period 1		
0.9	927	251
0.5	781	251
0.1	402	251
Period 2 high cost		
0.9	927	251
0.5	927	251
0.1	642	251
Period 2 low cost		
0.9	927	251
0.5	927	251
0.1	927	251

TABLE 6: Optimal battery size, B in kWh

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[5] Applying the price of carbon suggested by the EU Handbook (European Commission et al., 2020), €100/tonne, and the fuel consumption given in Table 3

	Period 1	Period 2 high battery cost, low inv.cost e-road	Period 2 low battery cost, high inv.cost e-road
Number of trucks to electrify[6] N	353,571	707,143	707,143
User cost of BOT - DIE per day and truck, €/day/truck $u_{DIE} - u_{BOT}$	-88		
User cost of BOT - BAT per day and truck, €/day/truck $u_{BAT} - u_{BOT}$		-106	-63
Total benefit of BOT, €/day $N(u_{BAT} - u_{BOT})$	31,009,811	74,736,101	44,541,423
Daily investment cost of e-road (discounted, 10 years 4%, MCPF 1.2) €/day I_1, I_{2low}, I_{2high}	25,683,970	15,410,382	23,115,573
Carbon emissions €/day	9,330,787		
NBCR = $\frac{\Omega}{I}$	0.64	3.65	0.73

TABLE 7: Welfare calculation, Net Benefit Cost Ratio.

5.2 Period 2

For the high and low battery cost scenarios, we compare the BOT to the BAT trucks, since diesel trucks have the highest user cost in both scenarios in period 2, see Figure 6.

Even in the scenario with low battery costs and high e-road infrastructure costs (scenario ii), the cost of the BOT truck is lower than that of the BAT truck because the BOT requires a smaller battery. Interestingly, the cost of the BAT truck is still the most sensitive to the share of long trips, x (i.e. it is the steepest line), because it has a smaller battery; the big battery of the BAT is useful also in the days the truck makes short trips because it saves costs by selling electricity to the grid. In the low battery cost and weight scenario, the cost of the BOT and the BAT are almost the same for the truck making short trips on 90% of the days, because the large battery of the BAT truck can be used for V2G on these days. But for trucks making long trips on 90% of the days, the cost is higher for the BAT, because the heavy battery reduces the payload of the truck, and it cannot be used for V2G more than 10% of the days. In both scenarios in the second period, the diesel truck is the most expensive, because of its high fuel cost. In the high battery cost and weight scenario i, the BAT truck becomes more expensive, and is barely cheaper than the diesel truck.

The welfare for the high and low battery costs scenarios is calculated as

$$\Omega_2 = N \sum_x \rho_x (u_{BOT}(x, B^{max}, 2) - u_{BAT}(x, B^{max}, 2)) + \pi I_2. \qquad (7)$$

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[6] We assume that on average only half of the trucks are electrified in the first period because it takes some time to build the e-road and adapt the truck fleet?

