Taking the Low-Carbon Road: Essays in Road Transport Decarbonization

Inaugural-Dissertation
zur Erlangung des Grades
Doctor oeconomiae publicae (Dr. oec. publ.)
an der Ludwig-Maximilians-Universität München

2021
vorgelegt von
Christina Michael Merdies Littlejohn

Referentin: Prof. Dr. Karen Pittel
Korreferent: Prof. Dr. Stef Proost
Promotionsabschlussberatung: 14 July 2021

For my family.

Inspired by the hard work and perseverance of those who came before me.

Dedicated to those to come.

May we tread softer on this pale blue dot.

Acknowledgements

I thank my supervisor, Prof. Dr. Karen Pittel, for her unwavering support and kindness throughout the years. Knowing that she truly cared about my success encouraged me to persevere through challenges. I thank my co-author Prof. Dr. Stef Proost for pushing me to think critically and expanding my grasp of economic intuition. I am grateful to have had the opportunity to work closely with and learn from him during our collaboration on chapters one and three. In addition, I thank the numerous colleagues that took an interest in my work and offered invaluable feedback, whether in the workplace or at conferences abroad. Most notably, those that I worked and studied with from the Center for Energy, Climate, and Resources at the ifo Institute in Munich and the Faculty of Economics and Business at KU Leuven.

Contents

List of Figures

List of Tables

Preface

Anthropogenic climate change is among the greatest threats to humanity and an impending tragedy for the ecosystem that sustains it. Limiting the effects of climate change on society, the global economy, and the Earth system will be one of the most challenging endeavors for my generation and those to come. Climate models from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming (2018) project extreme temperatures and increases in frequency and intensity of heavy precipitation and drought in the coming decades. Climate change has already impacted natural and human systems around the world. Many land and ocean ecosystems and the services that they provide are changing. The climate-related risks to health, economic certainty, and food and water security, are projected to increase with global warming of 1,5°C above pre-industrial levels. Without significant regime change, the globe is on track to overshoot this level of warming. According to IPCC (2018), to meet the 1,5°C with limited overshoot, global net anthropogenic CO_2 emissions must decline by 45% compared to 2010 levels by 2030 and reach net zero emissions by 2050. To achieve these extensive emissions reductions the international community must unite under a common goal.

The European Commission (EC) introduced the European Green Deal in December 2019 with the objective that the EU is the first climate-neutral continent by 2050 (EC, 2019a). The EC outlines a stepping stone to achieving this goal in their 2030 Climate Target Plan, which is a 55% emissions reduction below 1990 levels by 2030 (EC, 2020). Accounting for nearly 25% of the EU's GHG emissions, the transport sector is key to realizing the emissions reductions goals. According to the European Environment Agency (EEA), road transport accounts for over 70% of all GHG emissions from the transport sector (EEA, 2017). Consequently, the EC has developed a low-emission road transport strategy with three key areas for action: increasing the efficiency of the transport system, fast-tracking deployment of low-emission transport alternatives, and transitioning to zero-emissions vehicles (EC, 2016).

In this dissertation, I methodically analyze proposed EU policies that address each of these action areas and evaluate the cost-effectiveness and efficiency of each policy in achieving significant emissions reduction. I limit the scope of my analysis to light passenger transport and heavy road freight. As instruments for this analysis, I design theoretical models to depict the mechanisms underlying supply and demand and then calibrate the models to illustrate the relative costs of each policy scenario. The main contributions of this dissertation are three-fold. First, it investigates the importance of endogenous technical progress in existing and nascent technologies for achieving a cost-competitive low-emission transport system. Second, it examines the value of policy coordination amongst EU member states by scrutinizing incongruous national emissions targets. Third, it studies the impact of levying a distance tax that covers the external costs of road transport.

This dissertation is organized in three chapters, each of which addresses one or more of the EC's strategic action areas for achieving low-emission mobility. Chapters 1 and 3 are co-authored papers (with Stef Proost, KU Leuven) and Chapter 2 is single-authored. In the following, I will provide a synopsis of the primary results of this dissertation. A brief summary of each chapter can be found at the end of this preface.

The main instrument used by the EU to reduce CO_2 emissions in the light passenger car sector will be the limitation of the emissions of new cars sold in the EU in 2030 to practically half of the average emission level in 2019 (EC, 2019a). Electric vehicles are treated as zero-emission cars and, therefore, are key to achieving the emission reduction target. This dissertation compares how targeted consumer and supply chain policy instruments affect the share of electric vehicles adopted in the EU market (Chapter 1). Using a two-period model for the car manufacturing sector with gasoline car producers and electric car producers, I compare the cost efficiency of different policies to decrease CO_2 emissions. I model several policies that generate endogenous technological progress, such as tradable fuel efficiency standards, portfolio mandates for the share of electric vehicles, carbon taxes, vehicle purchase taxes, and subsidies for R&D. The primary question of this exercise is whether the current EU policy instrument of a tradable carbon emissions standard is optimal for achieving emissions reduction in light passenger transport. The central quantitative finding is that this instrument outperforms a portfolio mandate for the share of electric vehicles because it contains an incentive not only to lower the costs of electric vehicles but also to improve the fuel efficiency of existing gasoline-powered vehicles.

In 2019, the EU set a fuel economy standard for heavy freight trucks to reduce the fleet-wide average emissions for new trucks by 15% compared to 2019 levels starting in 2025 and by 30% starting in 2030. Some EU member countries find this standard to be too lax and are actively developing stricter national policies. This dissertation examines this quandary of incongruous national and EU policy in two ways. First, it investigates the impact of this incongruity on the cost of avoided carbon emissions and examines the potential for carbon leakage (Chapter 2). Second, it assesses how international competition affects investment in new infrastructure for zero-emission transport systems (Chapter 3).

The first inquiry into this quandary asks how a stricter fuel economy standard for heavy freight trucks in one EU member country affects emissions reduction behavior in the rest of the EU. For this analysis, I construct a dynamic partial equilibrium model of the heavy freight truck market and calibrate it using EU data. One key quantitative finding is that all emissions reductions in the stricter country that go beyond the EU standard will leak to the rest of the EU, because the rest of the EU can relax their reduction goals while maintaining the EU standard. Another key result is that one EU member country introducing a stricter standard can substantially lower the average cost of carbon savings for all EU members. This is because the stricter standard intensifies innovation in the truck manufacturing sector; as R&D investment increases the fuel efficiency significantly improves. With fuel efficiency improvement, trucking companies must purchase fewer high cost high fuel efficiency trucks to meet the EU standard. When there is one standard across the EU, over 90% of trucks must have high fuel efficiency, whereas when there is one country with a stricter standard the share drops below 75%. In this way, the total capital cost of the trucking fleet is substantially lower, which decreases the overall cost of carbon saved. The final important result is that the magnitude of a feebate policy has a significant impact on the fuel efficiency improvement and producer investment in R&D, while there is no effect on carbon leakage. Without a feebate system in place to make the purchase cost of high fuel efficiency trucks more attractive to trucking companies, producers invest significantly more in R&D to improve fuel efficiency and drive operating costs down.

With the second inquiry into this quandary of incongruous policy, this dissertation asks what would be the outcome of the non-cooperative game between a forerunner country that wants to install electric highways for heavy road freight trucks and a neighboring country that does not install electric highways. In this analysis, I design a strategic game with three players: the forerunner country, the lagging neighbor, and trucking companies. The neighboring country determines the level of its investment in catenary electric highway infrastructure and distance pricing policy for diesel and electric trucks based on the investment and policies of the forerunner country. Seeing the different distance pricing schemes, the trucking companies then decide which type of truck to purchase and operate in each country. The central quantitative finding is that the determining factor for a neighbor country to switch to electric trucks is 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.

In summation, this dissertation highlights the variation in cost-effectiveness and efficiency across several proposed policies for emissions reductions in light passenger and heavy freight road transport. It allocates newfound importance to choosing the optimal policy mix in each scenario, as the policies will have a significant impact not only on the overall cost of saved carbon emissions, but also on the amount of investment in innovative low- and zero-emission technologies. In addition, this dissertation presents a new perspective on the value of policy coordination – or lack thereof – for carbon emissions reductions.

Chapter 1 In this chapter, I use a two-period model for a dynamic cost comparison of two main types of policy instruments: carbon emission standards for new cars and a portfolio mandate with a minimum of electric vehicle sales. This chapter contributes to the literature in three key ways. First, it endogenizes the progress in the costs and performance of electric and gasoline vehicles by making technological progress a function of the policy instruments that are used. Second, it considers the role of the batteries in electric vehicles to increase the share of renewable energy in the transport sector via 'vehicle to grid' technology. Further, this chapter acknowledges the different vehicle deployment externalities as well as the network externality that arises in the development of electric vehicle charging infrastructure. Finally, it assesses a wide range of policy options to stimulate the penetration of electric vehicles. The numerical calibration shows that the market share of electric vehicles depends strongly on the type of policy instrument used but that the share of electric vehicles is not necessarily a good indicator for a successful carbon policy. The main result of this chapter is that a carbon emissions standard achieves emission reductions at a much lower cost than a portfolio mandate for electric vehicles.

An earlier version of this chapter has been published as CESifo Working Paper No. 7789.

Chapter 2 This chapter asks: how does one or more member nations enacting a stricter fuel economy standard impact the emissions reduction behavior for the rest of the EU? Further, to what extent is there carbon leakage and how does incongruous national and international policy affect the total cost of achieving the EU fuel economy standard? To answer these questions, I develop a two-period partial equilibrium model for the heavy freight truck manufacturing sector where each producer maximizes profits subject to a constraint on the average emissions intensity of the truck fleet sold. Producers invest in R&D in the first period to lower the marginal cost of fuel efficiency technologies in the second period. Demand for trucks is split between two regions: the member nations adopting stricter fuel economy standards and the rest of the EU. With the market equilibria for each region, I can evaluate the effects of incongruous fuel economy standards on the rate of high fuel efficiency truck adoption, the investment in fuel efficiency improvement technologies, and the regional distribution of carbon emissions. For a more comprehensive understanding of the impact of R&D, I conduct several policy simulations demonstrating that the magnitude of a Bonus-Malus policy has a significant impact on the fuel efficiency improvement and producer investment in R&D. Further, I conduct several policy simulations to demonstrate the impact of the size of the region opting for a stricter fuel economy standard on the magnitude of inadvertent carbon leakage in the rest of the

EU and the distribution of costs between the regions. This chapter reveals an inadvertent trade-off between a Bonus-Malus feebate system and the producer investment in R&D.

Chapter 3 The main purpose of this chapter is to provide a deeper understanding of how international competition affects investment in new infrastructure and distance tax pricing for long-haul electric trucks. It 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. 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. Heavy freight truck transportation within the EU is increasingly long distance rather than local, so the ultimate costs and emission reduction success will depend on whether the neighbors follow a forerunner country and how the forerunner deals with international trucking. What neighboring countries will do in response depends on strategic considerations, there will only be coordination when it brings significant benefits. International diesel trucks, when crossing the border of a forerunner country, will have to choose between paying high charges and transferring the load into an electric truck. Therefore, this chapter examines under what conditions neighbors with different climate policies will choose to follow an ambitious forerunner? I 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. The key insight of this chapter is that the major reason why a neighbor country would follow a forerunner is whether the technological progress for catenary electric trucks enables a significant decrease in the operating costs making electric trucks cheaper to use than diesel trucks.

An earlier version of this chapter has been published as CESifo Working Paper No. 8876.

Chapter 1

What is the role for Electric Vehicles in the decarbonization of the car transport sector in Europe?

1.1 Introduction

While countries across the EU continue to decrease national emissions through the EU ETS and building and electric appliance regulations, transport emissions continue to grow. Road transport is responsible for 73% of the transport emissions, and more specifically cars account for 44,5% of GHG emissions (EEA, 2017). The EU relies on two overlapping instruments to reduce CO_2 emissions in the light vehicle segment. First, there is the minimum 10% share of renewable fuels in the car sector and second, there is the CO_2 performance standard for passenger vehicles (EC, 2016). In the last years, the car sector relied mainly on biofuels to reach the mandated share of 10% renewable power in the transport sector. However, the recent directive on renewable energy in the EU (RED II), establishes new biofuel sustainability criteria that will be difficult to meet with the current biofuels; the minimum renewable energy share of transport will be met by the introduction of Electric Vehicles (EVs).

The main instrument used by the EU to reduce CO_2 emissions will be the limitation of the emissions of new cars sold in the EU in 2030 to practically half of the average emission level in 2019 (59g of CO_2 per vehicle kilometer rather than the 110-115g emitted in 2019) (EC, 2019b). The EVs count as zero-emission cars and are therefore an important element in achieving the emission reduction target.

In addition, EVs can act as an important complement to the generalized use of renewable electricity that is part of the European strategy to achieve the Paris Agreement targets. The battery of EVs, when connected to the grid can help to bridge the periods with low and high renewable production. In this way, EVs can add flexibility to the increasingly renewable power sector by acting as storage medium and shifting supply from the renewable off-peak to the less renewable peak demand hours. In addition, EVs can save electricity generation capacity and help in balancing the power sector. EVs will be essential to reduce carbon emissions in the transport sector[1] and to satisfy the renewable transport objective.

