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How to Be a Good Forerunner in Carbon Neutral Trucking

Abstract

EU countries want to decarbonize their road freight transport quickly. Long-haul electric trucks are a promising technology. There are several competing designs but at present the trade-off is between e-trucks with very large batteries and e-trucks with a smaller battery but combined with motorways electrified via catenary lines. In the latter case a combination of public investment (catenary lines on major motorways) and private investment (electric trucks) is required. As long-haul truck transport is partly international this raises problems of coordination among countries. We study the possible pricing and investment strategy of one forerunner country that faces lagging neighbors. The forerunner can make the use of electric trucks mandatory on its own territory by using very high road charges for diesel trucks. If it has opted for a catenary system, it faces still the choice of how it will price the use of its electric motorways. International diesel trucks, when crossing the border of a forerunner country, have to choose between paying high charges and transferring the load into an e-truck. We study the outcome of this international coordination game exploring the non-cooperative outcome varying the relative size of the forerunner in international truck traffic and varying the cost of electric highways.

Keywords: electric trucks, freight transport, climate policy, tax exporting, distance charging

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1 Introduction

The main purpose of this paper is to provide a deeper understanding of how international competition affects investment in new infrastructure for long-haul electric trucks. Sweden or California are more ambitious to reduce carbon emissions from trucking than their neighbors. Imagine a forerunner country or state starts building electric highways that allow electric trucks (ET) to be recharged continuously via catenary lines. Electric highways (EH) combined with battery capacity for the smaller trips connected to the highway allow the forerunner to electrify truck transportation and significantly reduce its carbon emissions.

Börjesson, Johansson, and Kageson (2020) made a cost-benefit analysis for the introduction of ET. They found electric trucks using electric highways a worthwhile public investment proposal in Sweden for carbon shadow values of 136 €/tonne of CO_2. This would reduce carbon emissions by one third for heavy trucks in Sweden. But truck transportation within a federation (EU, US) is increasingly long distance rather than local, so the ultimate costs and emission reduction success will depend on whether the neighbors follow the forerunner and how the forerunner state or country deals with international trucking. What neighboring countries will do in response depends on strategic considerations as there will only be coordination when it brings significant benefits. This is the main research question of this paper: will neighbors with different climate policies follow the ambitious forerunner?

Options to reduce carbon emissions from heavy trucks

There are four options to reduce dependence on oil and decarbonize heavy trucks: improve fuel efficiency per ton kilometer, improve the load factor of trucks, switch to alternative fuels and powertrains or switch transport modes and use rail and waterways.

At present, the main EU initiative is the regulation that forces all new heavy trucks to reduce their carbon emissions by 15% in 2025 and by 30% in 2030 (EC, 2019c). Improving fuel efficiency can be achieved by using existing technologies such as aerodynamic truck fittings, low rolling resistance tires, and automated transmission systems. There may be further advances in fuel efficiency (IEA, 2017a), however, at some point the marginal cost of these efficiency measures will become very high and one will need to switch to carbon-neutral fuels.

The average load factor is in the range of 70% for larger trucks (Schroten et al., 2019). It is advocated that a much higher load factor is possible with better coordination. This may be out of reach for several reasons. First, the incentives to achieve a better load factor are already present: every empty truck kilometer is costly in terms of capital and driver wages for the trucking company. Second, trucks are often dedicated to carry one type of goods only: a milk truck is not allowed to bring back a load of gasoline.

This leaves us with alternative fuels. As sustainable biofuels have only limited potential, one is left with the choice between battery electric trucks and hydrogen fuel. The latter option is, for the moment, losing the game for two reasons. First, due to the progress in electric battery size and density. Second, because the conversion of renewable energy into hydrogen has a very low overall efficiency (35%) (Belmans and Vingerhoets, 2020).

Waterways and rail are only options for particular categories of (bulk or container) goods, so we focus mainly on freight transport that is difficult to substitute and has to use trucks. According to Börjesson, Johansson, and Kageson (2020), who use a detailed freight model, the modal substitution between freight modes when ET are progressively introduced is small: on the order of a few percent in Sweden.

Infrastructure for electric heavy trucks

In this paper, we will focus on battery electric trucks as the primary alternative to existing diesel trucks. We consider battery-electric and plug-in hybrid trucks, both of which are in the early development stage with pilot projects in Sweden, Germany, and California. Plug-in hybrid trucks are expected to have a large battery together with a diesel engine. In this way, they are intended to be a bridging technology from traditional diesel engines to battery-electric powertrains. But we concentrate on the endpoint of the technology development: the full electric truck.

As battery weight will probably remain an important limitation for electric trucks, one needs either a very quick charge for the battery or a continuous power supply for most of the journey. So, the battery-electric trucks face the additional cost of electric motorway infrastructure. Technologically, there are two ways to supply electricity in a continuous way to trucks: by induction and by connecting to overhead lines via a catenary. The overhead line catenary system promises to be the cheapest and this option is now considered for deployment at the major motorways. On the motorways, the electric trucks would operate using the overhead lines but on the other connecting roads, the trucks would operate on their battery (see Figure 1)[1].