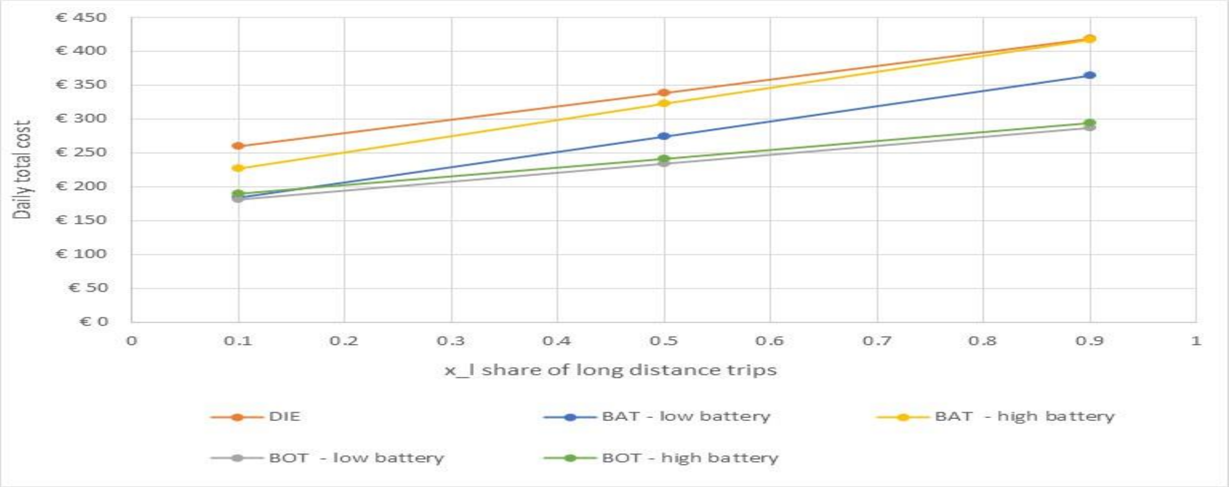

FIGURE 6 average daily cost of different trucks with payload V in period 2

5.3 Welfare optimal decision

Using the results reported in Table 7, in the first period, the welfare effect of installing e-roads is positive. There would be a weak welfare gain of the e-road even if the carbon cost associated with the diesel truck was already internalized. In the second period, the welfare effect is positive in both scenarios. Nonetheless, since the e-road is welfare-increasing in the second period for both scenarios and welfare increasing in period one, assuming only an economic life of 10 years, the recommended policy advice would be to construct the e-road in the first period. This strategy would not only contribute to the target for carbon emissions in the EU ESR sector by 2030 but also reduce the investment and maintenance cost of the e-road in the second period due to learning by doing.

6. International cooperation

6.1 Set-up

In the previous section, it was assumed that the decision to construct an electric road is coordinated by the EU, using average density and truck trip characteristics, resulting in its construction along the 30,000 km long TEN-T road network. Furthermore, the analysis assumed that the maintenance cost is evenly distributed among all users, and therefore that the user charge is the same over the whole network, regardless of substantial variations in traffic flow across the TEN-T road network. This coordination assumes full cooperation.

In this section, we examine the effect of a lack of coordination and cooperation, when each country independently decides whether to build an e-road or not. We do this for a two-country case, where one country is better suited for e-roads than a neighbouring country. Both countries have domestic trips and international trips where they use the road network of the neighbour.

The first country (country D, Germany) is a relatively dense and large country with a high average flow of heavy trucks on the core TEN-T road network but a low share of international traffic. The second country (country S, Sweden) is a less dense and smaller country with a lower average flow of heavy trucks but a high share of international traffic. We expect that the share of international trips is higher in a small and less dense country because there is a smaller probability to find the right trade match within the country.

Table 8 shows the decision structure. Both countries can decide to invest in e-roads: indicators iD and iS = 0 mean no investment in the country while iD and iS = 1 stand for investment in e-roads the country. These investment decisions need to be taken in the first and second period and will generate country welfares in the first period $D\Omega_1$, $S\Omega_1$ and in the two scenarios in the second period $D\Omega_{2i}$,..,$S\Omega_{2ii}$. The country's welfares will depend on the investment decisions in the two countries as the international trips also use the network of the neighbour.

A cooperative equilibrium can always do as well as the non-cooperative equilibrium and possibly better. Cooperation, in the form of a subsidy to S from D, makes only sense when installing e-roads in both countries produces lower total cost levels than only installing it in country D.

$$D\Omega(iD = 1, iS = 1) + S\Omega(iD = 1, iS = 1) < D\Omega(iD = 1, iS = 0) + S\Omega(iD = 1, iS = 0) \tag{8}$$

We study this problem using the Nash-Bargaining solution (Nash, 1950). This starts from the threat point (iD=1,iS=0) and next maximizes the product of the utility functions to find the allocation of the benefits of cooperation. The net utility function UD of country D for the bargaining is defined as the cost advantage of the solution where also country S invests in e-roads minus the transfer T from D to S

$$UD(T) = D\Omega(iD = 1, iS = 1) - D\Omega(iD = 1, iS = 0) - T(D\ to\ S) \geq 0 \tag{9}$$

And similarly for country S

$$US(T) = S\Omega(iD = 1, iS = 1) - S\Omega(iD = 1, iS = 0) + T(D\ to\ S) \geq 0 \tag{10}$$

Maximizing the product UD(T) · US(T) w.r.t T does not give us extra information because we have discrete investment decisions. The only requirement is that both UD(T) and US(T) are positive.