In this chapter, we compare how targeted consumer and supply chain policy instruments affect the share of EVs. The direct effects of regulations and price incentives on EV penetration have already been widely studied using empirical consumer choice models. We offer three complementary contributions to this literature. The first contribution is to clarify the discussion on the role of different policy instruments on future costs and performance via R&D and learning by doing, thereby including the lagged effects of policy instruments. This is necessary to arrive at a correct dynamic cost comparison of policies. The second contribution is to also include a reduced representation of the power sector and the third contribution is to include some external effects of car use in addition to climate impacts.

To include the learning by doing and the R&D effects, we adapt the renewable electricity model of Fischer and Newell (2008) to the passenger car market. EVs can become cheaper through two knowledge building effects: learning by doing

[1]As the emissions in the EU electricity sector are capped by the tradable emission scheme (ETS), the net carbon emissions of an EV are zero. Since 2018, matters are more complicated as the EU-ETS has been turned into a hybrid system because the number of permits issued each year will be a function of the stock of unused allowances. See Perino (2018) and Bruninx, Ovaere, and Delarue (2019).

and pure R&D. Also, the fuel efficiency of conventional Gasoline Vehicles (GVs) can improve over time thanks to pure R&D. How much both technologies improve depends on the policies in place. Policies can incentivize car producers to produce more electric cars (learning by doing) but can also stimulate them to invest in R&D that reduces the costs of EVs and the cost of more fuel efficient GVs. Consumers are differentiated in function of the number of days per year they make a short or long trip. This differentiation serves two purposes. As EVs still have a difficulty to cover the long trips, this will segment the consumers between EV adopters and GV adopters. The number of days with short trips will also determine the availability of batteries for Vehicle to Grid (V2G) storage. The electricity production model used is simple and the V2G option is modelled as in Greaker, Hagem, and Proost (2019).

We use a two-period model for a simplified dynamic cost comparison of two main types of policy instruments: carbon emission standards for new cars and a portfolio mandate with a minimum of electric vehicle sales. This numerical comparison shows that the market share of EVs depends strongly on the type of policy instrument used but that the share of EVs is not necessarily a good indicator for a successful carbon policy. We find that the carbon emission standards for new cars with a tradable permit scheme across car producers achieves the emissions reduction goals at a lower cost than the portfolio mandate that focusses on a minimum share of new electric cars.

This chapter is organized as follows: In Section 1.2 we provide a review of the existing literature on policies for EV adoption. In Section 1.3 we survey the existing policy instruments with a focus on the EU and in particular on Germany. In Section 1.4 we present the formal model and in Section 1.5 we derive the effects of different policy instruments in the theoretical model. In Section 1.6 we discuss the calibration of the model using data for the German and European EV market. We present the policy results in Section 1.7, Section 1.8 delineates the key caveats of our model, and Section 1.9 concludes.

1.2 Literature review

There are several strands of literature that are significant to our research. We begin by reviewing the existing methods for modelling the impacts of climate policy on the development of the transport sector. This is followed by an outline of the research on EVs and the electricity grid. Next, we examine the literature on policy intervention in the transport sector and we conclude with the literature on the infrastructure challenges of widespread EV adoption.

To accurately account for the role of new technologies in climate policy, there are two approaches: an aggregate economy wide approach and a sectoral approach. Within the aggregate approach, one method is to take an existing computable general equilibrium (CGE) model and build out the transport sector in more detail to differentiate between a limited number of vehicle classes (see Paltsev et al. (2018), Zhang et al. (2017)). Another method within the aggregate model approach is to use an integrated assessment model which offers a detailed breakdown of the energy sector and then add a more detailed transport-energy demand function (see Pietzcker et al. (2013), Tattini, Maurizio, and Karlsson (2018), van der Zwaan, Keppo, and Johnsson (2013)). In the aggregate approach, technological progress is usually taken on board via a learning curve. The learning curve relates the future costs of a given technology to the number of installations. These models excel in trading off efforts in different sectors but fall short in the selection of policy instruments. In addition, the use of the learning curve approach tends to overstate the technological progress effects of additional installations (Nordhaus, 2014). The second, sectoral or partial equilibrium approach, can focus much better on the effects of policy instruments on the car transport market.

In this chapter, we employ a partial equilibrium model of the car transport market. In his recent survey of technological progress, Popp (2019) stresses the importance of integrating endogenous technological progress in the assessment of policies. For the integration of endogenous technological progress, we follow a similar approach as Fischer and Newell (2008). They use a stylized model of the electricity sector with two sub-sectors (a representative fossil fuel firm and renewable firm) which incorporates learning by doing and R&D investment for renewables with two stages to allow time for innovation. Using this simple model, they assess various policy options for reducing carbon emissions in the electricity sector. Eggert and Greaker (2014) modelled endogenous technological progress in a similar way for biofuels and their use in cars. Creti, Kotelnikova, Meunier, and Ponssard (2018) used a partial equilibrium model of the car sector to analyze when learning by doing would propel the hydrogen car into the market. In our model, consumers demand car transportation services that they can buy from gasoline car producers and from electric car producers. We allow for endogenous technical progress for EVs but also for fossil fueled cars and the technical progress originates not only from learning by doing, but also from pure R&D investment.

The literature on Electric Vehicles (EVs) focuses mainly on the speed of penetration of EVs as a new technology and on the possible barriers. The penetration is a function of the cost decrease over time and depends on the importance of car attributes such as the range and the refueling network. See Brownstone, Bunch, and Train (2000) for one of the first studies. Li, Long, Xing, and Zhou (2017) and Coffman, Bernstein, and Wee (2017) are recent reviews of the consumer behavior towards EVs. van Biesebroeck and Verboven (2018) provide a survey on the barriers to the large-scale production and market penetration of EVs.

There are several papers focused on identifying the various types of policy intervention for EV penetration in the transportation sector (see Anderson and Sallee (2011), Anderson and Sallee (2016)). van der Steen et al. (2015) provide a general overview of government policy intervention strategies and differentiate the type and effect of policies implemented upstream on the producers, downstream on the consumers, and system-wide on the network. Hardman, Chandan, Tal, and Turrentine (2017) find in their review that financial purchase incentives have been effective in increasing the sales of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Maciuli, Konstantinaviciute, and Pilinkiene (2018) examine the different opportunities for local and national governments to stimulate EV adoption.

In this chapter, we assess the effectiveness of policies aimed at both the supply and demand sides of the EV market. An important assumption in this chapter is that both consumer and producers act in a rational way. Policy makers in the EU and US often rely on a stream of literature that states car buyers are behaving myopically: consumers underestimate future fuel savings (see Brown (2001), Greene (2010), Busse, Knittel, and Zettelmeyer (2013)). Recent econometric evidence for the European car market contradicts this assumption and shows that consumers take into account approx. 90% of future fuel consumption costs (Grigolon, Reynaert, and Verboven, 2018). Reynaert (2020) contends EU car manufacturers behave as rational producers in their non-compliance to the current carbon emission standard. According to Reynaert, the compliance costs of the carbon emissions standard are too high compared to the current car fuel prices. In the absence of strict enforcement, the producers offer cars that minimize the total user costs of cars which results in less efficient cars than required by the standard.

Richardson (2013) reviews the literature regarding the ability of EVs to improve the integration of renewable energy sources into the existing electric grid. Further, Dallinger, Gerda, and Wietschel (2013) state that in a future with high renewable energy penetration in the electricity sector, EVs can store excess renewable energy produced in the off-peak periods and use it in the peak period where there is less renewable production. While we do not model the electricity sector explicitly, we model Vehicle to Grid (V2G) and consider the impacts of shifting electricity demand from off-peak (high renewable production) to peak periods (low renewable production).

There is limited literature concerned with the infrastructure challenges of EV adoption. Consumers with a garage can charge their car at home but those without a garage or those who are on a long trip have to rely on the public charging infrastructure. Charging infrastructure for cars is a well-defined network good and therefore exhibits network effects. Greaker and Midttømme (2016) assert that a failure to account for network effects can hinder the adoption of existing clean technologies. Further, Greaker and Kristoffersen (2017) argue that the lack of charging technology harmonization contributes to negative network externalities and impedes widespread EV adoption. Springel (2018) studied the Norwegian EV market, where penetration of EVs in new car sales is high ($>$ 30% in Oslo). Her estimates find that consumers are more likely to purchase EVs when the network is denser and that charging stations are more likely to enter when there is a larger stock of EVs. Li, Long, Chen, and Geng (2017) study the US market where penetration is much lower. They also find that diverting some of the subsidies for the purchase of EVs to the development of the charging network could be more effective in terms of EV penetration. Zhou and Li (2018) focus on the critical mass problem in the deployment of charging stations where the low adoption equilibrium may be the outcome in more than half of the U.S. Metropolitan Statistical Areas. We emphasize the production side of EVs and

GVs, but we include a simplified version of the charging station network effects via an average charging cost that is decreasing in the share of EVs.

The passenger car sector is an important source of carbon emissions but is also characterized by several other externalities, including congestion, non-carbon air pollution, noise, and accidents. The existing set of policy instruments to stimulate the adoption of EVs carries the risk of making these externalities worse. Wangsness et al. (2020) show that the Norwegian EV policy mix, which guarantees a low variable cost to EV users, induces a significant increase in car use and a decrease of Public Transport use in Oslo. This emphasizes the importance of including these externalities in the EV promotion policy.

Compared to the literature, this chapter offers several contributions. First, it endogenizes the progress in the costs and performance of EVs and of GVs by making technological progress a function of the policy instruments that are used. Second, it considers the role of the batteries in the EV to increase the share of renewable energy in the electricity sector via V2G. Further, we consider the different car use externalities as well as the network externality that arises in the development of EV charging infrastructure. Finally, it assesses a wide range of policy options to stimulate the penetration of EVs.

1.3 Current policy incentives for EV adoption

In the EU, there are two policy directives for the car manufacturers. First, there is the carbon emission standard for cars that requires a maximum emission rate of 95 g/vehicle-km by 2021 and the decision is to further decrease the emission rate by 37,5% in 2030 (EP, 2019). Second, there is the portfolio mandate requiring a minimum of renewable energy in the transport sector, which was mainly geared to be renewable biofuels. However, the new RED II policy package that is being adopted by the European Parliament is now much more demanding on the sustainability of the biofuels than in the RED I package. As this implies that the role of biofuels will decrease, the role of electricity has to increase.

The EU also requires national governments to support the achievement of the policy objectives for the manufacturers by using additional policies at the level of the carbon intensity of the fuel used, at the level of the refueling infrastructures, and at the level of the adoption of EVs by car buyers. Enactment and enforcement of these initiatives are left to the member states. Some member states have added a strict target for the share of EVs in new vehicle sales. These member state policies have been surveyed in OECD/IEA (2017) and almost all member states have adopted a combination of reduced purchase taxes (or higher subsidies) and subsidized recharging points. All EU countries offer slightly different policy mixes. Rather than use an average value of policy instrument implementation across the EU, we use present policies in Germany, the largest car market in the EU, as representative for the EU.

Germany offers, in addition to motor vehicle tax exemption and purchase subsidies, parking privileges to EV drivers (EAFO, 2019).[2] While many countries implement consumer-targeted policies, only the member countries that produce cars enact specific R&D policies for producers.

In this chapter, the baseline scenario will assume that the main EU-policy goal is a 37,5% reduction of the carbon emission standard of new cars by 2030 compared to 2021. This requirement is defined at the Tank to Wheel emission level. We implement this requirement at the aggregate sales level for cars. The EVs are considered as zero carbon emission vehicles in the regulation. This is correct in the case of the EU where the electricity sector is covered under the EU ETS cap. For the sake of generality, we will also present carbon emissions as a function of the type of electricity used to fuel the cars as this is more relevant for other continents. Given the difficulties to define sustainable biofuels or produce substitute carbon free liquid fuels, we assume that the electrification of the car stock will be the major way in which the renewable fuel obligation for transport fuels (RED-II) will be met. This means that we will neglect the RED-II policy constraint in our policy assessment.

Present market shares (2015-2020) for BEV are of the order of 6% in Germany and 2% in most EU countries (IEA, 2021).

[2]The tax exemption is valid for 10 years after the purchase date of the EV (AIMVM, 2017).

1.4 Building the model

1.4.1 The range of policy instruments

In this chapter, we estimate the impacts of different policy instruments. First, we evaluate an aggregate tradable carbon emission standard. The second major instrument we discuss is a portfolio mandate for electric cars. Both policy instruments are imposed at the aggregate EU level for the sales of new cars. Next, we discuss the effects of an EV purchase subsidy and a subsidy for en-route charging equipment. Finally, we assess a high purchase tax for fossil fuel cars.