[1]Detailed information on the demonstration project can be found at Siemens AG / Siemens Mobility GmbH (2017)

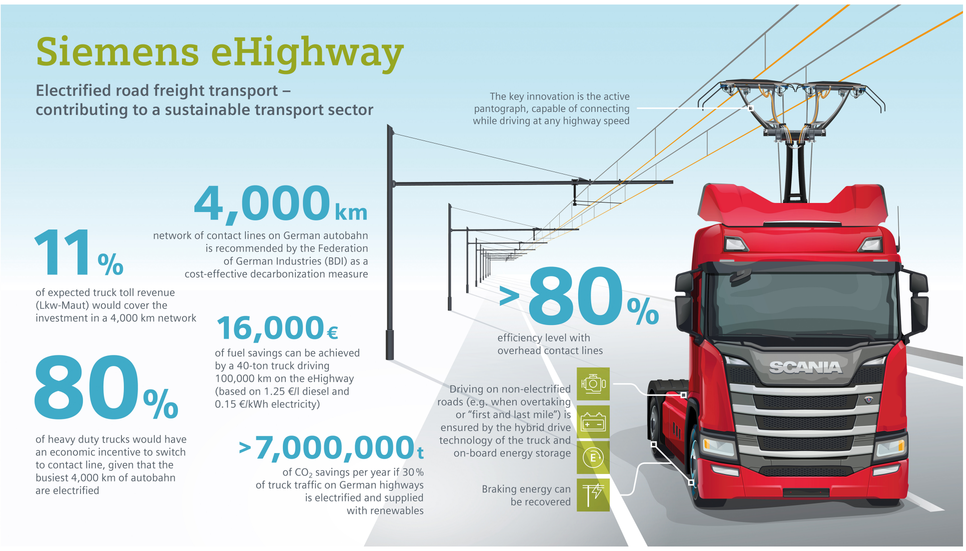

Figure 1: Siemens eHighway catenary electric truck

Neighboring countries choosing different options

As technologies are in full development and countries want to move at different speeds for decarbonizing their transport sector, coordination issues will appear. The very ambitious countries may develop electric motorways and promote the development of electric trucks, other countries may wait with the electric motorway. To analyze the problem, we need to take into account two more dimensions of the problem. First, we need to distinguish domestic and international truck traffic. Second, diesel fuel taxes are the ideal carbon tax but their potential is limited by tank tourism: it is very difficult for a country to raise diesel taxes because trucks can fuel abroad. For this reason, the main instrument used by an individual member country are distance taxes. They are not yet introduced by all European countries, but countries will almost be forced to install them because a country with distance taxes always wins the fuel tax game (Mandell and Proost, 2016).

Consider now one forerunner country (Sweden) and one neighboring country (Germany) and concentrate on the steady state where the whole truck fleet is re-optimized. When the forerunner installs electric highways, it can differentiate its distance charges for trucks to incentivize the use of electric trucks. This can force the domestic trucks to switch to electricity, but for international truck transport the problem is different. As long as the neighboring country does not install electric motorways, there are two solutions. Either international trucks will remain diesel trucks and they are used for the whole trip through both countries, or they have to use a tractor-trailer combination where they switch between diesel and electric tractor at the border. This second option is clearly more extensive.

Research questions

The research questions for this paper now become clear. First, what would be the outcome of the non-cooperative game between a forerunner country that wants to install electric highways and a lagging neighbor that does not install electric highways? Second, how costly is the forerunner strategy for this country? Third, what are the possible gains of cooperation when the two countries install electric highways?

This paper is organized as follows: Section 2 will outline the game tree and define the analytical model. Section 3 deals with the model calibration, Section 4 discusses the numerical results, and Section 5 concludes.

2 Building the model

2.1 Game tree

To gain insight we use a formulation with only two countries where one country is a forerunner in installing electric highways and the second country is the lagging neighbor.

We have a game with three players: the forerunner country, the lagging neighbor country and the truck companies. Figure 2 presents the game tree for the non-cooperation case: the forerunner can decide to install or not install electric highways. When it installs electric highways, it has also to decide on the level of its distance charges. In the EU, the distance charges cannot discriminate against trucks from other countries, one can only discriminate in function of objective criteria, such as the environmental performance or the axle weight. This means that the forerunner will certainly set the distance charge (on diesel trucks) high enough to force domestic trucks to become electric, otherwise their investment would be pointless. The forerunner could even opt for a much higher distance charge on diesel trucks so that international trucks coming from a lagging neighbor country have to switch tractors at the border.

Once the forerunner has installed electric motorways and decided on its distance charge, the neighbor has to decide whether it also invests in electric motorways or not and what diesel and electric distance charge it should use.

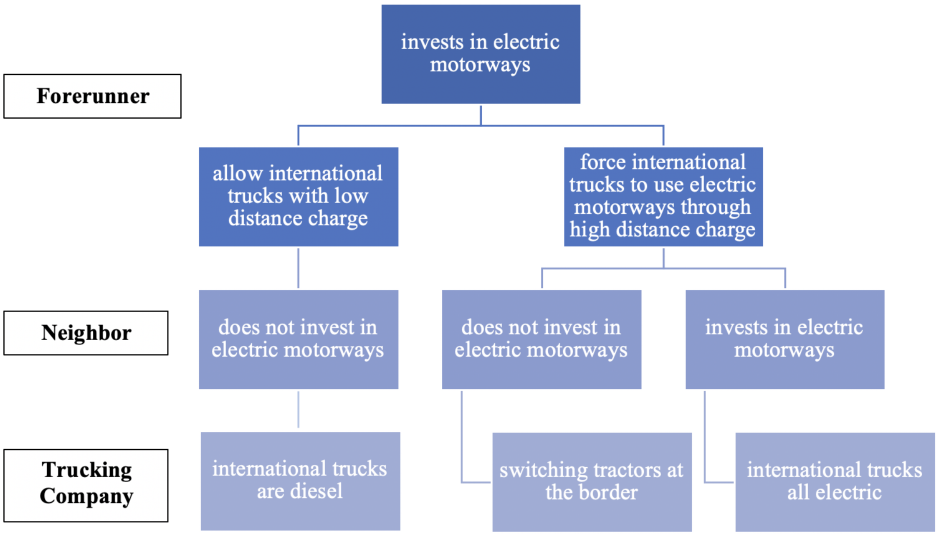

Figure 2: The game scenarios

Once the two countries have set their infrastructure and pricing policies, the domestic and international trucking companies decide on the type of truck they use. As, by assumption, the trucking companies face perfect competition, the user cost of both types of trucks will determine the volumes of domestic and international trucking and the type of truck that is used.