6.2 Assumptions and input data

Compared to the previous section, we need to specify, for the two countries, the density characteristics of their TEN-T network and the share of domestic and international truck trips. For domestic trips, we assume that the distribution of trucks with respect to share of trucks with long-distance days x is the same[7] in the two countries (as in Table 2). For international trips, we assume that all trips are long-distance. The share of long-distance trips in country $C \in \{D, S\}$ that are international is denoted γ_C. We do not distinguish between the origins of the trips as we assume that the cost and the gains from trade are shared equally between

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[7] As Sweden is the less dense country, one could assume that the number of long trips is higher in Sweden and that the share of the distance driven in S by international trips is also higher, but we have no strong evidence for this. It would make the case for building electric roads stronger.

the two countries. Moreover, we assume that the share of the distance driven in S and D is δ=0.5 in both.

	D (Germany)	S (Sweden)
Flow relative to average flow in EU	178%	53%
Share of EU trucks (proportional to population)	21%	2.6%
Km electric road in Core network	21%	9.5%
Share of domestic trips	90%	50%

TABLE 8 input data for the big(D) and small (S)country

Table 8 summarises the input data for each of the two countries, which are taken from Table 22 in CEDR (2020). The average AADT (annual average daily traffic, F) for heavy vehicles in the EU TEN-T core road network is just above 5000. For Germany, it, $F_{\mathrm{C=D}}$, is higher than this, 178%, and for Sweden, $F_{\mathrm{C=S}}$ it is lower, 53%.

We also need the total number of trucks, N, by country country $C \in \{D, S\}$. We assume that the county's share of the total number of trucks in the EU is proportional to the country's share of the EU population. Germany has just over 20% of the total EU population, and of the TEN-T network. Sweden has less than 3% of the EU population but as much as 9,5% of the TEN-T network, is much less densely populated than Germany. Finally, the share of international traffic by country, γ_C, is taken from Eurostat (2022), for Germany and from the Swedish Transport Administration (2021) for Sweden. It is $\gamma_{C=D}$ =10% for Germany and $\gamma_{C=S}$ =50% for Sweden.

We assume that the costs of electricity supply are the same in both countries as both countries are interconnected and there is one European electricity market. The maintenance cost of the e-road per truck kilometre will be lower in countries with high flow of trucks on the road network than in the country with low flow of trucks. To consider this, the length of the electrified TEN-T road network by country, is denoted LC, and the average traffic flow denoted FC. This means that the cost of electricity (including maintenance) charged from the e-road is country specific, $f_{pC}^{e} = f + \frac{M_p}{F_{\mathrm{C}}}/k_e$ (remember that $p \in \{1,2\}$ is period).

We adjust (3) to define the daily average cost for the BOT truck for country in period p if both countries have an electric road. The daily average cost consists of a weighted average of three costs: first the short domestic costs, next the international long trips and finally the domestic long trips.

$$u_{BOT}(x_l, C, p) = \Big\{P_p^b + (1-x)k_p\big[\,(\theta_s l_s\, f_{pC}^e + (1-\theta_s)\,(f_e^h\, l_s - (f^s - f^h)\big(B/k_p - (1-\theta_s)l_s\big)\big] + (1-\gamma_C)xk_p\left[\theta_l l_l f_{pC}^e + \frac{f^h B}{k_p} + f^0\left(l_l - \frac{B}{k_e} - \theta_l l_l\right) + v\left(\,l_l - \frac{B}{k_e} - \theta_l l_l\right)^{1.2}\right] + \frac{1}{2}\gamma_C x k_p\left[\theta_l l_l \overline{f_p^e} + \frac{f^h B}{k_p} + f^0\left(l_l - \frac{B}{k_e} - \theta_l l_l\right) + v\left(\,l_l - \frac{B}{k_e} - \theta_l l_l\right)^{1.2}\right] + ((1-x)l_s + x l_l((1-\gamma_C) + 0.5\gamma_C))(t + v_a)\Big\}\left(\frac{V}{(V-wB)}\right) + aB \qquad (11)$$

The term $\frac{1}{2}\gamma_C x k_p\left[\theta_l l_l f_{pC}^e + f^h B/k_p\right]$ reflects country C's cost for the international trucks, which only takes half of the cost of international trips into consideration. For international trucks, travelling half of the distance in each country, the average electricity cost on the e-road in the two countries is denoted $\overline{f_p^e} = \frac{1}{2}\sum_{C=1,2} f_{pC=1}^e + f_{pC=2}^e$.