These instruments are always combined with a subsidy for R&D and the current tax on motor fuels. Compared to most other sectors, the transport sector is characterized by very different externalities (congestion, conventional air pollution, accidents, noise) where climate damage is only one of many. In Europe, the major instrument for carbon emissions reduction is the high gasoline (and diesel) tax, it acts as a carbon tax and is important in raising tax revenues. It also keeps other externalities like congestion under control, be it inefficiently. In Germany, the gasoline tax accounts for nearly 60% of the consumer fuel price. Further, as shown in Figure 1.1 from the OECD (2013), the gasoline tax is nearly 300 €/tonne CO_2, over ten times higher than the EU ETS price of 25 €/tonne CO_2. In an ideal scenario, one can use the gasoline tax as a pure carbon tax and

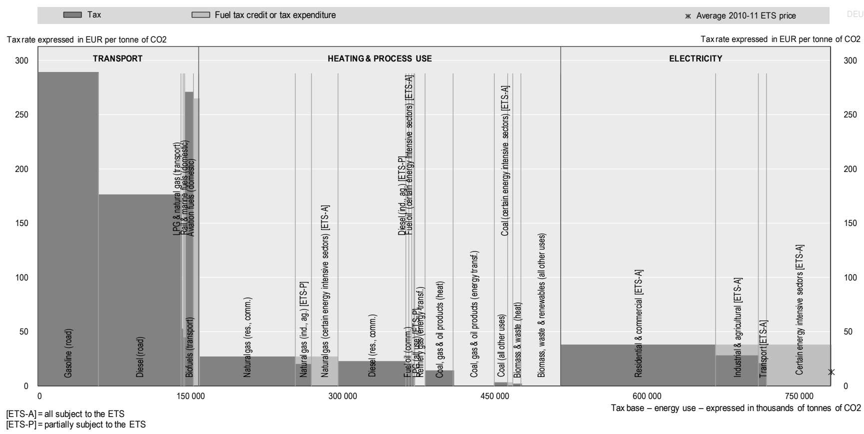

Figure 1.1: Effective carbon taxes by sector in Germany

complement it with other taxes (road pricing, other externality taxes, standards) that target the other externalities. This would be a major structural change in the way car transport would be taxed and would go beyond the scope of this chapter. Further, it would require the simultaneous treatment of all externalities and this would no longer allow us to focus on the carbon efficiency (see Proost and van Dender (2008) for an example). In order to have a correct comparison between EV and GV for the non-climate externalities (noise, other air pollution), we foresee a distance tax that is differentiated between EV and GV. We summarize the different policy instruments discussed in this chapter in Table 1.1.

Table 1.1: Policy instruments included in the model

Potential instruments	Carbon emissions standard	Portfolio mandate	Other policy combinations
Tradable emis. standard	X		
Portfolio mandate for EV		X	
Gasoline tax	current level	current level	current level
R&D subsidy	X	X	
Distance tax	X	X	X
GV purchase tax			X
Refueling infrastructure subsidy	X	X	X

1.4.2 The choice of cars by consumers

We consider only two technologies: gasoline or diesel vehicles[3] (GV) and battery electric vehicles (EV). There are two periods $t = 1, 2$, each representing a number of years n_t. Vehicle users are differentiated by the number of days with long trips that they make in a year. This characteristic is important for two reasons.

[3]Diesel engines perform slightly better than gasoline vehicles in terms of net carbon emission per vehicle-km. But since 'diesel-gate', diesels have lost market share because the effective abatement of conventional air pollution turned out to be more costly than before. In the rest of this chapter we focus on gasoline technology but substituting it with diesel technology would not make any difference at the level of aggregation of this chapter.

First, long trips with an EV are more difficult when one must recharge en-route. Second, days with short trips allow EVs to be used as storage for the grid. In the model presentation, we assume that we have M vehicle owners that are uniformly distributed[4] over the number of long trip days. The number of vehicle owners and the length of the short and long trips are given. This means that the mileage of each type of individual and of the total population are fixed. This condensed model generates the shares of electric and gasoline vehicles for given vehicle prices, fuel costs and taxes.

Let l_m be the number of days with long trips for user m and $(365-l_m)$ the number of days with short trips for user m. The total rental cost of a gasoline vehicle in period t is the annuity of the purchase price plus the cost of use. The purchase price of a gasoline vehicle is P_t^G, the producer price on an annual basis, plus the annual vehicle ownership tax, τ_t^G. As we use costs on an annual basis and as total vehicle ownership as well as annual mileage is fixed for each population segment, car purchase taxes and ownership taxes have the same effect. The usage cost U_t^G is a function of the variable cost per km driven, v_{tg}, and a tax per unit distance, t_{td}^G. This distance tax corrects for driving externalities such as noise, non-carbon emissions, accidents, and traffic congestion. As gasoline vehicles may also make progress in fuel efficiency over time, we introduce the fuel consumption per unit distance, f_t.

Therefore, the total annual cost of a user of type m of a gasoline vehicle with unit fuel consumption f_t is:

$$C^G(m) = P^G + \tau^G + d(m) \cdot U^G \tag{1.1}$$

where total annual distance $d(m) = l_m \cdot d_l + (365 - l_m) \cdot d_s$. Where d_s and d_l are the distances covered during a short and long trip day. The user cost is $U_t^G = f_t \cdot v_{tg} + t_{td}^G$ where the variable cost $v_{tg} = r_{tg} + t_{tg}$, with t_{tg} the gasoline tax and r_{tg} the gasoline resource cost. As there is a direct proportionality between the consumption of gasoline and the emission of carbon, the gasoline tax is a de facto carbon tax.

We can calculate total annual carbon emissions per gasoline vehicle X_{tm}^G with

[4] In the simulations we use triangular distribution of the number of long days per car.

the carbon emissions intensity factor per unit fuel consumed[5] x_g^{cl}.

$$X_{tm}^G = d(m) \cdot f_t \cdot x_g^{cl} \tag{1.2}$$

We will make use of the imputed damage for carbon emissions, and define this as dam^{cl} in € per unit emissions, therefore we have the annual damage of emissions for a GV

$$C(X_{tm}^G) = X_{tm}^G \cdot dam^{cl} \tag{1.3}$$

We measure the non-climate annual external costs of gasoline vehicle operation $C(Y_m^G)$ in € per unit distance using y^G as the sum of several externalities: $y^G = y_A + y_{OP}^G + y_N^G$ where y_A represents externalities due to accidents and congestion, y_{OP}^G represents non-carbon air pollution, and y_N^G represents noise pollution. These additional external costs vary with the length of the trip, so we have y_l^G and y_s^G for the non-climate external costs incurred during long trips and short trips, respectively. For instance, the cost of accidents and congestion increases in the length of the trip.

$$C(Y_m^G) = l_m \cdot d_l \cdot y_l^G + (365 - l_m) \cdot d_s \cdot y_s^G \tag{1.4}$$

The external costs of climate and other externalities do not enter the user cost, but they are included in the social welfare calculation.

The purchase price of an electric vehicle is the producer price on an annual basis $P_t^E(B)$ plus the annual vehicle ownership tax (or subsidy), τ_t^E. The purchase cost of an electric vehicle is increasing in its battery capacity B. The usage cost depends on the length of the trip and is decreasing in the capacity of the battery. For one short trip, the usage cost is

$$U_{ts}(B) = d_s(e \cdot p_{off} + t_{td}^E) - (B - d_s \cdot e)(p_{peak} - p_{off}) \tag{1.5}$$

where e is the energy efficiency of the EV. As p_{off} and p_{peak} are the prices of electricity in the off peak and peak period, $U_{ts}(B)$ is the cost of electricity used to travel d_s km, assuming the battery was charged during off-peak hours, plus the tax per unit distance t_{td}^E, minus the savings realized by using the car for storage, i.e. selling back the unused energy to the grid, during peak hours. For

[5]We use a tank to wheel emission factor as this emission factor is also used in the EU regulation.

long trips the user incurs, instead of savings, additional electricity and disutility costs of en-route charging. For one long trip, the usage cost is

$$U_{tl}(B) = d_l \cdot t_{td}^E + B \cdot p_{off} + (p_{ch} + z - P^P \cdot q_t^E)(d_l \cdot e - B) \tag{1.6}$$

where p_{ch} is the price of electricity at the charging station, and z is the user's disutility from en-route charging in terms of time lost and $P^P \cdot q^E$ is the benefit of a wider recharging network where P^P is the recharging access cost reduction of an extra EV and q^E is the total number of electric vehicles. The user cost of charging stations decreases as the total amount of EVs sold increases (see Li, Long, Chen, and Geng (2017) and Springel (2018)). In the simple model, we assume that all EVs use the same charging technology, such that we have technology harmonization avoiding the harmonization issue. Following Greaker, Hagem, and Proost (2019), we posit first that the cost of charging en- route is sufficiently high so that for a short trip, there is never a need to recharge the EV, so $B > d_s \cdot e$. Secondly, we assume that the battery cost in a car is higher than the cost of a fixed stand-alone battery $B < d_l \cdot e$. In this way, we have lower and upper bounds for the size of the car battery. For a given electric vehicle user, the total annual cost is

$$C_t^E(m, B) = P_t^E(B) + \tau_t^E + (365 - l_m)U_{ts} + l_m \cdot U_{tl} + CHE_t \tag{1.7}$$

where $CHE_t = k - s_{t,ch}$ and k is the total annuity cost of home charging equipment for the user. This may be subsidized by an amount $s_{t,ch}$.

In the absence of a strict CO_2 cap for the electricity sector, there can be CO_2 emissions generated by charging EVs with fossil fuel electricity. Then we measure the carbon emissions intensity of the peak electricity per kWh with x_e^{cl}. We assume that off-peak electricity is generated with renewable sources, therefore it has negligible emissions. Under this assumption we can calculate total annual emissions per vehicle, X_m^E.

$$X_m^E = \big[l_m(d_l \cdot e - B) - (365 - l_m)(B - d_s \cdot e)\big]x_e^{cl} \tag{1.8}$$

We assume that the off-peak electricity is renewable while the peak electricity is not. Note that, in this case, the substitution of peak electricity by renewable electricity made possible by the use of spare battery capacity during short trips leads to a decrease of total carbon emissions.

There are non-climate external costs $C(Y_m^E)$ from operating an electric vehicle, which we estimate in € per unit distance with y^E. As with GVs, y^E is the sum of accident and traffic congestion y_A, non-carbon air pollution y_{OP}^E, and noise pollution y_N^E. Further, these external costs vary with trip length, so we have y_s^E and y_l^E and we can express the total non-carbon external costs as a function of trip length:

$$C(Y_m^E) = l_m \cdot d_l \cdot y_l^E + (365 - l_m) \cdot d_s \cdot y_s^E \tag{1.9}$$

We assume that all vehicles contribute equally to congestion and accidents whether they are GVs or EVs, so y_A is constant across vehicle types. Further, we posit that EVs are quieter than GVs, therefore $y_N^E < y_N^G$, and EVs produce less non-climate emissions than GVs such that $y_{OP}^E < y_{OP}^G$.

We normalize the distribution of m users with the maximum number of long trips $m(l \leq l^{max}) = 1$ and the number of m users with the minimum number of long trips $m(l \leq l^{min}) = 0$. Let l^o be the number of long trip days from which it becomes interesting to have a GV, then we have the total number of EVs given by

$$\begin{aligned} q_t^E &= m(l \leq l^o) \cdot M \\ q_t^G &= [1 - m(l \leq l^o)] \cdot M \end{aligned} \tag{1.10}$$

1.4.3 Gasoline vehicle production

The producers of GVs maximize profits under perfect competition. There is only one standard type of gasoline vehicle and we assume users are not myopic: they choose the car that has the lowest cost for their user profile.

We consider two cases for the cost functions for gasoline cars. In the first case the fuel efficiency or carbon emissions standard[6] is not constrained. Then, each producer wants to offer a vehicle with a fuel consumption per mile f that minimizes users' costs and this implies that the carbon efficiency is a function of the fuel cost and an average mileage. In the second case, the minimum carbon efficiency

[6] When less carbon intensive fuels (biofuels) are used, the fuel efficiency is not equivalent to the carbon efficiency but as we assume a decreasing role for biofuels, we neglect this difference in the rest of the chapter.

is constrained by the government. In the EU, the second case is more realistic as producers tend to underperform compared to the carbon emissions standard (Reynaert, 2020): consumer fuel prices and the cost of more fuel-efficient cars are such that fuel producers produce cars that are not carbon efficient enough. Producers of gasoline vehicles can meet the carbon emissions standard by either making their car more fuel efficient or by buying carbon efficiency credits fec_t from producers of EVs at a price $pfec_t$. We assume that there is good monitoring of the realized minimum fuel efficiency (here maximum fuel consumption per vehicle km f^{max}) and that the fine is sufficiently high to make all car manufacturers comply.