Each country has, in principle, many instruments to steer the type of truck and the volume of truck use: diesel fuel tax, distance tax on diesel trucks, distance tax on electric trucks as well as the price of electricity. These instruments largely overlap each other. Therefore, we chose the distance tax on diesel trucks as the principal policy instrument and keep the diesel fuel tax constant and identical for the forerunner and the neighbor.

2.2 Assumptions and model set-up

We use a model set-up that is inspired by Mandell and Proost (2016). This was a model to study international tax competition for fuel and distance taxes for trucks. That model will be extended for environmental considerations and for investment decisions.

We assume that the neighboring country (N) has size 2γ and the forerunner (F) has size $2(1-\gamma)$, where $\gamma \in [0.5, 1]$. On average, domestic trips in the neighboring country will cover a distance γ and in the forerunner country, domestic trips will cover a distance $(1-\gamma)$. International trips will be of length 1 with a part γ in the neighboring country and a part $(1-\gamma)$ in the forerunner country. The trip length is fixed, though the number of trips is variable.

We begin by assuming linear demand functions for domestic trips in the forerunner country (d_F) and domestic trips in the neighboring country (d_N) in function of the user costs k_F and k_N for domestic trips.

$$\begin{aligned} d_F &= a - bk_F \\ d_N &= a - bk_N \end{aligned} \tag{1}$$

The linear demand function for international trips (d_{int}) is the same in both countries and is a function of the user cost for international trips K_{int}.

$$d_{int} = \alpha - \beta K_{int} \tag{2}$$

We will denote the demand for truck trips in tonne-kilometers (tkm) travelled. The demand for truck trips can be segregated into electric d^e and/or fossil fuel d^f truck trips in tkm. We assume that domestic trucking and international trucks have each a fixed annual mileage so that the average cost per mile is constant and that we do not have to bother about the number of trucks. This assumption also implies that trucking companies will either choose an electric truck or a diesel truck for their domestic trips and select one type of truck for their international trips.

Domestic trucks can only use the local road network and buy fuel locally. The generalized cost of local transport by fossil fuel trucks is determined by the total capital and fuel cost before taxes c^f, the fuel tax t^f, and the distance charge t^d. The generalized cost of local transport by electric trucks is determined by the total capital and electricity cost before taxes c^e, the electric motorway network connection tax t^e, and the distance charge t^d. We can differentiate the distance charge for fossil fuel trucks t^d_{FT} and electric trucks t^d_{ET} as the different trucks have different environmental externalities. The fuel, electricity, and distance charges will differ between the two countries and will also depend on the relative size and importance of international demand.

Therefore, the generalized cost of a single domestic trip (k) for the forerunner and the neighboring country will be a function of the relative distance:

$$\begin{aligned} k^f_F &= (1-\gamma)(c^f_F + t^f_F + t^d_{FT,F}) \\ k^e_F &= (1-\gamma)(c^e_F + t^e_F + t^d_{ET,F}) \end{aligned} \tag{3}$$

$$\begin{aligned} k^f_N &= \gamma(c^f_N + t^f_N + t^d_{FT,N}) \\ k^e_N &= \gamma(c^e_N + t^e_N + t^d_{ET,N}) \end{aligned} \tag{4}$$

The trucking companies will choose the truck technology with the minimum cost. The total cost of domestic trips equals the total distance travelled d times the unit cost of a diesel or an electric truck:

$$
\begin{aligned}
TC_F &= d_F(1-\gamma)\ \min\Big((c_F^f + t_F^f + t_{FT,F}^d), (c_F^e + t_F^e + t_{ET,F}^d)\Big) \\
TC_N &= d_N(1-\gamma)\ \min\Big((c_N^f + t_N^f + t_{FT,N}^d), (c_N^e + t_N^e + t_{ET,N}^d)\Big)
\end{aligned} \tag{5}
$$

The generalized cost of international trips by diesel trucks equals the sum of costs at home and abroad.

$$
\begin{aligned}
K_{int}^f &= c^f + \gamma t_{FT,N}^d + (1-\gamma) t_{FT,F}^d + \sigma[\![t_F^f, t_N^f]\!] t_N^f + (1 - \sigma[\![t_F^f, t_N^f]\!]) t_F^f \\
\text{where: } \sigma[\![t_F^f, t_N^f]\!] &= \gamma - \rho(t_N^f - t_F^f)
\end{aligned} \tag{6}
$$

Note that,

$$
\begin{aligned}
\sigma[\![t_F^f, t_N^f]\!] = 1 \text{ when } t_F^f - t_N^f \geq \frac{1-\gamma}{\rho} \\
\sigma[\![t_F^f, t_N^f]\!] = 0 \text{ when } t_N^f - t_F^f \geq \frac{\gamma}{\rho}
\end{aligned} \tag{7}
$$

International fossil fuel freight trucks will minimize their diesel fuel costs by refueling in the country with the lower diesel fuel tax that they drive through. We use a reduced form formulation $\sigma[\![t_F^f, t_N^f]\!]$ to capture this cost minimization process where the market share $\sigma \in [0,1]$ in the international trucking fuel market is a function of the two diesel tax rates. The parameter ρ is a measure of the intensity of tax competition; a small ρ means that an increase in the fuel tax difference between the forerunner and the neighboring country does not strongly affect the market share σ in the international trucking fuel market.