If country C is the only county investing in e-roads, the θ_l is replaced by $0.5\theta_l$ and $\overline{f_p^e}$ is replaced by f_{pC}^e for international trips in (11). Hence, the international traffic can only use the e-road within the country, where 50% of the travel distance is made. This requires a bigger minimum battery size to avoid recharging. We further assume that if country C does not invest in e-roads, it has no BOT trucks, even if the other country invests in e-roads.

In the non-cooperative equilibrium, the total welfare in each of the two countries for period 1 and scenarios i) and ii) for period 2 is computed using (11) and its equivalent for the BAT truck. To avoid double counting, the benefit of reduced carbon emissions in period 1 is only considered for the truck distance travelled within each country's border.

6.3 The non-cooperative and cooperative equilibrium, period 1

Table 9 shows total welfare for the two countries for the cases where only one country and when both countries invest in e-roads. We compare for each combination of investments in e-roads, the difference in the user cost of the diesel truck with the BOT truck, because in period 1 the diesel truck is the relevant second-best option in our calculation. We find that in the Nash equilibrium, Germany invests in e-roads, but Sweden does not (iD=1,iS=0).

€/day	Benefit for D (big country)		Benefit for S (small country)	
	Only D has e-roads	D & S have e-roads	Only S has e-roads	D & S have e-roads
Number of trucks	75,254	75,254	9,241	9,241
total cost of BOT - DIE per day and truck, €/day/truck (incl. maintenance cost of e-road).	-97	-110	-40	-108
total benefit of BOT per day	7,290,225	8,259,310	371,859	998,451
invest cost of e-road	5,437,501	5,437,501	2,444,441	2,444,441
Carbon emission	1,493,936	1,493,936	183,445	183,445
NBCR	0.42	0.59	-0.97	-0.72
Total benefit of BOT - DIE	2,259,159	3,228,244	-2,378,025	-1,751,433
Benefit of cooperation		969,085		626,592

TABLE 9 Welfare calculation for e-roads period 1. Big (D) and small (S) county

The reason why Germany invests in e-roads and Sweden does not is that there are the number of trucks is eight times higher (requiring batteries) in Germany than in Sweden, more than three times larger traffic flow on the TEN-T network, and that 90% of long-distance traffic is driven inside Germany. For Sweden, investing in e-roads is not welfare-increasing because the flow of trucks on its network is too small. Adding German BOT trucks on the Swedish network helps but is insufficient to make Sweden install e-roads.

Since iD=1,iS=0 is the Nash equilibrium we use as the threat point for the bargaining solution. It may be the case that the absence of e-roads in country S decreases the benefit of the e-road in country D. This brings us to the second step, a cooperative solution, where country D gives subsidies to country S to install e-roads. Cooperation makes sense when (8) holds. TABLE 9 shows that the gain for Germany of being able to use the e-roads in Sweden amounts to 969,085 €/day. But this is insufficient to pay for the net costs in Sweden of installing e-roads (1,751,433). Hence, in period 1 only Germany will install a network of e-roads.

6.4 The non-cooperative and cooperative equilibrium, period 2

In period 2, the countries learn what state of the world will be realized: high or low battery costs and low or high e-road investment costs. Results are reported in Table 10.