Following the Fischer and Newell (2008) technique to introduce endogenous technological progress, we assume that the gasoline car producers can, in the first period, invest in a better knowledge base that helps to reduce the costs of more carbon efficient vehicles in the second period. The knowledge base is produced by two factors: learning by doing as well as by pure R&D. Learning by doing decreases costs by drawing on the accumulated production, also known as the experience curve approach. The pure R&D is the second way to increase the knowledge base. It is difficult to separate the effects of learning by doing and pure R&D. Aghion et al. (2016) in their study of the patents firm-level panel data on auto industry innovation distinguishing between "dirty" internal combustion engine and "clean" e.g., electric, hybrid, and hydrogen patents across 80 countries, show that both factors matter. They showed that the innovation activities of all automobile producers react to fuel price incentives, that gasoline car firms specialize in fuel efficiency patents and greener car producers specialize in patents bringing down the costs of electric vehicles. They also show that there are important localized spillovers. In our formulation, we limit the effect of the knowledge base of gasoline cars to the costs that are specific to the fuel efficiency efforts of gasoline cars. This is in line with the separation in Aghion et al. (2016) between dirty patents and grey patents, where the grey patents are the ones that are related to the reactions of the fossil fueled cars to fuel price changes. The total investment in R&D for fuel efficiency and the learning by doing will then reduce the fuel efficiency related costs in the second period.

The total knowledge base in the first period is K_1^G, in second period is K_2^G and is defined by the following expressions:

$$
\begin{aligned}
K_1^G &= 1 \\
K_2^G &= \left(\frac{H_2^G}{H_1^G}\right)^{\eta^H} \left(\frac{Q_2^G}{Q_1^G}\right)^{\eta^Q} \\
H_2^G &= n_1 h_1^G \\
Q_2^G &= n_1 q_1^G
\end{aligned}
\tag{1.11}
$$

The total knowledge built up via investments h^G in R&D for gasoline cars and the accumulated production Q^G both contribute to the knowledge stock, where n stands for the length of the period in years and q stands for the production per year. R&D and learning-by-doing can be complements or substitutes. η^H represents the elasticity of product costs with respect to R&D investment and η^Q represents the elasticity of product costs with respect to cumulative production, we refer to this mechanism as 'learning by doing'.

We now discuss the model equations assuming a tradable carbon emissions standard policy. The GV firm's profit equals total sales times the producer price for GV, P_t^G, minus a production tax on GV, ϕ_t, minus total production costs for GV, $G(q_t^G)$, minus the expenses for R&D and minus the costs of the necessary carbon efficiency credits it needs to buy when it does not meet the carbon emissions standard. The firm maximizes the sum of profits in the first period, made up of n_1 years, and discounted profits from the second period, made up of n_2 years. $R(h_G)$ is subsidized by the government at a rate σ_G.

$$
\begin{aligned}
\Pi_G = n_1 &\left[(P_1^G - \phi_1)q_1^G - G(K_1^G, q_1^G) - (1-\sigma_G)R(h_G) - \left(\frac{1}{f_1^{max}} - \frac{1}{f_1}\right) pefc_1 \cdot q_1^G\right] \\
&+ \delta n_2 \left[(P_2^G - \phi_2)q_2^G - G(K_2^G, q_2^G) - \left(\frac{1}{f_2^{max}} - \frac{1}{f_2}\right) pefc_2 \cdot q_2^G\right]
\end{aligned}
\tag{1.12}
$$

The production cost of GVs has constant returns to scale and consists of a part that is non fuel-efficiency related (NFP) and a part that is fuel efficiency related. The fuel efficiency related costs will decrease when the knowledge level K^G increases. The cost of increasing fuel efficiency is quadratic in $1/f$. The knowledge level K is a function of learning by doing Q and investments in R&D H for gasoline cars. At the start of the first period, the knowledge level is set to 1 but in the second period, the accumulation of knowledge decreases the costs of improved fuel efficiency.

$$G(K_t^G, q_t^G) = q_t^G \left[NFP + \frac{1}{K_t^G}(i_g + 0.5 j_g \cdot f_t^{-1}) f_1^{-1} \right] \tag{1.13}$$

We assume perfect competition in the production of cars, so every manufacturer takes prices of cars in the two periods as given. Maximizing profits generates equilibrium market prices for GV in the first and second period as well as firm optimal investments in R&D and a firm optimal fuel efficiency:

$$\begin{aligned}
\frac{\partial \Pi^G}{\partial q_1^G} &= n_1 \left[(P_1^G - \phi_1) - G_{q_1^G}(K_1^G, q_1^G) - \left(\frac{1}{f_1^{max}} - \frac{1}{f_1} \right) pefc_1 \right] \\
&\quad - \delta \rho n_2 \left[G_{Q_2^G}(K_2, q_2^G) n_1 \frac{\partial K_2^G}{\partial Q_2^G} \right] = 0 \\
\frac{\partial \Pi^G}{\partial q_2^G} &= n_1 \left[(P_2^G - \phi_2) - G_{q_2^G}(K_2^G, q_2^G) - \left(\frac{1}{f_2^{max}} - \frac{1}{f_2} \right) pefc_2 \right] \\
\frac{\partial \Pi^G}{\partial h_1^G} &= -n_1(1 - \sigma_G) R_h(h_1^G) - \delta \rho n_2 G_{H_2^G}(K_2^G, q_2^G) n_1 \frac{\partial K_2^G}{\partial H_2^G} = 0 \\
\frac{\partial \Pi^G}{\partial f_t^{-1}} &= 0 \Rightarrow i + j f_t^{-1} = pefc_t
\end{aligned} \tag{1.14}$$

The first equation shows that the price of a GV will equal the marginal production cost in the first period plus the carbon efficiency credits it will need per car minus the cost decrease it can realize in the second period thanks to learning by doing in the first period. Of the knowledge the firm did build up in the first period, only a share $\rho \leq 1$ can be captured by the firm due to spillovers that cannot be valorized by patents[7].

The investment in pure R&D helps to reduce the cost of more fuel efficient vehicles in the second period, again only a share ρ is captured by the firm. The level of fuel efficiency of cars is, in each period, pushed until the marginal cost of more fuel efficiency equals the price of a carbon efficiency credit. Note that knowledge efforts are directed mainly to reduce the cost of making cars more fuel efficient: the stricter the carbon emissions standard, the higher the marginal cost of fuel efficiency efforts, the higher the price of carbon efficiency credits and the higher the payoff of knowledge building.

[7] This is a reduced form representation of a representative firm in a sector with innovation spillovers. All knowledge is ultimately adopted and licensing revenues cancel out between firms. See Fischer and Newell (2007).

We will also model other policy instruments. A popular policy contender is the portfolio mandate by which the car market has to reach minimum market share α of EVs. This can be implemented via a tradable portfolio credit with a value *prport* that will be received by EV manufacturers for every EV they sell and by making the GV producers buy a proportion $\alpha/(1-\alpha)$ of the portfolio credit for each GV they sell. The portfolio credit cost is then added to the marginal cost of the GV. Prices of GV will be increased and EV prices decreased until the desired portfolio is reached.

1.4.4 Electric vehicle production

Similarly, EV producers maximize the sum of the discounted profits in the first period and second period. The total cost in the first period consists of production costs, $G(K_t^E, q_t^E)$ and the R&D investment made by the firm, $(1-\sigma_E)R(h_E)$ and the sales of carbon efficiency credits to the GV industry. Where q_t^E is the production of EVs in period t, K_t^E is the knowledge stock for EVs and σ_E is the share of R&D expenditure that is paid by the government. As the main challenge in terms of technological progress is to make batteries cheaper (and lighter), we assume that the knowledge stock serves to decrease the cost of the battery component of EVs. Production costs are proportional in output and decreasing and convex in knowledge stock. The knowledge stock is built up in the first period by the total sales of EVs (learning by doing) and by the total investment in pure R&D. EV producers maximize profits:

$$\begin{aligned}\Pi_E = n_1 &\left[(P_1^E - \nu_1)q_1^E - G(K_1^E, q_1^E) - (1-\sigma_E)R(h_E) - \left(\frac{1}{f_1^{max}}\right) pefc_1 \cdot q_1^E\right] \\ &+ \delta n_2 \left[(P_2^E - \nu_2)q_2^E - G(K_2^E, q_2^E) - \left(\frac{1}{f_2^{max}}\right) pefc_2 \cdot q_2^E\right]\end{aligned} \tag{1.15}$$

where ν_t is the production tax (or subsidy) for EVs.

The production cost of EVs has constant returns to scale and consists of a non-battery part (NBP) and a battery part (B).

$$G(K_t^E, q_t^E) = q_t^E \left[NBP + \frac{a}{K_t^E} B\right] \tag{1.16}$$

The battery part decreases with additional knowledge but is linear in the battery power per car. We have the same knowledge building formulae as with GVs (see

Equation 1.11).

$$
\begin{aligned}
K_1^E &= 1 \\
K_2^E &= \left(\frac{H_2^E}{H_1^E}\right)^{\eta^H} \left(\frac{Q_2^E}{Q_1^E}\right)^{\eta^Q} \\
H_2^E &= n_1 h_1^E \\
Q_2^E &= n_1 q_1^E
\end{aligned}
\tag{1.17}
$$

The optimal production level of electric vehicles in the two periods and the investment in pure R&D in the first period are determined by the first order conditions:

$$
\begin{aligned}
\frac{\partial \Pi^E}{\partial q_1^E} &= n_1 \left[(P_1^E - \nu_1) - G_{q_1^E}(K_1^E, q_1^E) - \left(\frac{1}{f_1^{max}}\right) pefc_1 \right] \\
&\quad - \delta\rho n_2 \left[G_{Q_2^E}(K_2, q_2^E) n_1 \frac{\partial K_2^E}{\partial Q_2^E} \right] = 0 \\
\frac{\partial \Pi^E}{\partial q_2^E} &= n_1 \left[(P_2^E - \nu_2) - G_{q_2^E}(K_2^E, q_2^E) - \left(\frac{1}{f_2^{max}}\right) pefc_2 \right] \\
\frac{\partial \Pi^E}{\partial h_1^E} &= -n_1(1-\sigma_E) R_h(h_E) - \delta\rho n_2 G_{H_2^E}(K_2^E, q_2^E) n_1 \frac{\partial K_2^E}{\partial H_2^E} = 0
\end{aligned}
\tag{1.18}
$$

1.4.5 The electricity market

In this stylized model, the electricity market has two types of production: peak fossil fuel production and off-peak renewable production. To represent the different costs of the peak and off-peak electricity, we have one peak electricity production technology and one renewable production technology. Using peak load pricing theory, the marginal cost of peak electricity (excluding climate permits) equals p_{peak} and is equal to the variable fossil energy cost plus the capacity cost divided by the length of the peak period. For the off-peak electricity we have a cost p_{off}. As we assume that the fossil fuel plant is only used in the peak period and as we assume that there is no peak shifting in the total electricity demand, we take the peak and off-peak prices of electricity as given and these can be considered as the opportunity costs of peak and off-peak power. We can include in the model two types of electricity demand during the peak and off-peak: demand by the vehicle sector and demand by all other sectors. The demand for electricity by the car sector is determined by the share of EVs and the annual distance that they travel. Demand for electricity by all other sectors is given by a representative demand function. But as long as the prices of electricity do not change, we do not have to consider the demand for electricity of the other sectors.

1.4.6 Social welfare function

In this welfare optimization problem, we maximize the sum of total consumer surplus and producer surplus in the vehicle market and in the electricity market plus the government surplus, represented by CS_V, PS_V, CS^{ot}_{EL}, PS_{EL} and GS, respectively. And we minimize the sum of the carbon and other external emissions damage costs produced by the gasoline and electric vehicles, C^E_Y, C^G_Y, C^E_X and C^G_X.

$$W = CS_V + PS_V + GS + CS^{ot}_{EL} + PS_{EL} - C^E_Y - C^G_Y - C^E_X - C^G_X \tag{1.19}$$

In the set up of the model, we assume that peak and off-peak electricity prices are fixed in both periods, therefore we do not need to include electricity market surplus (except for the EV owners) in the welfare maximization problem.

$$W = CS_V + PS_V + GS - C^E_Y - C^G_Y - C^E_X - C^G_X \tag{1.20}$$

The total government surplus is given by the gasoline and electric vehicle producer and consumer taxes,

$$\begin{aligned} GS = {} & n_1 \left[(\phi_1 + \tau^G_1) q^G_1 + (\nu_1 + \tau^E_1 - s_{ch})(q^E_1) - \sigma_G R(h_G) - \sigma_E R(h_E) \right] \\ & + \sum_{m=0}^{m(l^o_1)} d(m) \cdot (t^E_{d,1}) + \sum_{m=m(l^o_1)}^{M} d(m)(t^G_{d,1} + f_1 \cdot t_{g,1}) \\ & + \delta n_2 \left[(\phi_2 + \tau^G_2) q^G_2 + (\nu_2 + \tau^E_2 - s_{ch})(q^E_2) \right] \\ & + \sum_{m=0}^{m(l^o_2)} d(m) \cdot (t^E_{d,2}) + \sum_{m=m(l^o_2)}^{M} d(m)(t^G_{d,2} + f_2 \cdot t_{g,2}) \end{aligned} \tag{1.21}$$

Where we have included both the production and consumer taxes, summed over the total distance travelled for each mode for each user.