As electric vehicles cannot fuel strategically, the generalized cost of international trips for electric freight trucks will be equal to the non-fuel and non-tax related cost per mile c^e plus the variable cost of the part of the trip in the neighboring country plus the variable cost of the part in the forerunner country:

$$
K_{int}^e = c^e + \gamma(t_{ET,N}^d + t_N^{el}) + (1-\gamma)(t_{ET,F}^d + t_F^{el}) \tag{8}
$$

And when the tractors need to be switched at the Swedish border, we have an additional switching cost SC:

$$
K_{int}^{switch} = \gamma(c^f + t_{ET,N}^d + t_N^{el}) + (1-\gamma)(c^e + t_{ET,F}^d + t_F^{el}) + SC \tag{9}
$$

We assume that domestic governments set taxes and decide to invest or not in electric highways in function of the sum of consumer surplus of domestic trucking (cs) plus half of the consumer surplus from international trucking (CS) plus the total tax revenues minus the total external costs (ec) within the country and minus the infrastructure costs of implementing electric highways (IT). Because both countries benefit from international trips through trade, we assume that they share equally in the gains from the international transaction, so we count only half of the consumer surplus from international trucking. The main external cost we consider is climate damage. In this way, the more importance a country places on climate goals – and the stricter its climate policy – the higher the value of the external costs ec it considers. The external cost is expressed per kilometer, considering a standardized long-haul truck that complies with the emission standard.

In the baseline scenario, the forerunner and the neighboring countries only use diesel trucks, there is no investment in electric highways, and the objective function of the neighboring country becomes:

$$\begin{aligned} cs_N\{k_N(.)\} + d_N\{.\}\,\gamma\,(t^d_{FT,N} + t^f_N - ec^f_N) \\ +0.5CS\{K_{int}(.)\} + d_{int}\{.\}(\gamma t^d_{FT,N} + \sigma t^f_N - \gamma ec^f_N) - IT_N \end{aligned} \tag{10}$$

The two first terms represent the effects on domestic trucking: the consumer surplus of domestic trucking and the total tax revenue from trucking minus the external cost. The third and fourth term represent the consumer surplus and the tax revenue and environmental costs from international trucking. The last term represents the fixed investment and maintenance costs of electric highways, the variable costs of electric highways are included in the electricity costs of trucks.

3 Solving the game

We will consider four scenarios: no electric highways in either country, electric highways in both countries, and electric highways in the forerunner with and without high distance charges. We solve for the non-cooperative outcome of these four cases. To solve the game, we need to compare the pay-off functions of the two countries for each of the two options with or without electric highways. We take as the baseline scenario, the case where both the forerunner and the neighbor do not invest in electric highways and both countries have fossil fuel trucks operating domestically and internationally. Put another way, climate is somewhat important but not sufficient to spur investment in electric motorways.

For each of the three possible scenarios, we need to determine the Nash equilibrium of the distance tax for fossil driven trucks and the distance tax for electric trucks. The Nash equilibrium can result in electric highways in one country, then the domestic road freight will be electric but the international road freight in that country can only become electric in two cases. The first case is when both countries have electric highways and the second case is when the country with electric highways forces the trucks to change their tractor when they enter the country. In the numerical solution, we also take into account that there is learning by doing when more than one country adopts electric highways. This will result in a lower investment cost for the lagging neighbor. As this is a fixed cost, it will not affect the optimal tax setting expressions we use for the formal solution of the game.

We can study the Nash equilibrium by deriving the first order conditions with respect to the distance charges for fossil fuel (diesel) trucks t^d_{FT} and electric trucks t^d_{ET} and evaluating the resultant reaction equations. One could also add fuel taxes as policy instruments, but they are to some extent substitutes for distance taxes. In order to simplify the analysis, we keep the fuel taxes fixed. We start with the baseline case.

3.1 No electric highways

Assume first inelastic domestic demand, then:

$$t^d_{FT,N} = \frac{0.5d_{int}}{-\frac{\partial d_{int}}{\partial t^d_{FT,N}}} + ec^f_N - \frac{\sigma}{\gamma} t^f_N \tag{11}$$

The distance charge on diesel trucks (LHS) will equal the external cost (second term) corrected for the part that is already internalized by the fuel tax (third term) plus half of the marginal distance tax revenue (first term). The revenue motive only counts for half, because the neighboring country will incur half of the efficiency losses in case the taxes are set too high.

If domestic demand is elastic, then:

$$\begin{aligned} t^d_{FT,N} &= \left(0.5d_{int} + (ec^f_N - t^f_N)\frac{\partial d_N}{\partial t^d_{FT,N}} + (ec^f_N - \frac{\sigma}{\gamma} t^f_N)\frac{\partial d_{int}}{\partial t^d_{FT,N}}\right)(-A)^{-1} \\ \text{where } A &= \frac{\partial d_{int}}{\partial t^d_{FT,N}} + \frac{\partial d_N}{\partial t^d_{FT,N}} \end{aligned} \tag{12}$$

The optimal distance tax reaction function has again a revenue term that is now mitigated by the domestic demand elasticity – the distance tax will now also distort local transport decisions when it becomes too high. The optimal distance tax internalizes the external environmental costs to the extent that it is not internalized by the fuel tax.

We have a similar type of reaction function for the forerunner's distance tax on diesel trucks. The Nash equilibrium will contain higher distance taxes in the forerunner country than in the neighboring country because the neighbor has more to gain by higher taxes as the share of international traffic is relatively more important.

3.2 Electric highways in forerunner with high switching costs

In this case the distance taxes in the forerunner country will certainly favor the use of electric trucks for domestic trucking, otherwise their investment in electric highways would be pointless. But as long as the switching costs at the border (changing tractors) are high, and as the forerunner bears half of the additional switching costs because the international transport surplus is shared between the two countries, it will prefer that international trucks continue to use diesel trucks and opt for a fuel distance tax that is not too high.

As the forerunner wants its domestic trucks to be electric but keep the distance tax for diesel trucks relatively low, it has to use a high diesel fuel tax. In this way it can avoid the extra costs of changing tractors at the border. In this case, all international diesel trucks will do all of their fueling in the neighboring country, so $\sigma = 1$. The neighbor's distance taxes for diesel trucks will still be used to extract revenue from international trucking. In this case, the neighbor has the same diesel distance tax reaction function as before except that $\sigma = 1$.