€/day	D		S	
	Only D invests	D and S invest	Only S invests	D & S invest
scenario i) high battery cost & weight + low investment and maintenance cost of e-road				
Number of trucks	150,508	150,508	18,481	18,481
total cost of BOT – DIE	-101	-106	-67	-91
total benefit of BOT per day	15,238,617	15,908,787	1,246,710	1,674,602
invest cost of e-road	3,262,501	3,262,501	1,466,664	1,466,664
NBCR	3.47	3.68	-0.35	-0.06
Total benefit including trucks + infrastructure	11,323,616	11,993,786	-513,288	-85,395
Benefit of coordination		670,170		427,892
scenario ii) low battery cost & weight + high investment and maintenance cost of e-road				
Number of trucks	150,508	150,508	18,481	18,481
total cost of BOT - DIE	-56	-60	-10	-37
total benefit of BOT per day	8,379,204	8,966,029	185,607	685,031
invest cost of e-road	4,893,751	4,893,751	2,199,997	2,199,997
NBCR	0.51	0.63	-1.12	-0.89
Total benefit including trucks + infrastructure	2,506,703	3,093,528	-2,454,389	-1,954,965
Benefit of coordination		586,825		499,424

TABLE 10 Welfare calculation for e-roads period 2. Big (D) and small (S) county

For country D, it is always welfare increasing to invest in e-roads, whatever the smaller country S does. For country S, it is not welfare increasing to invests in e-roads, unless it is subsidized:

- if battery costs turn out to be low and investment costs are high for e-road cost increase of 513,288 (only S) and of 85,395 (S+D)
- if battery costs turn out to be high and investment costs low for e-road. cost increase of 2,454,389 (only S) and of 1,954,965 (S+D)

The Nash equilibrium in period 2 is that only Germany will build the e-road (iD=1, iS=0) in both scenarios. Cooperation only makes sense if condition (8) holds. This is the case in scenario i) with high battery cost, but not in scenario ii) with low battery cost. Therefore, if scenario i) occurs, cooperation will take place, resulting in Germany subsidizing Sweden with an amount between €85,395 and €670,170. Subsequently, both (9) and (10) will be positive.

7. Conclusions

In this paper we analyzed the economics of e-roads for the truck sector in the EU distinguishing the medium and the long term. The costs of trucks include the capital and maintenance costs as well as the fuel costs and the battery electric trucks have Vehicle to Grid benefits. The total costs include the investment costs of recharging batteries and the costs of electric roads. In the medium term the expected costs of diesel, battery only trucks and of overhead line trucks are known. For the longer term two scenarios of battery costs and electric roads are considered.

In a first representation of the EU network, we use average truck density conditions for the TEN-T network. In this case, the installation of e-roads passes the cost benefit test in the medium and long term, although only marginally for the case of low battery cost development.

In the second representation of the EU network, we consider two neighbouring countries where each country can decide on the installation of e-roads. International trucking utilizes the network in both countries. In this case, it is only welfare-increasing to invest in e-roads in the large country with a substantial volume of heavy domestic trucks. In the small country with lower volumes of domestic heavy trucks, e-roads will not be welfare-increasing. Hence, the Nash equilibrium is that the large country invests in the e-road but not the small.

One can overcome this non-cooperative solution through cooperation in the scenario where the cost of batteries develops slowly, and the investment cost for the e-road develops favourably. In this scenario, we find that both countries can benefit from a bargaining solution in the long term, where the larger country subsidizes the smaller country to build electric roads, benefiting both nations. Still, we can conclude that even if e-roads can be welfare increasing, they are not everywhere in the TEN-T network.

There are many caveats in our analysis. Background assumptions on the developments on battery and overhead lines are crucial and the range we considered may still be too narrow. Many other parameters play a role in the assessment: future diesel and the electricity prices are uncertain. Moreover, our representation of the EU network by either average conditions for the TEN-T network or by the conditions in two neighbouring countries is simplistic. What is needed is the representation of the TEN-T network where each of the 27 countries can decide on the investments of e-road infrastructure over time.