1.5 Solving the model

1.5.1 Market equilibrium

In our model, the car ownership and the car use are given. The equilibrium value of interest is therefore the market share of GVs and EVs.

The major disadvantage of EVs compared to GVs is their limited range. So, we can expect a user equilibrium where EVs are selected by consumers that make mainly short trips. So, we look for l_t^o, the number of long trips for user m where she is indifferent between using a gasoline vehicle and an electric vehicle. To do this we compare the total cost of both vehicles. The break-even point will be determined by the number of long trips where the consumer costs in the first period for GV and EV are equalized. In the second period, the threshold number of long trips can increase due to stronger technological progress for EVs. The equilibrium is influenced by the exogenous policy interventions.

The easiest way to determine, for a given set of policy parameters, the threshold number of long trips l^o, is to use l^o as a control variable and to check the slope of total cost functions as a function of the number of long trips l.

Taking the derivative of the total annual cost for the m-th EV user, $C^E(m)$, yields the following expression:

$$\frac{\partial C^E(m)}{\partial l_m} = (d_l - d_s)t_d^E + (B - d_s \cdot e)p_{peak} + (p_{ch} + z - P^P \cdot q_t^E)(d_l \cdot e - B) \quad (1.22)$$

where the first term represents the additional distance charge for one extra day with a long trip, $(B - d_s \cdot e)p_{peak}$ represents the lost opportunity of storage and $(p_{ch} + z - P^P \cdot q_t^E)(d_l \cdot e - B)$ represents the total cost of charging en-route. This expression is constant and the slope will be higher for a small battery car than for a large battery car.

Taking the derivative of the total annual cost for the m-th GV user, $C^G(m)$, yields the following expression:

$$\frac{\partial C^G(m)}{\partial l_m} = (d_l - d_s)\left[f \cdot v_g + t_d^G\right] \quad (1.23)$$

As both $\frac{\partial C^E(m)}{\partial l_m}$ and $\frac{\partial C^G(m)}{\partial l_m}$ return scalars, we know that $C^E(m)$ and $C^G(m)$ are linear in l_m.

We can represent the car market equilibrium graphically. In the graph A represents the following formula:

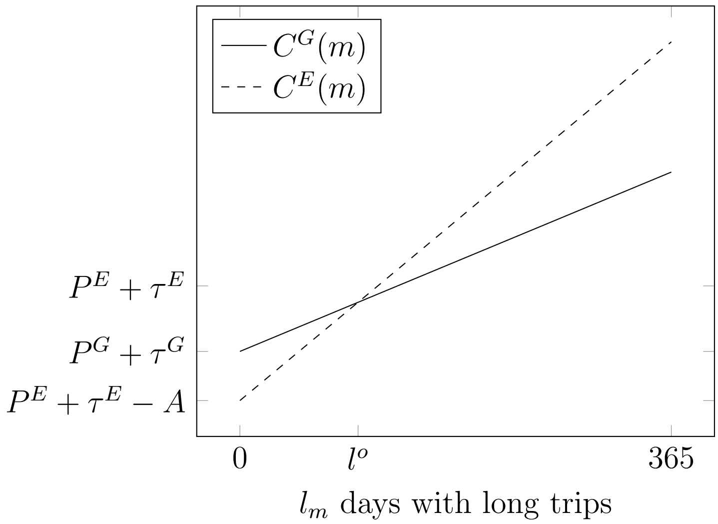

Figure 1.2: Illustration of user equilibrium mechanism for one period

$$A = 365(B - d_s \cdot e)(p_{peak} - p_{off}) \tag{1.24}$$

which is the annual benefit of selling stored battery electricity during the peak. If $l_m = 0$, then all trips are short and every day the vehicle user can sell excess electricity to the grid. From this graph, it is clear that for $l_m < l^o$ users prefer electric vehicles, and for $l_m > l^o$ users prefer gasoline vehicles.

1.5.2 Comparative statics

Equalizing $C^E(m^o) = C^G(m^o)$, we can solve for l^o

$$l^o = \frac{P^E - P^G + \tau^E - \tau^G + CHE + 365(U_s - d_s \cdot U^G)}{(d_l - d_s)U^G - (U_l - U_s)} \tag{1.25}$$

Consider first an increase in the battery capacity B. This has two benefits: it decreases the costs of the long trips and allows to gain more storage credits on short trip days. This would lead to more EVs: the slope of the $C^E(l)$ would become flatter but it also increases the cost of an EV and this shifts the $C^E(l)$ upwards such that the end result is undetermined.

Lower costs for en route charging (denser network, faster charging) will of course lead to higher penetration of EVs:

$$\frac{\partial l^o}{\partial p_{ch}} < 0 \qquad \frac{\partial l^o}{\partial P^P} < 0 \tag{1.26}$$

As EVs also can serve a storage function, lower costs of off-peak electricity (lower renewable costs in the off-peak) also increases the market share of EVs:

$$\frac{\partial l^o}{\partial p_{off}} < 0 \tag{1.27}$$

Conversely, as we increase the price differential of peak and off-peak electricity, the potential benefit to EV users of selling excess power increases.

We can also prove that to decrease emissions via more storage of renewable off-peak electricity, we must increase l^o. First, we find the total emissions from our stylized vehicle model.

$$\begin{aligned} \Delta X_V &= X_G - X_E \\ &= [l^o \cdot d_l + (365 - l^o) \cdot d_s] \cdot f \cdot x_g^{cl} - [l^o(d_l \cdot e - B) - (365 - l^o)(B - d_s \cdot e)]\, x_e^{cl} \end{aligned} \tag{1.28}$$

When we differentiate with respect to l^o we need to consider that, as we increase l^o we are increasing the number of EVs, and thereby EV emissions, while reducing the number of GVs, and thereby GV emissions. Therefore, we represent the derivative

$$\frac{\partial \Delta X_V}{\partial l^o} = (d_l - d_s) \cdot (f \cdot x_g^{cl} - e \cdot x_e^{cl}) \tag{1.29}$$

Assuming that $x_g^{cl} > x_e^{cl}$, the change in emissions depends on the fuel efficiency of GVs and the energy efficiency of EVs. As long as $e > f$, emissions will decrease as l^o increases, which is the outcome we expect as the share of EVs increases.

1.5.3 Optimal policy

In the optimal case, we need to correct all externalities. There are 5 externalities that need correction: the climate externality, the other external costs associated to car use, the learning by doing externality for EV producers, the R&D pure knowledge externality for EV batteries and GV fuel efficiency, and the network externality of the charging stations.

This requires at least 5 instruments: a tax per unit of carbon emitted, a tax to correct for the other externalities, a subsidy to pay for the external pure R&D externalities, a subsidy to correct for the learning by doing externalities, and a subsidy for the network externalities in the EV recharging network.

We can solve for the optimal amount of government funded R&D σ and the optimal EV tax (or subsidy) ν to correct the knowledge spillovers, when we set the first order conditions for profit maximization equal between the market correcting and market optimal scenarios. In this way, we have for electric vehicles:

$$\begin{aligned} \sigma &= 1 - \rho \\ \nu_1 &= (1-\rho)\delta n_2 G_K(K_2, q_2^E) K_H(H_2, Q_2) \end{aligned} \tag{1.30}$$

We have similar results for the optimal level of R&D and learning subsidies. In the first-best solution, the government subsidizes R&D to compensate the share of knowledge that is not retained by the firm. The production subsidy in the first period is equal to the lost benefits of first period learning that affect second period production.

To correct for the other externalities we need distance taxes that cover the other externalities (noise, non-carbon emissions, congestion, and accidents) as well as a carbon tax. In this way, $t_d^G = y_{ot}^G$, for GVs and $t_d^E = y_{ot}^E$ for EVs.

Building the model, it is clear that electric vehicle production depends on production costs, the cost of R&D, and the share of retained knowledge. Gasoline vehicle production depends on GV vehicle production tax and sales tax, as well as on the possibilities to bring down the fuel efficiency costs via knowledge build up that is for GVs limited to the R&D route only. Consumer demand depends on the vehicle purchase price, annual ownership tax, vehicle emissions, usage fees, and ease of use.

1.5.4 Selected policies for simulation

We will concentrate the policy analysis on 2 alternative policies:

Tradable portfolio mandate: One can oblige the car retail sector to sell a minimum market share of EVs. The best way to operationalize this measure is to use portfolio credits where the GV producers have to buy credits from the EV manufacturers.

Maximum tradable carbon emissions rate or minimum tradable fuel efficiency rate: An upper limit on the carbon emissions rate puts pressure on GV producers to reduce the emissions intensity of their vehicles. As EVs have zero emissions by definition, GV producers can pay EV producers to achieve the required emission rate

Both policies include *Subsidized charging stations*: Subsidizing charging stations increases the frequency and dispersion of en-route charging opportunities, effectively extending the driving range for EVs. By expanding the driving area range, a larger cross-section of consumers is interested in driving EVs.

We will also experiment with a *Tax on GV purchase or Subsidy for EVs*: this policy is used widely to promote the use of a cleaner vehicle technology. As total car ownership is given, a tax on GV purchase has the same effect as a subsidy for EVs.

The common objective of all the policies is to achieve the same reduction in the average carbon emission rate of new cars, where the carbon emission rate for EV is taken to be 0. This decrease in the average carbon emission rate is decided exogenously at the EU level. Finally, recall that in this model the mileage and car ownership are fixed, so that rebound effects of more efficient cars are neglected.

1.6 Calibration of the numerical model

1.6.1 Focus of the model

We calibrate the model to Germany. We are interested in European policy assessment, but as Europe only sets the broad policy options, it is better to look into one concrete country with its actual policies rather than to examine an average of policy measures over EU countries. But as we analyze the effect of the broad European policy options, we assume that the car manufacturers respond to the simulated policies at the European market scale when they decide on production and R&D investments, so the policy options we discuss are, by assumption, common to all member countries. We consider only two types of cars: gasoline cars and battery electric cars. We leave out the diesel cars as it is not clear whether the latest generations of diesel cars (EURO 6) do, in general, comply with the emissions standards for conventional pollution (NO_x) and may, therefore, be banned in more and more areas (ICCT, 2018). We also leave out the plug-in electric vehicles (PHEV). Hybrid technology may be interesting but up to now it is difficult to monitor to what extent they are effectively used in electricity engine mode and not in fossil engine mode.

We build a two-period model, where the first period of 5 years can be understood as covering the target year 2021 and a second period of 10 years where the target year is 2030. The present EU policy target for 2021 is a fuel efficiency of minimum 95 g CO_2 or 4,1 L/100 vehicle-km (vkm) (tank to wheel and NEDC test procedure) and for 2030 the target is a reduction of another 37,5% to reach 59 g CO_2 (or 2,56 L/100 vkm). The EC allows trading of carbon efficiency credits, the so-called "pooling" and "trading" schemes (EC, 2017a).

1.6.2 Calibration challenges

Dealing with new technologies is inherently difficult for several reasons. First, there is the uncertainty on the costs of future technologies. Second, the present prices may already be set strategically in the sense of selling more in order to benefit from the learning by doing mechanism. Third, the car market is a monopolistic competition market. We neglect the monopolistic feature of the market by assuming perfect competition as this allows us to analyze more carefully other mechanisms like technological progress. We return to this assumption later.

We proceed in the following way. We start by recalling the empirical basis of car consumers and producers in the EU. Next, we calibrate the model to the Norwegian policy experience that achieved a 30% market share for new cars in 2017 using a 100% purchase tax on GVs. This is the only case where EVs achieved a large market share up to now. In a final step, we look into the estimates of the cost development of new technologies. We conclude with a set of parameter estimates that will be used in the policy analysis.

1.6.3 Empirical basis for the EU passenger car market

A crucial assumption for the choice between fossil fuel and electric cars is the trade-off between purchase costs and fuel costs. For an accurate characterization of the trade-off, we rely on Grigolon, Reynaert, and Verboven (2018) who estimated a supply and demand model for the EU car market exploiting the differences across EU countries in fuel costs and purchase costs for gasoline and diesel cars and including the monopolistic competition features of the car market. They found that consumers are not systematically myopic in their car purchase decisions. Their central estimate is a discount rate of 5,7% for a vehicle lifetime of 10 years[8]. This is the estimate we will use in the model.

A second empirical insight we will use is the explanation given by Reynaert (2020) for the gap between the current fuel efficiency of cars and the fuel efficiency standard imposed by the European Commission. As car manufacturers were not fined for the fuel efficiency gap, they offer vehicles with a fuel efficiency that minimizes the sum of total user costs and purchase costs. The gap of 20% to 40% in the fuel efficiency achievements becomes then a rational response of the car manufacturers. This implies that, for the consumer, the possible fuel expenditure savings of 1 liter of gasoline per 100 vkm, or 225 € per year (15.000 km/year, price of fuel 1,5 €/liter), are smaller than the manufacturing cost of making a car that is 1 liter per 100km more efficient. This implies that the cost of increasing the fuel efficiency by 1 liter per 100 vkm has to be larger than the discounted value of fuel savings for 10 years at 5,7% interest rate so larger than 1679 € extra per vehicle.