In the forerunner country there will also be a distance tax on diesel trucks that takes now into account that international trucks take diesel fuel in the neighboring country and that domestic trucks all run on electricity:

$$t^d_{FT,F} = \left(0.5d_{int} + ec^f_F \frac{\partial d_{int}}{\partial t^d_{FT,F}}\right)\left(-\frac{\partial d_{int}}{\partial t^d_{FT,N}}\right)^{-1} \tag{13}$$

The distance tax on electric trucks equals the external cost as electric trucks are only used by domestic trucks.

3.3 Electric highways in forerunner with low switching costs

When switching costs are relatively low, the forerunner may prefer an equilibrium where all traffic within its borders is carried out by electric trucks. In this case, we assume that international trucking will switch trucks at the border. In this way, the neighbor's trucks will operate only within its borders and vice versa. The switching cost will increase the user cost of international trucking and the loss of consumer surplus will be shared among the two countries.

To start the computation of the equilibrium reaction functions, we can assume again that the fuel tax in the forerunner country is very high as it will not be used by domestic nor by international trucks. The forerunner's distance tax for diesel trucks will also be very high as one wants to avoid all diesel trucks. The distance tax for electric trucks can now be increased and will take away part of the surplus of international trucks:

$$t^d_{ET,F} = -0.5 d_{int} \left(\frac{\partial d_F}{\partial t^d_{ET,F}} + \frac{\partial d_{int}}{\partial t^d_{ET,N}} \right)^{-1} + \left(ec^{el}_F - t^d_{ET,F} - t^e_F \right) \tag{14}$$

Of course, the reaction functions are implicit equations and the switching cost will decrease the international trucking demand.

When it comes to the neighboring country, the switching costs decrease the international road traffic, so it may lower the distance tax to lessen the blow of the consumer surplus loss. The optimal distance tax has the same expression as in the case with no electric trucks.

3.4 Electric highways in both countries

As opposed to diesel trucks, electric vehicles cannot fuel strategically. There will be tax exporting in distance tax revenues with a high distance tax on electric trucks that is too high.

4 Numerical illustration

To explore the investment and distance tax competition dynamic between asymmetric countries, we calibrate the model for Sweden as the forerunner and Germany as the lagging neighbor.

In 2017, the total amount of goods transported by road in Germany and Sweden amounted to 313.000 million tonne-km (tkm) and 37.000 million tonne km, respectively (Eurostat, 2017). International transport between the two countries amounted to 16.000 million tkm. For Germany, this represents 5% of total freight demand, while in Sweden it is equal to almost 50% of all domestic truck transport volume, which underscores the asymmetry of these countries. We will later make sensitivity studies on the relative importance of the two countries. To do this, we keep the international transport flows constant and redistribute the domestic transport flows over the two countries. In this way the international truck transport flows vary in importance and this will turn out to be important for the distance tax setting.

We base our calculations on a heavy-duty truck with an annual mileage of 100.000 km and an average payload of 20 tonnes. In the base scenario, the fuel and electricity taxes are exogenous (based on EEA (2019) and Eurostat (2019a). The average costs given in Table 1 of diesel truck transport is assumed to be 73 €/1000 tkm of which 25% stems from fuel cost (based on IEA (2017a)). We take the average cost of battery-electric truck that has a 285-kWh battery and 150 km all-electric range to be 106 €/1000 tkm, of which 6% is the electricity cost.[2] This cost estimate is based on the IEA estimate that battery-electric trucks are presently at least 80% more expensive than traditional diesel trucks given the current fledgling market for heavy duty battery applications.

Table 1: Average costs of diesel and electric trucks

	Capital cost	Fuel cost	Fuel tax	External cost	EH cost	Total w/o EH cost	Total w/ EH cost
F / D	55	18	1,2	30		104,2	104,2
N / D	55	18	1,2	27,4		101,6	101,6
Before tech progress							
F / E	100	6	0,35	25	6,46	131,35	137,81
N / E	100	6	0,35	25	5,82	131,35	137,16
After tech progress							
F / E	64	6	0,35	25	3,23	95,35	98,58
N / E	64	6	0,35	25	2,91	95,35	98,25

F = Forerunner N = Neighbor D = Diesel E = Electric

With technological progress expected for batteries, the incremental cost of catenary electric trucks may decrease by 80% (IEA, 2017a) and in Table 1 this makes the capital cost plus fuel cost of electric trucks more interesting than the diesel truck. As the cost of batteries is mainly driven by the demand for electric cars, we consider this technological progress as exogenous in this paper.

The technological progress for catenary electric trucks can only make them competitive if the cost of installing electric highways (EH) is not prohibitive. Fraunhofer ISI (2018)

[2]This assumes an electric truck efficiency of 69 kWh/1000 tkm (Liimatainen, van Vliet, and Aplyn, 2019).

estimates the cost to construct a catenary electric road system at 1,7 million € per km in both directions. Using a 20-year time horizon and 5% interest rate, the annualized cost to electrify all motorways in Sweden is around 290 million € and for all motorways in Germany it is 1.774 million € (IEA, 2017a). This is the estimate we use when only Sweden builds electric motorways. When also Germany builds electric motorways, there is a learning by doing effect that reduces the unit cost of infrastructure by 50%.

To appreciate the potential interest of electric highways, even if it is a fixed cost, we can look into the average cost of infrastructure for the domestic truck tkm plus half of the international truck tkm. The average cost of the electric highway infrastructure without technological progress is then 5,82 €/1000 tkm for Germany. It is only when technological progress decreases the investment cost by 50% that catenary trucks become really interesting: even in Germany, the average cost, including external costs and infrastructure costs, would become lower for an electric truck than for a diesel truck. Another insight we can extract from Table 1 is that the average cost of the catenary truck option is more interesting than the full electric truck option that foregoes the recharging via catenary lines. Dropping the catenary electricity supply option would save 5,82 (2,91 with tech progress) €/1000 tkm, but could increase the capital cost of the electric truck by 31,5 €/1000 tkm.