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Appendix 1: Detail of data used

		source
x_l , $(1 - x_l\ )$	Average share of days with long trips per year and average share of short trip days per year. 75%, 10% and 15% has $x_l \in$ 0.1, 0.5, 0.9, respectively.	(van Grinsven et al., 2021, Figure 3) and own calculations
l_l , l_s	Truck distance covered on a long trip and short trip day $l_l = 675$ km/day and , $l_s = 299$ km/day	From assumptions of maximum distance without a (overnight) break
v	the cost of waiting for recharging the battery. Recharging capacity on route (Kwh/h) 350 kw/h, implying v = 20€/h / 350 kw/h = 0.06 €/kWh	ICCT (2021)
$k_d, k_{e,1,2}$	fuel consumption for diesel and electric trucks (battery and motorway trucks) period 1 2 (diesel only in period 2) for standard weight 0.307 l/km 1.1 kWh/km2	ICCT (2021)
$f_{d1,2}$	diesel cost per liter 1.08€/l, eu average	the ICCT (2021) , Table 9
$t_{d1,2}$	diesel tax per liter in48€/l , eu average	the ICCT (2021) , Table 9
$f^o_{a1,2}$	electricity cost per kWh on route for battery electric truck 1,2 0.41€/kWh	ICCT report (2021), fig 7
$f^h_{e1,2}$	electricity cost electric truck per kWh for home charging in period 1,2 0.16 €/kWh	ICCT (2021), Table 10
$f^e_{a1,2}$	Electricity cost per kWh on electric road, period 1, 0.149 €/kWh. period 2, high cost: 0.133 €/kWh low cost: 0.128 €/kWh	Assume user cost 2% of maintenance cost (Oeko Institute, 2020). Also in TRV UK report (Ainalis et al., 2020)
$f^s_{e1,2}$	Electricity price per Kwh for V2G sales. Mid of charging at home and en route. 0.28€/kWh	no source
$t_{e1,2}$	electricity tax per kWh in period 1,2, eu average 0.06 €/kWh	ICCT (2021), Table 10
$P_{d1,2}$	daily capital cost of diesel truck 89€/day	the ICCT (2021)

$P_{o1,2}$	daily capital cost of e-road truck period 1,2, excluding battery cost: 74€/day	Kunnel 2019 and the ICCT (2021)
$P_{a1,2}$	daily capital cost of BAT period 1,2, , excluding battery cost 59 €/day	(ICCT, 2021)
Discount rate	4%, Depreciation period of a truck 7 years.	
Length of road network TNT- N	30 000 km	(Transport & Environment, 2021)
average ADDT heavy	6600 vehicle per day[8]	(CEDR, 2020)
No of trucks doing long -and medium haul trips	700,000 trucks[5]	(CEDR, 2020) (van Grinsven et al., 2021, Figure 3) (Transport & Environment, 2021)
Investment cost of e-road	period 1 1,240,000€/km period 2 high 1,116,000 €/km period 2 low 744,000 €/km	Current cost TrV (2021), and assume 0.9 and 0.6 in period 2
a	daily cost of battery per kWh period 1 150 €/kwh period 2 high 125 €/kwh period 2 low 75 €/kwh	ICCT (2021)
w	weight of battery per kWh period 1 0.008 tonne/kWh period 2 high 0.005 tonne/kWh period 2 low 0.004 tonne/kWh	(Basma et al., 2021)
B	net Battery size KwH = gross capacity/1+reserve margin)	
v	waiting cost	calculated = 0
θ (l)	share of truck distance on the e-road On the TNT-N network: 73% long haul and 62% medium haul.[9] Sweden 60% long haul and 40% medium haul.	(Transport & Environment, 2021) Trv (2021)
V	Payload standard truck 27 tonne	ICCT (2021)
ρ	Share of trucks from abroad.	EU stat[10]

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[8] Roughly 40 000 vehicles per day on average and on average 10% is heavy (CEDR, 2020). Almost all of the 10% long – and medium haul (van Grinsven et al., 2021, Figure 3). This means 4 000 trucks per day. Given 30 000 km of the network: This is on average 225,000 trucks: Long and medium haul (we assume 50%-50%).

[9] Freight transport to or from the hubs in this network make up 80% of the total EU road freight activity (tkm) and 88% of the total long-haul activity. The road transport to and from the TEN-T network is 44% and 37% (medium-haul) and 44% (long-haul). Hence, we assume that for long-haul, the trucks run 44%+44%/3*2=73% on the TNT-N network (or the e-road network). For medium-hall we assume 43.5%+37%/2 = 62% are on the TNT-N network.

[10] https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Road_freight_transport_by_journey_characteristics#Road_freight_transport_performance_by_type_of_operation_.28in_tonne-kilometres.29