In this model the mileage for each type of trip is kept constant. This raises a problem when through fuel efficiency improvements for GVs and the switch of GV to EV, the variable costs decrease as the rebound effect can become important. As we focus on the choice between two car technologies, we decided to only take into account the effect of the changes in the variable costs on the selection of the two car technologies. The disadvantage of EVs for long trips is taken into account by the subjective costs of refueling of EVs. However, we also need to take into account the low variable cost advantage of EVs for short trips. We therefore include for the EVs an extra consumer surplus in the form of a lower

[8] See Table 3, model I in Grigolon, Reynaert, and Verboven (2018). If one uses a longer lifetime, one needs to adjust the discount rate downwards

user cost for the difference in variable costs between GVs and EVs. But we also include in the welfare cost an additional external congestion cost for short trips as these are mostly in urban areas.

1.6.4 Fuel efficiency costs and technical progress

We can compare two approaches: one is the technical cost curve using engineering estimates and the other is the revealed preference approach using market data. The EC (2017a) produced technical cost estimates for fuel efficiency improvement of 15% in 2025 and of 30% in 2030. The results (expressed as additional manufacturing costs) are summarized in Table 1.2.

Table 1.2: Engineering estimates of fuel efficiency costs

	2025 (-15% 2015 level)	2030 (-30% 2015 level)
Absolute values (€)	400 - 500	1000 - 1200
Increase in vehicle cost	1,5 - 3%	4,5 - 6,5%

Assuming rational consumers and the non-compliance we found for the EU fuel efficiency standards, the additional cost is larger than 360 € per year to improve the fuel efficiency of the car from 5,6 L/100 vkm to 4,1 L /100 vkm. We estimate it to be 2686 €[9] per car otherwise the manufacturers would have complied with the standard. We add 50% to this cost of fuel efficiency improvements and use then 540 € as the additional yearly cost to comply with the emission standard for 2021 (from 5,6 to 4,1 L/100 vkm) and 2804 € additional yearly cost to achieve the standard for 2030 (from 5,6 to 2,56 L/100 vkm). Both cost estimates assume there is no specific R&D effort to bring these costs further down.

Comparing Tables 1.2 and 1.3, the "revealed preference estimates" from the car market are an order of magnitude larger than the engineering estimates. According to Gillingham and Stock (2012) this is not uncommon and is partly a matter of concept. We will use the high revealed preference estimate as this is consistent with the rational behavior of consumers and manufacturers that we

[9]The consumer saves 225 € per year if fuel costs 1,5 €/L and he drives 15.000 km/year. So improving the fuel efficiency from 5,6 to 4 will cost 1,6 (225) or 360 € on a yearly basis and using a discount rate of 5,7% for 10 years produces a car cost increase of 2686 €.

Table 1.3: Revealed preference estimates of fuel efficiency costs

	Present realization	2021 standard	2030 standard
Emission standard	5,6 L/100 vkm	4,1L/100 vkm (95g CO_2/vkm)	2,56L/100 vkm (59,4g CO_2/vkm)
Additional manufacturing cost		540 €/yr/veh (4.029 €/veh)	2.804 €/yr/veh (20.921 €/veh)

assume. We will return to this assumption later.

1.6.5 Costs and technical progress in batteries

There are several estimates about future battery costs. Figure 1.3 summarizes the estimates of the U.S. Department of Energy (U.S. DOE, 2017) from the OECD/IEA (2017) Global EV Outlook for the progress in costs for a battery pack designed to deliver 320 km range. For sufficiently large battery volumes (production of 200.000 batteries per year), the price of batteries could decrease to 200 $/kWh. Batteries in a 60 kWh car represent up to 40% of the costs

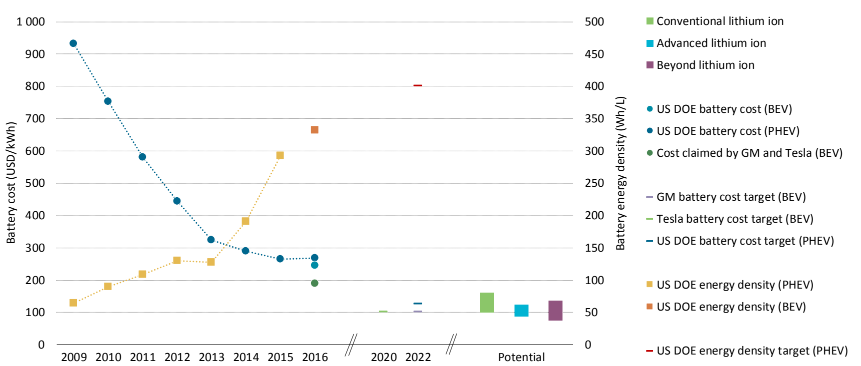

Figure 1.3: Estimates of progress in battery costs

of an EV (Kochhan et al. (2017) and OECD/IEA (2017)). For an electric car with a 30 kWh battery, the purchase cost (before taxes and subsidies) is around 36.000 € (EAMA, 2019). This is in the range of prices we find on the European market. The total EV price is decomposed into a 9.000 € cost for the battery (300 €/kWh) and a 27.000 € cost for the rest of the car.

For GVs we use a consumer price of 26.110 € for a car that has a fuel efficiency of 5,6 L/100km (EAMA, 2019).

1.6.6 A calibration test with the Norway experience

It is difficult to calibrate a model with a new type of vehicle when this new type has a market share of only 1 or 2% in most EU countries. For this reason, we calibrate the model, using the experience in Norway, (more precisely the greater Oslo area) that achieved a 30% penetration of EVs in the new car market in 2017 (Haugneland et al., 2017). Of course, this is a very rough approach but it can be justified for the stylized model we use here. Norway achieved this result using a wide set of policies (see Wangsness et al. (2020)). We focus on two of the policy parameters: a purchase tax for fossil cars of 100% and a dense refueling network for EVs. When we use our dynamic two period model, we also have to specify the policy goals and instruments for the second period. Norway has announced to ban fossil fuel cars in 2025. However, it is not clear whether the car manufacturers will adapt their R&D and whether economics of scale and learning by doing will really be set in action to make this happen as Norway is a small country. Setting on hold the technical progress, the model is calibrated by an additional cost constant for EVs such that the 100% purchase tax on GVs achieves indeed the 30% penetration of EVs in the first period. In Norway the price of electricity is uniform so vehicle to grid (V2G) operations play no role in this calibration.

1.6.7 Other calibration parameters

The full list of parameter values are given in A.1. Here we discuss a few assumptions.

First, we use a triangular distribution of long trips days between 20 and 100 long trip days per year. On short trip days (365 days – number of long days), cars drive 10 km and on long trip days they drive 350 km. This gives the average mileage of 14.000 km per year in Germany (based on Pasaoglu et al. (2012)).

The second assumption that merits attention are the peak and off-peak prices of electricity. In many European countries there are not yet peak and off-peak differentiated prices. When the European power sector will be largely renewable, there will be a need for prices that are differentiated between periods with enough wind and solar energy (off-peak) and the other periods (peak). Prices in the off-peak will be low (0,15 €/kWh) but not zero as there are other uses of electricity in off-peak periods. In the peak period we use a value of 0,30 €/kWh that corresponds to the price of generation power with a peaking gas plant during a few hundred hours a year.[10] Charging an EV can also raise balancing and distribution network issues when it is not coordinated. This is the reason why we use a high price per kWh (0,60 €/kWh) for charging en-route.

1.6.8 Choice of model parameters on technical progress

One of the uncertainties relates to the effects of knowledge building on the costs of the two types of cars. We use the following five assumptions:

First, EVs and GVs have many components in common and technological progress is important for all kinds of functionalities of a vehicle. This means that we are not interested in technological progress regarding safety, entertainment, suspension, self-driving cars, etc. So, for GVs we only consider the additional costs related to improving the fuel efficiency. For EVs, we consider only the costs of batteries.

The second assumption relates to the initial stock of knowledge for both types of cars and the modelling of the learning by doing component of the knowledge building. The problem is that for EVs, one starts with a small initial production (1 or 2% of car market) and one can argue that there are learning and possible scale effects in the production and the marketing of EVs. For GVs, there is a long history of mass scale production and they have already a dominant market share. So, it is difficult to argue that there are important learning by doing effects for GVs, even if they are specific to the fuel efficiency related component. For this reason, we only kept the learning by doing component for the knowledge building in the battery costs of EVs.

The third assumption relates to the production of knowledge by pure R&D. Is there a reason to have another cost function for R&D for EVs than for GVs? Of course, there is more experience with GVs but labs and universities have studied

[10] On-peak and off-peak prices are based on electricity prices for households in Germany (Eurostat, 2020a).

electric cars for many years and there are trained scientists for both technologies. So, we assumed the same cost function for R&D for both technologies. In addition, we assume that both types of R&D do not crowd out each other, they call upon a different pool of engineering knowledge.

The fourth assumption relates to the initial stock of knowledge for both technologies. Our formulation is based on the ratio of new knowledge versus existing knowledge (K_2/K_1). We set the initial knowledge base for both technologies equal to 1. In Table 1.4, we illustrate the effects of the two types of learning on the battery costs of EVs and on the fuel efficiency costs of GVs. The coefficients used for the technical progress are $\eta^Q = \eta^H = 0{,}15$ for both EVs and GVs, where the mechanism for cost reduction is given in Equations 1.11 and 1.17 .

Table 1.4: Effect of technical progress on period 2 costs in baseline

	Gasoline vehicle (cost of fuel efficiency improvement)	Electric vehicle (battery cost)
EV production x2 and R&D expenditure x2	0,901	0,81
EV production x4 and R&D expenditure x4	0,81	0,66

For GVs, we only have knowledge building by R&D as the GV market is a more mature market.

A final parameter that needs to be calibrated is the cost of pure R&D. We know that there is a large R&D investment in the European automobile sector. In 2016, the top 2.500 companies in the "Automobiles and parts" sector invested some 55 billion € in R&D (Tagliapietra and Zachmann, 2018), part of which was for the power trains. If we can assume that half of the total R&D investment is related to power trains and using a total EU car production of 17 million vehicles (EAMA, 2019), this would mean an investment for R&D per car of the order of 3.235 €. Translated into annual equivalent investments per car (annuity factor of 7,466), this is 433,3 €/car.

1.7 Policy simulations

Our central research question is: what is the cost of reducing carbon emissions in the car sector and how is this cost related to the choice of policy instruments. We emphasize the role of the choice of policies on the induced technical progress.

As mileages and car ownership are fixed, reducing CO_2 emissions implies moving to a combination of more fuel efficient gasoline cars and electric cars. More particularly, we take as given the EU objective to reduce average CO_2 emissions of new cars to 95 g/vkm (or 4,1 liter gasoline/vkm) over a period of 5 years and a reduction to 59 g/vkm (or 2,56 liter gasoline /vkm) after 15 years. Figure 1.4

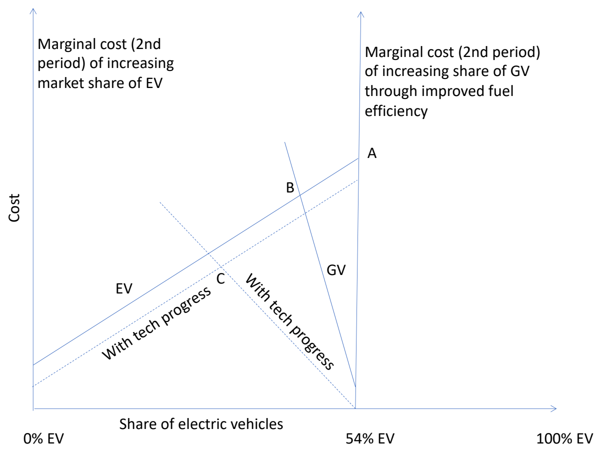

Figure 1.4: Marginal cost of market shares to achieve emissions target

gives the intuition of the results to be expected from the policy simulations. This figure measures from left to right the share of EVs and the social marginal cost (EV line) in the second period of achieving the policy objective via an increase in the share of EVs. This cost is upward sloping because, for given technology and battery size, an EV has a handicap for substituting longer trips. When there is no technological progress for EVs and GVs do not improve their fuel efficiency, we need to reach point A where the share of EVs equals 54%. This share is needed to reach the required average carbon efficiency in period 2.[11] Now introduce the option for GVs to improve their fuel efficiency but still rule out technological progress. The marginal cost of increasing the share of GV beyond 46% consists in increasing the fuel efficiency and is measured from right to left starting at the axis 54%. This gives a new optimum point B. Introduce now

[11] $(0,457)(5,6L/100km) + (0,543)(0L/100km) = 2,56L/100km$

technological progress for EVs and GVs that is produced by learning by doing and R&D in the first period. In Figure 1.4 this means that both marginal cost curves decrease and one ends up in point C. This represents the vehicle mix that minimizes the cost of achieving the carbon efficiency objective.