There are two more important cost parameters that need to be discussed to judge the economics of electric trucks. The first is the external cost of trucks. The second factor is the distance tax on trucks. The external cost of trucks consists of non-climate related costs and the climate costs. The non-climate external cost of fossil fuel trucks includes the costs of air pollution, noise, accidents, congestion, and infrastructure wear and tear (van Essen et al., 2019). The external cost of fossil fuel trucks in Sweden is 30 €/1000 tkm, based on a climate damage cost of 100 €/tonne of CO_2. In Germany, the external cost of fossil fuel trucks is 27,4 €/1000 tkm, based on a much lower climate damage cost of 28 €/tonne of CO_2. The external cost of electric trucks in both countries is 25 €/1000 tkm (van Essen et al., 2019). Accidents and congestion costs are identical for the two truck technologies. Electric trucks will have higher infrastructure wear and tear costs due to the heavy battery; however, with reductions in climate, noise and air pollution, they are expected to generate an overall lower external cost compared to diesel trucks.

Note the relatively minor role for climate costs in the overall average costs of different types of trucks. When Sweden takes a damage value for greenhouse gas emissions of 100 €/tonne of CO_2, this translates into a 5 € extra per 1000 tkm to be compared with a fuel cost of 16 € for a diesel truck.

Ideally, the distance tax is set equal to the external cost. In practice, countries use the distance taxes not only to pay for external costs, but also to extract revenues from foreign trucks. The distance taxes rather than the external costs will determine the type of truck selected by the trucking companies.

For the calibration of the model we need two more data. The cost of switching trucks is set equal to 4 €/1000 tkm, which includes the time delays, labor, and equipment required to unload and load the electric and diesel trucks (Hanssen, Mathisen, and Jørgensen, 2012). To calibrate our linear demand functions for domestic and international transport we need the price elasticity. We take the fuel price elasticity of -0,25 and the distance charge elasticity of -0,125 (based on De Jong et al. (2010)) which come down to a money cost elasticity of -0,5. All data used are summarized in 5.

We discuss the results in two steps. First, we analyze the outcome of the distance tax setting game for each possible electric highway equipment scenario. Next, we analyze the pay-off for the different players by adding the electric highway investment costs.

4.1 Distance taxes

To clarify the insights of our results, we use identical fuel taxes for the forerunner and the neighboring country. This means that there will be no competition on fuel taxes and we can concentrate on the setting of distance taxes for diesel and for electric trucks. Two elements will drive the results. First, the higher assessment of the climate damage by the forerunner that leads to a higher external cost for diesel trucks than in the neighboring country. Second, the relative size of the country that makes tax exporting more interesting for the smaller country. For comparison: Germany has a relative size ($\gamma = 0,85$), so the forerunner Sweden would be a rather small country. We include in all the tables a sensitivity study on the relative size parameter, varying γ from 0,5 to 0,9.

The results reported in Table 2 represent the Nash equilibrium of distance taxes in €/1000 tkm for each scenario. As the investment costs for electric highways are fixed costs, we consider them only in Table 3.

We start by discussing the case where both countries are of equal size, $\gamma = 0,5$. First, as expected, in the case where both countries use only diesel trucks or only electric trucks there is pure tax exporting: each country taxes the international traffic above the external cost in order to get extra distance tax revenues. In the case of diesel trucks, we see for the forerunner 30,58 €/1000 tkm and for the neighbor, 27,96 €/1000 tkm. The forerunner sets a higher diesel distance tax because it considers a higher external climate cost. In the

Table 2: Optimal distance taxes varying relative country sizes

	$\gamma = 0,5$	$\gamma = 0,7$	$\gamma = 0,9$
Diesel trucks only			
F / D	30,58	31,74	37,16
N / D	27,96	27,44	27,12
Forerunner electric; int'l diesel trucks			
F / D	31,77	32,94	38,36
F / E	25,00	25,00	25,00
N / D	27,93	27,43	27,11
Forerunner electric; Border-switching			
F / D	>31,77	> 32,94	> 38,36
F / E	26,40	27,46	32,42
N / D	27,98	27,40	27,05
Both countries electric trucks			
F / E	26,64	27,92	33,98
N / E	26,64	26,04	25,67

case of electric trucks, both countries set a distance tax of 26,64 €/1000 tkm. Collectively, they create a welfare loss by setting the tax above the marginal external cost. However, in a non-cooperative equilibrium each country still benefits from raising its taxes on international trucks.

The smaller the forerunner country's size, the higher it will set the distance tax as the cost of distorting domestic trucking becomes less important. Further, they will be in a position to gain more from taxing international traffic as the countries share the consumer surplus from international trucking equally, despite the size difference. The neighboring country faces the opposite incentives; the larger that it is, the lower it will set the distance tax as this will hurt less domestic trucking and will attain disproportionately lower gains from international trucking.

Next, consider the second case where the forerunner has domestic electric trucks, but all international trucks remain diesel trucks. The forerunner will set the distance tax on electric vehicles equal to the external costs of the electric domestic trucks (25 €/1000 tkm). The forerunner's distance tax on diesel trucks 31,77 €/1000 tkm, however, will increase as this tax now only falls upon international trucking where the tax revenue motive plays. The tax will not be too high in order to prevent international trucks from switching at the border. The neighboring country has a smaller external cost for diesel trucks and domestic diesel trucks are relatively more important. For this reason, the neighboring country sets a lower diesel distance tax. Moreover, the neighbor could easily use a slightly lower fuel tax and in this way it gets all the fuel tax revenue from international trucking.

In the third case, the international trucks driving in the forerunner country have to switch to an electric tractor and this implies that forerunner's distance tax on electric trucks now becomes also an instrument to export taxes and this increases the tax. Additionally, the tax will become higher when the forerunner is relatively smaller. The neighbor continues to use diesel trucks within its borders and it sets the distance tax slightly higher than the external cost because there remains a revenue motive for the international diesel trucks on its territory.

Fourth, when both countries only use electric trucks, we see the same profile of tax exporting as in the case with diesel trucks only: distance taxes will be higher than the external costs of electric trucks that amount to 25 €/1000 tkm.

4.2 Welfare

In Table 3, we calculate the welfare gains of the scenario where both countries have the same size for each of the four scenarios. Table 3 gives the three main components of the welfare per country on an annualized basis. The first column reports the change in consumer surplus from domestic trucking plus the tax revenues on domestic trucks plus the change in external costs. The second column gives the change in half of the consumer surplus from international trucking plus the change in tax revenues and external costs. The last column gives the annualized cost of electric highways.

When only the forerunner installs electric highways and only domestic trucking is electrified, there is an important gain in domestic consumer surplus (3.464 million €/year) for the forerunning country. This is the result of the much lower operating and external cost of the electric trucks. The major cost is the investment in electric highways (516 million €/year). The international consumer surplus and tax revenues barely change. The welfare gain is entirely due to the assumed strong technological progress in catenary trucks: without the technological progress of an 80% reduction in the incremental cost of this type of trucks (from 100 to 64 €/1000 tkm), there would be a loss of domestic

Table 3: Welfare breakdown compared to 'diesel trucks only' case (mill €)

	Domestic CS + tax revenue - EC	0,5 Int'l CS + tax revenue - EC	EH investment
Forerunner $\gamma = 0,5$			
F / D & N / D	16.349	806	
F / E ; int'l diesel trucks	+ 3.464	- 10	- 516
F / E; Border-switching	+ 3.175	+ 4	- 516
F / E & N / E	+ 3.127	+ 126	- 516
Neighbor $\gamma = 0,5$			
F / D & N / D	17.322	806	
F / E ; int'l diesel trucks	+ 4	- 1	
F / E; Border-switching	-1	+ 4	
F / E & N / E	+ 2.541	+ 126	- 258

consumer surplus of 9.943 million € instead of the gain of 3.464 million €.[3] To guarantee that there is a break-even result in terms of welfare with domestic electric trucks, one needs technological progress that decreases the cost of catenary electric trucks from 100 to 77 €/1000 tkm. In the neighboring country, there are almost no welfare effects as, by assumption, only the forerunner country switches to electric trucks.

In the third case, the forerunner country forces the international trucks to change tractors at the border. The main change is in the international surplus: operating costs decrease as international trucks use electric tractors in the forerunner country, however, the added cost of switching tractors at the border results in a net increase in operating costs. Per 1000 tkm, these effects are small: operating costs are 3 € cheaper for an electric truck compared to a diesel truck but there is a cost of 4 € for switching tractors at the border. There is a small gain for the international consumer surplus (+ 4 million €) but this is compensated by the loss in domestic consumer surplus as the distance tax is now increased beyond the external cost of electric trucks. In summary, forcing international trucks to switch tractors at the border is not welfare improving for the forerunner country.

In the fourth case, both countries install electric highways. Now, there is a welfare benefit for the forerunner country that is generated by the lower operating costs of domestic

[3]This is the result of optimal distance charges that are slightly different than the one of Table 2 because the optimal tax setting depends on the operating costs.

trucks and international trucks. However, the net welfare effect for the forerunner country is still highest when the forerunner country has only the domestic trucking powered by electricity. The neighboring country also benefits from switching to electricity, but the gain for its domestic trucks is lower than for the forerunner country because of the lower climate damage it considers. When both countries install electric highways, one can expect that learning by doing reduces the installation costs of electric highways. Here, we assumed a reduction in the installation cost in the neighbor country by a factor of two.

As the neighboring country benefits from installing electric highways, the Nash equilibrium will be that both countries install electric highways and that all domestic and international truck traffic is electrified. This result hinges on the technological progress for catenary trucks and to a much lesser extent on the learning by doing for the installation of electric highways. When there is less technological progress for electric trucks, the forerunner may still find it interesting to see electric trucks operate domestically. But the appetite of the neighbor to install electric trucks will be smaller as the climate damage is smaller. Even the learning by doing for the installation of electric highways may be insufficient to convince the neighbor country to electrify its trucking.

Consider next the case of a small forerunner, whose domestic transport is only 10% of the sum of domestic transport in both countries. Table 4 reports the welfare effects with technological progress for this case where the forerunner is smaller ($\gamma = 0,1$).

Table 4: Welfare breakdown when forerunner is small (mill €)

	Domestic CS + tax revenue - EC	0,5 Int'l CS + tax revenue - EC	EH investment
Forerunner $\gamma = 0, 1$			
F / D & N / D	2.999	826	
F / E ; int'l diesel trucks	+ 963	- 2	- 103
F / E; Border-switching	+ 658	- 55	- 103
F / E & N / E	+ 593	+ 108	- 103
Neighbor $\gamma = 0, 9$			
F / D & N / D	31.493	826	
F / E ; int'l diesel trucks	+ 1	- 1	
F / E; Border-switching	+ 21	- 55	
F / E & N / E	+ 3.921	+ 108	- 464

In the baseline, the forerunner levies large distance taxes to extract revenue from international trucks as the tax distortion on domestic trucking has become less important. Again, in this case the forerunner country will benefit from having domestic traffic electrified. Forcing international trucks to become electric by switching at the border is not beneficial for the forerunning country. Therefore, as in the scenario with equal-sized countries, the Nash equilibrium will have both countries electrifying their truck transport. The determining factor remains the technological progress for catenary electric trucks and less so the cost reductions in the electric highways.