1.7.1 The role of induced technological progress

Table 1.5 compares the efficiency of the carbon emission standard (ES) and EV portfolio mandate (PM) in reaching the common policy goal in each period. The common policy goal is to reduce emissions of cars from the current 110 g CO_2/vehicle-kilometer (vkm) to 59 g CO_2/vkm after 15 years (end of period 2) with an intermediate target of 95 g CO_2/vkm after 5 years (end of period 1). We will use the improvement of the gasoline fuel efficiency from the current 0,056 L/vkm to 0,041 L/vkm (after 5 years) and 0,0256 L/vkm after 15 years as equivalent units for emission reduction. Overall results in terms of average welfare costs are represented in Figure 1.5. The easiest instrument to understand

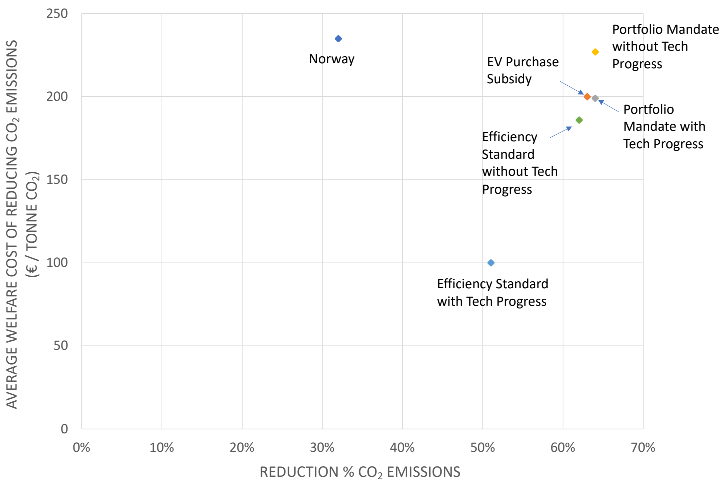

Figure 1.5: Average welfare costs to achieve the period 2 emissions target

is the portfolio mandate where the targets have to be met by increasing the market share of EVs that have zero emissions. We assume here that the GVs keep their current fuel efficiency level of 0,056 liter/ vkm.[12] This implies that the EVs have to reach a market share of 27% at end of period 1 and a market share of 54% at the end of period 2. The GV producers have no incentive to improve the fuel efficiency as the policy instrument requires them only to contribute to

[12]We assume that GV producers do not decrease the fuel efficiency of their cars. In our model simulations, we keep the gasoline tax unchanged so that they have no incentive to change the initial fuel efficiency level.

the EV market share by buying portfolio credits from the EV producers. If all car producers produce both GVs and EVs, the portfolio mandate could also be achieved with a cross-subsidy for the production of EVs. In the absence of induced technological progress (Column 1) we see that in the first period, the GV producers have to pay 886 €[13] for every EV, so per GV this is 328 € on an annual basis. In the second period, the share of EVs needs to be higher, as EVs have a higher user cost for longer trips, they need a lower purchase price and this requires a higher portfolio credit for the EVs (1764 €). Together with the lower market share of GVs, this results in an increase of the purchase cost of GVs on an annuity basis of 2070 € per gasoline vehicle.

The purchase cost of EVs is but one of the elements in the user cost equilibrium (cfr. Section 1.5.1) as also the fuel costs, the V2G benefits, and the endogenous refueling network density play a role. Column 1 further reports the fuel efficiency for GVs in period 1 and period 2, as well as the battery cost reduction (0 as there is, by assumption, no technological progress). The table reports the total cost index as well as the % reduction in CO_2 emissions and the average cost of emission reduction per tonne of CO_2 that is high (226 €). To put this cost in perspective, it can be compared with the current gasoline tax (0,68 € /L) that comes down to 293 € / tonne of CO_2.[14] The 293 €/ tonne means that for a gasoline car producer, making his car more fuel efficient so that it reduces emissions by 1 tonne, would increase the manufacturing cost by 293 €. Replacing part of the GVs by EVs would save emissions at a lower cost: 165 € per tonne because EVs have very low emissions. This average cost of emission reduction is computed in welfare terms taking into account the differences in other external costs between the two types of vehicles. An EV has an advantage over GVs in terms of air pollution and noise for short trips (mainly in urban areas) as well as the benefits of V2G.

Although the reduction of the average emission per car is the policy target and is the same for all scenarios, there will be differences in CO_2 emissions. A higher share of EVs decreases the total emissions more than proportionally because the EVs are used for more and more long trips.

[13]This is an annual equivalent; this means that the EVs receive a credit of 6610 € per car produced.

[14]We take the gasoline cost and tax for Germany from OECD (2016a) and OECD (2016b).

Table 1.5: Effect of technological progress

	NO tech progress PM	WITH tech progress PM	NO tech progress ES	WITH tech progress ES
Market share EV 1	27%	27%	1%	1%
Market share EV 2	27%	27%	1%	9%
Price EV 1 (€)	3940	3944	4720	4736
Price EV 2 (€)	3062	2528	4754	3484
Price GV 1 (€)	3827	3828	4026	3837
Price GV 2 (€)	5570	4826	3693	4222
Fuel eff 1 (L/vkm)	0,056	0,056	0,04088	0,0449
Fuel eff 2 (L/vkm)	0,056	0,056	0,04088	0,0288
Battery cost reduction	0%	97%	0%	97%
Total cost index	100 (=211)	97	102	82
€/tonne CO_2 saved	226	199	186	100
CO_2 emission reduction P1, P2	27%, 64%	27%, 64%	26%, 62%	23%, 51%

PM = Portfolio Mandate ES = Emissions Standard

We can now introduce the effects of technological progress. In the case of the portfolio mandate, the technological progress is limited to the EVs because the fuel efficiency of the GVs does not matter for meeting the portfolio standard. The producers of EVs benefit from the two mechanisms to reduce the costs of EV batteries. First, they realize that producing a larger quantity and selling below the marginal cost in the first period (cfr. Equation 1.18) decreases their production cost in the second period, part of this cost reduction spills over to the rest of the industry but there remains a clear incentive to produce more and achieve a stronger learning by doing effect. When the market share of EVs increases in the first period to 27%, there is a significant learning by doing effect. The second mechanism that is activated by the EV producers is the pure knowledge build up about battery production that requires firms to invest in

R&D. EV producers invest nearly 10% of their income in the first period in pure R&D. This allows them to reduce the cost of batteries by 97%. This does not increase the share of EVs because the EV-share is determined by the binding portfolio obligation. But the technological progress reduces the costs of meeting the target and the costs per tonne of CO_2 saved is reduced to 199 €/ tonne of CO_2.

Next, we analyze the carbon or fuel emissions standard that forces car producers to achieve a lower average emission rate in the first period and an even lower emission rate in the second period. The incentives for the GV producers are now different. They have to meet the average emission rate. They can do this by making their cars more efficient and also by buying carbon efficiency credits from EV producers. They will balance the two options so as to minimize their overall production costs. When technological progress is excluded, this forces the GV producers to make more efficient GVs (0,0488 L/vkm) but this is expensive and increases the production cost of GVs (annual equivalent) to 4025 €. They need to complement this effort with carbon efficiency credits they buy from EV producers. In the second period, reaching the fuel efficiency target becomes very expensive for the GV producers and they have to mainly rely on purchasing fuel efficiency permits from the EV producers. In the end, this solution produces slightly less CO_2 emission reduction: there are less EVs but the GVs are more fuel efficient. CO_2 emissions are also reduced at slightly lower cost than in the case of the portfolio mandate, all this in the absence of technological progress.

Introduce now technological progress: we have learning by doing and pure knowledge build up for EVs and for GVs but we only take into account the pure knowledge build up. With the carbon emissions standard, the GV producers have a strong incentive to reduce the cost of fuel efficiency improvement via R&D expenditures as the cost of reaching the target in the second period is very high. The investments in R&D allow them to improve the fuel efficiency from 0,056 L/vkm (starting value) to 0,0288 L/vkm after 15 years. For the last bit (to reach the target 0,0254 L/vkm), they rely on carbon efficiency credits of EVs. The share of EVs in the second period is lowest in this scenario.

The most important advantage of this policy scenario is the lower cost of reducing CO_2 emissions. Total emission reductions are somewhat lower than in the other scenarios (51% in the second period rather than 64%) but the overall cost of the scenario is much lower and so is the cost per tonne of CO_2 saved that becomes 100 €/tonne CO_2. The main reason is that the option to improve the fuel efficiency of GV has become interesting for GV producers so that they will invest in bringing down the cost of fuel efficiency improvements.

Figure 1.5 summarizes our results in terms of average costs of CO_2 emission reduction. This figure adds the EV purchase subsidy (or GV tax) case that has the same average cost as a portfolio mandate because, in our model, the car ownership is fixed and there is no penalty for the use of public funds. The "Norway" scenario that achieves the 30% penetration of EV with a purchase tax on fossil cars performs worse as an action by one isolated country is unlikely to stimulate technological progress.

A portfolio mandate forcing a bigger market share for EVs is currently discussed by several governments: Norway wants to ban fossil cars by 2025, France and the UK have announced plans to ban the sales of fossil cars by 2040 and some big cities (Paris) also want to ban fossil cars by 2030. According to our analysis, this is a costly policy at the aggregate level. The high cost results from neglecting the option to make gasoline cars more fuel efficient.

1.7.2 The importance of battery size and V2G

Up to now we assumed a standard battery size of 30 kWh in all scenarios. The optimal battery size depends on the importance of the V2G benefits and on the number of long trips. A larger battery is more expensive but allows to store and sell more electricity on days with short trips and allows to lose less time for refueling during long trips (see Greaker, Hagem, and Proost (2019)). In principle, one needs to choose an optimal battery size for their annual number of long trip days, so the optimal battery size would be different for every individual.[15]

We only used one size of batteries in all the simulations: 30 kWh. When we vary the size of the battery (see Table 1.6) we find that the cost of emission reduction decreases but that the market share of EVs is not strongly affected.

[15] One could also argue that the optimal fuel efficiency is different for every individual as not all individuals drive the same distance.

Table 1.6: Effect of battery size on cost of saved CO_2 (€/tonne CO_2)

	30 kWh	40 kWh	50 kWh
Portfolio mandate	151	124	98
Carbon emissions standard	82	78	74

The V2G option was embedded in all simulations and is driven by the difference between peak and off-peak electricity prices. When we use uniform electricity prices, the V2G option is no longer interesting for the EV owners and there is no transfer anymore from off-peak to peak periods. Table 1.7 shows that this will increase the cost of reducing CO_2 emissions mainly in the portfolio scenario as in this scenario the EV market share is highest.

Table 1.7: Role of V2G for period 2 emissions reduction and cost

	With V2G		Without V2G	
	Cost (€/tonne CO_2)	% emissions reduction	Cost (€/tonne CO_2)	% emissions reduction
Porfolio mandate	151	78	192	64
Carbon emissions standard	82	51	100	51

The high share of EVs in the portfolio mandate also enables a significant increase in the CO_2 emissions savings in the second period. Turning the V2G option on or off has almost no effect on the market share of EVs because this share is mainly dictated by the average fuel efficiency target. Figure 1.6 illustrates effect of battery size and V2G on CO_2 emissions reductions in period 2 and the average welfare costs of achieving these CO_2 emissions reductions.

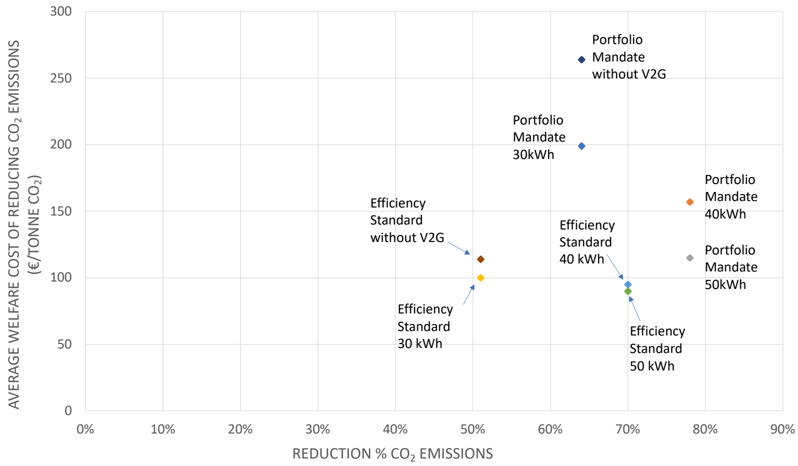

Figure 1.6: Average cost of emission reduction varying battery size and V2G

1.8 Caveats

1.8.1 Model assumptions

We used a simple model that is missing some important dimensions. First, it focuses on the sales of new cars and takes the mileage and lifetime of cars as fixed. This may overestimate the savings of fuel and CO_2 emissions as there will be a rebound effect when the variable cost of driving becomes much smaller. On the other hand, more fuel-efficient cars, electric or not, will be more expensive and this may decrease car ownership and prolong the life of cars.