5 Conclusions

The aim of this paper is to provide a deeper understanding of how international competition affects investment in new infrastructure and distance tax pricing for long-haul electric trucks. We design a game that analyzes the possible pricing and investment strategy of one forerunner country that wants to invest in electric trucks and catenary electric highway infrastructure, but faces lagging neighbors. We study the outcome of this international coordination game exploring the non-cooperative outcome varying the relative size of the forerunner in international truck traffic and varying the cost of electric highways. Though this stylized model may not capture all of the costs associated with the transition from fossil fuel to electric trucks, it provides several insights into the international welfare gains associated with a forerunner country taking the leap, regardless of its relative size.

An important insight is that we still need a significant drop (36%) in the purchase costs of catenary electric trucks before a forerunning country that uses a high carbon value (100 €/tonne CO_2) decides to install electric highways. Forcing international trucks to switch to an electric tractor is not interesting for the forerunner country. The major reason why a neighbor country using a lower carbon value would electrify too is, again, the technological progress for catenary electric trucks that enables a decrease in the operating costs and makes electric trucks cheaper to use than diesel trucks.

We consider several model extensions that we leave for future research. First, making fuel taxes endogenous in the model, such that they respond to the strategic distance taxes set in each country. Second, introducing dual engine trucks as a third vehicle option. The dual engine trucks would have a lower capital investment and higher operating costs compared to the electric truck. While this could serve as a bridging technology from diesel to full electric trucks for the neighboring country, it could also hinder adoption of electric vehicles in the neighboring country. Finally, including transit countries, such as Switzerland, that trucks pass through without making any deliveries. A transit country will have a different strategy for setting distance taxes and installing electric highways given that it does not benefit from international 'pass through' trips. Depending on the size and location of the transit country it can levy exorbitant distance taxes thereby earning revenue for the government, without a significant reduction in the number of transit trips. A successful example of this policy in a transit country is the Heavy Vehicle Tax in Switzerland, which levies a fee on all trucks over 3,5 tonnes entering Swiss borders (Eidgenössische Zollverwaltung, 2017). This fee is set based on the truck's weight, emissions, and the number of kilometers driven in Switzerland. In this way, it addresses the carbon emissions and congestion-related externalities arising from the 'pass through' trips.

Appendix

Parameter	Value	Units
Germany domestic road freight	297	billion tkm
Sweden domestic road freight	37	billion tkm
International road freight	16	billion tkm
Average truck payload-mileage	2.000.000	tkm
Capital cost fossil fuel truck	55	€/1000 tkm
Capital cost electric truck	100	€/1000 tkm
Fuel efficiency	24	L/1000 tkm
Diesel cost	18	€/1000 tkm
Electric truck fuel efficiency	69	kWh/1000 tkm
Electricity cost	6,21	€/1000 tkm
External cost diesel truck neighbor	27,4	€/1000 tkm
External cost diesel truck forerunner	30	€/1000 tkm
External cost electric truck	25	€/1000 tkm
Electric highways infrastructure annuity	136.412	€/km
Germany total length of motorways	13.009	km
Sweden total length of motorways	12.132	km
Distance charge elasticity	-0,125	
Fuel price elasticity	-0,25	

References

Belmans R. and P. Vingerhoets (2020). Molecules: Indispensable in the Decarbonized Energy Chain. *EUI RSCAS PP 2020/01*. Florence School of Regulation.

Börjesson M., M. Johansson, and P. Kageson (2020). The economics of electric roads. *Working Papers in Transport Economics 2020:1*.

De Jong, G., et al. (2010). Price sensitivity of European road freight transport – towards a better understanding of existing results. Report 9012-1 for Transport & Environment.

Eidgenössische Zollverwaltung (2017). Leistungsabhängige Schwerverkehrsabgabe. Schweizerische Eidgenossenschaft.

European Commission (2019c). Regulation (EU) 2019/1242 CO_2 emission performance standards for new heavy-duty vehicles. textitOfficial Journal of the European Union, L 198 / 202 - 240.

European Environment Agency (2019). Transport fuel prices and taxes in Europe. EEA, Copenhagen.

Eurostat (2017). Inland freight transport. `https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Inland_freight_transport,_2017.png`. Accessed 10 November 2019.

Eurostat (2019a). Electricity prices for non-household consumers. `https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Electricity_prices_for_non-household_consumers,_first_half_2019_(EUR_per_kWh).png`. Accessed 17 November 2019.

Eurostat (2019b). Total length of motorways. `https://ec.europa.eu/eurostat/databrowser/view/ttr00002/default/table?lang=en`. Accessed 15 November 2019.

Fraunhofer ISI (2018). Alternative drive trains and fuels in road freight transport – recommendations for action in Germany. Karlsruhe, Berlin, Heidelberg.

Hanssen, T., T. Mathisen, and F. Jørgensen (2012). Generalized transport costs in intermodal freight transport. *Procedia – Social and Behavioral Sciences 54*, 189-200.

IEA (2017a). The Future of Trucks: Implications for energy and the environment, OECD/IEA, Paris.

Liimatainen, H., O. van Vliet, and D. Aplyn (2019). The potential of electric trucks – An international commodity-level analysis. *Applied Energy 236*, 804-814.

Mandell, S. and S. Proost (2016). Why truck distance taxes are contagious and drive fuel taxes to the bottom. *Journal of Urban Economics 93*, 1-17.

Schroten A. et al. (2019). Transport taxes and charges in Europe. EC, Brussels.

Siemens AG / Siemens Mobility GmbH (2017). eHighway Solutions for electrified road freight transport. https://press.siemens.com/global/en/feature/ehighway-solutions-electrified-road-freight-transport. Accessed 05 May 2020.

van Essen, et al. (2019). Handbook on the external costs of transport – Version 2019. CE Delft, Delft.