Second, we assumed rational car consumers and producers. If car consumers would be myopic as advanced by the EC (2017b) this would imply that the current car market equilibrium offers cheap opportunities to improve fuel efficiency. This is in line with the low engineering estimates of the costs of improving fuel efficiency (cfr. Table 1.1). Then imposing fuel efficiency targets becomes the primary policy instrument as the high gasoline tax would not do its job properly. In terms of instrument choice, the automobile industry has to comply with the fuel efficiency standard but faces consumers that are biased against high initial vehicle costs, so against EVs. This normally gives rise to an equilibrium with a higher share of more efficient gasoline cars.

Third, we assumed perfect competition in the car market although the car market is characterized by monopolistic competition. Introducing the fuel efficiency regulation implies that R&D expenditures will increase fixed costs and more fuel-efficient cars will also imply a higher variable cost. Higher vehicle costs force manufacturers to increase prices and this leads to lower diversity in the supply of cars. But our model has fixed car ownership, so introducing monopolistic competition would not give a very different result.

1.8.2 Commitment issues

In the two-period model, the endogenous technological progress is driven by the possibilities to decrease the costs of meeting the stricter targets in the second period. The R&D investments have to be made in the first period and firms will only make these investments when they are sure that the government commits to the strict targets. The experience with fuel efficiency targets in the EU shows that imposing strict targets is not sufficient: car manufacturers did not comply and only delivered the fuel efficiency level justified by the present gasoline price. The commitment and enforcement problem also appeared for conventional emissions of diesel cars ("diesel-gate"). When there is no strict monitoring and strong sanctioning, the GV producers will simply select the fuel efficiency that minimizes the full user costs of GV owners, the fuel efficiency will not improve, and the EVs will barely enter the market. Table 1.5 illustrates that, in the absence of technological progress, meeting the targets becomes very costly. This could happen when automobile firms do not believe the commitment of the government and do not invest in R&D.

Yao (1988) studied the emission regulation of cars in the US in the early seventies. The US government did not know the efficiency of investments in R&D, though the industry knew or had at least less uncertainty about the costs. In a multi-period model, the industry association is afraid of revealing its R&D productivity in the first period as it risks the ratchet effect. Government may in this case impose an even stricter target in the second period. So, the industry may very well choose a strategy where it underinvests in R&D and shows high costs of meeting the target in the first period hoping that the government will set more lax targets. This story has been repeated in California regarding the portfolio mandate imposing a minimum share of zero emission cars.

The problem is solved when the government can commit itself for a long period. This is difficult as a new government can easily change the law. Perhaps the best guarantee for commitment by the EU is a good cost benefit analysis showing that the costs of the regulation are in line with the benefits. In the current assessment of the fuel efficiency standards (EC, 2017a), there are two weak points. First, the use of engineering estimates are much lower than the revealed cost estimates. Second, the climate objectives of the EU may not be shared by the rest of the world and mechanisms like the green paradox decrease the credibility of the fuel efficiency targets.

1.8.3 Federal and international coordination

The fuel efficiency targets we analyzed here are set at the level of the European market for new cars. This gives a lot of flexibility for the car manufacturers but has strong implications for the individual member states. Some cities and member states want to set themselves a minimum share of EVs or want to set a tougher fuel efficiency target for cars. The net effect of these uncoordinated policies could be null. As the car manufacturers have to meet a European wide average, when one member state is more ambitious, the manufacturers can reduce their efforts in the rest of the federation. This mechanism was demonstrated in the USA where 14 states did set more ambitious targets for greenhouse gases (the so called "Pavley" limits). Goulder, Jacobson, and van Benthem (2012) showed that 74% to 65% of the efforts leaked away at the federal level. I will revisit this mechanism in Chapter 2.

The model we analyzed focused on the EU carbon policy. However, the climate problem is a world problem where the role of EU emissions is decreasing as its emissions will approach 10% of total emissions. EU efforts can have a positive and a negative spillover outside the EU. The positive spillover can come from the transfer of fuel efficiency technology to the rest of the world. Car manufacturers in the rest of the world will be forced to adopt the same efficiency standards if they want to sell cars in the EU (Barla and Proost, 2012). The negative spillover of the EU fuel efficiency efforts can come from the green paradox as fuel efficiency efforts may shift rather than reduce the consumption of oil (see Aune et al. (2015)).

1.9 Conclusions

In this chapter, we used a two-period model for the car manufacturing sector with gasoline car producers and electric car producers to compare the cost efficiency of different policies to decrease the CO_2 emissions of cars. Both types of cars have endogenous technological progress that is triggered by environmental policies, including tradable fuel efficiency standards, portfolio mandates, carbon taxes, purchase taxes, and subsidies for R&D. Electric vehicles can also be used for vehicle to grid operations where off peak (renewable) electricity can be stored in the battery to reduce the load in the peak hours.

The current EU policy instrument is a tradable carbon emissions standard where gasoline fueled cars can improve their fuel efficiency and can purchase carbon efficiency credits from EV producers as EVs are considered as zero-emission cars. We show that this instrument outperforms the portfolio mandate where the same reduction of the average emission rate is obtained with lower costs. The carbon emissions standard is better because it contains an incentive to improve the fuel efficiency of GVs through R&D. The carbon emissions standard is dynamically more efficient than a portfolio mandate that targets a high share of EVs. With endogenous technological progress, the cost of saving CO_2 emissions is reduced to about 100 €/tonne CO_2. However, these investments in technological progress require that car producers consider the EU target as credible and a real commitment. The EU fuel efficiency target for 2021 will very likely not be met and this means that car producers may not take the current targets as a strong commitment from the side of the policy makers.

We consider several potential model extensions. First, endogenizing congestion and modeling car use as a function of price. In this way, the annual vehicle mileage is no longer fixed and the rebound effects from V2G are more pronounced. Because the aim of this chapter is to analyze emissions reductions policy for five and ten year periods, daily price-dependent driving patterns fall outside the scope of necessary variables for this analysis. Second, introducing more heterogeneity in the vehicle options, such that there is a range of fuel efficiencies for GVs and a range of battery sizes for EVs. While this extension adds more specificity to the model, the key insights will be similar. Third, expanding the model to the international market and incorporating strategic trade and technology spillovers from multinational producers. As this extension asks a separate question regarding the inner workings of the international EV market and multinational production strategy, we leave it to further research.

Chapter 2

Inadvertent Repercussions of Surpassing the EU Fuel Economy Standard in Heavy Duty Freight

2.1 Introduction

Freight is a sleeping giant in the transport sector. Accounting for more than 35% of all transport-related CO_2 emissions, as of 2017, road freight vehicles were responsible for nearly half of global diesel demand (IEA, 2017a). In the European Union, road freight demand has increased 400% since 1990, largely as a result of economic growth and globalization. As a result of the high quality highway networks and advanced supply chain and logistics systems, Europe has the largest fleet of road freight vehicles (IEA, 2017b). Without substantial policy intervention, road freight is predicted to be a primary source of CO_2 emissions growth in the coming decades (Muncrief and Sharpe, 2015). To force fuel efficiency improvement, in 2014, the EU composed a strategy to reduce carbon emissions from heavy freight trucks by certifying, monitoring, and reporting emissions (EC, 2019c). To realize their strategy, the European Commission developed VECTO, a simulation tool to determine CO_2 emissions and fuel consumption data for new trucks (EC, 2019c). In 2019, the EU set a concrete fuel economy standard for heavy freight truck manufacturers to reduce the fleet-wide average emissions for new trucks that they produce by 15% compared to 2019 levels starting in 2025 and by 30% starting in 2030 (EC, 2019c). Some countries, such as Sweden, have found this standard to be too lax and are actively developing stricter national policies. This chapter addresses two research questions: how does one or more member nations enacting a stricter fuel economy standard for heavy duty trucks impact the emissions reduction behavior for the rest of the EU? Further, to what extent is there carbon leakage and how does incongruous national and international policy affect the total cost of achieving the EU fuel economy standard?

Heavy freight trucks account for 65% of all freight activity (Muncrief and Sharpe, 2015). The market for these trucks is highly consolidated with just four manufacturers (Daimler, VW Group, Volvo, and Renault-Nissan Alliance) producing over 60% of the heavy freight trucks sold in the EU (IEA, 2017a). In this way, most trucks used in the EU are also produced in the EU. Shipping companies generate the demand for road freight and then contract out the individual deliveries to trucking companies. These trucking companies generally operate small truck fleets and maximize their profits by minimizing their costs of satisfying shippers' freight demands.

With time, reliability, and cost constraints, and no shortage of freight demand, these trucking companies operate in a highly competitive market. It follows that each company is motivated to reduce costs. Fuel represents around 25% of heavy freight operating cost and there are many technologies on the market to improve fuel efficiency (IEA, 2017a). There have been several regional policies to address fuel efficiency, such as the Lean & Green forum to provide reliable information about efficiency technologies to many EU countries, but none have stimulated significant investment in heavy freight truck fuel efficiency (IEA, 2017a).

In this chapter, I use a two-period model for the heavy freight truck manufacturing sector that produces low and high fuel efficiency trucks. Investment in R&D can reduce the costs and improve the fuel efficiency of the high fuel efficiency trucks. Demand for trucks is split between two regions: the member nations adopting stricter fuel economy standards and the rest of the EU. There is perfect competition in the production sector, where each producer maximizes profits by taking prices as given for new trucks and investing in fuel efficiency technologies subject to the fuel economy standard constraints. Based on the additional emissions reductions in the stricter region, the rest of the EU countries increase their emissions, which I refer to as 'leakage' (compared to the scenario where all member countries have the same emissions reduction target), such that the EU standard is met at the lowest cost. I show that redistribution of carbon emissions is an unavoidable result of incongruous national and international road freight policy. This chapter reveals an inadvertent trade-off between a Bonus-Malus feebate system and the producer investment in R&D.

The chapter is organized as follows: Section 2.2 provides a literature review, Section 2.3 outlines the model structure, and Section 2.4 explains the solution procedure. In Section 2.5, I delineate the data and calibration parameters required to solve the model and in Section 2.6, I analyze the policy impacts of each scenario. In Section 2.7, I conclude.

2.2 Literature review

This chapter draws upon two strands of literature. The first is the relationship between environmental policy and technological innovation, and the second is economic losses and carbon leakage arising from nested regulation.

There is considerable literature on the theoretical role of endogenous technical change in reducing the cost of achieving environmental policy (see Goulder and Schneider (1999), van der Zwaan et al. (2002), Acemoglu et al. (2012)). Several empirical studies affirm this theory. For instance, Calel and Dechezleprêtre (2016) find evidence that the EU ETS increased low-carbon innovation in regulated firms by 10%. I incorporate endogenous technical change using an approach similar to Fischer and Newell (2008). They represent R&D for renewables in the electricity sector by using a two-period model where investment in the first period leads to lower marginal costs of renewables in the second period. While much of this literature examines the effects of endogenous change on market-based policies (carbon taxes), I consider a performance standard, which is a second-best policy. As second-best policies are generally more palatable in political discussions, governments are more likely to implement them.

In his seminal work on the fiscal effects of nested regulation, Oates (1972) presents his decentralization theorem that centralized policy is optimal when there are inter-jurisdictional spillovers. Carbon emissions leakage is an example of an inter-jurisdictional spillover arising from incongruent national and international policy. Oates' work provides the foundation for a growing body of literature on carbon leakage resulting from incongruent national and international climate change policy (see Felder and Rutherford (1993), Barker et al. (2007), Perino, Ritz, and van Benthem (2019)). Given the importance of transport in achieving climate goals, there are several papers addressing the impact of nested policy in reducing transport emissions. Eliasson and Proost (2015) examine the spatial and inter-temporal consumption leakage that arise when international climate agreements are not binding and only a subset of countries take action to reduce emissions in the transport sector. Goulder, Jacobson, and van Benthem (2012) find that carbon leakage resulting from nested state and federal fuel economy regulations for passenger transport implies that the cost of avoided emissions is 50% higher than in the case with a national policy (and therefore no carbon leakage). This chapter builds upon the insights of these two papers. I aim to quantify the orders of magnitude for carbon leakage, R&D investment, and the overall cost of carbon saved in achieving the EU heavy duty freight fuel economy standards. A key literary contribution of this chapter is to explain the mechanism underlying the additional costs of incongruous national and international transport policy and how these costs are distributed.

2.3 Building the model

2.3.1 Overview

The numerical simulation model from the Goulder, Jacobson, and van Benthem (2012) paper on carbon leakage in the U.S. light-duty automobile market serves as a template. In their model, production is a Bertrand competition among a fixed number of producers. This requires the assumption that producers can separately control the characteristics and prices of vehicles in each market that they operate. I do not impose this assumption in my model, and instead model the trucking production sector with perfect competition. Modeling the oligopolistic market structure with several competitors would not bring very different results in terms of pricing and costs compared to a perfect competition setting (Simon, 1984). Therefore, I choose to drop the imperfect competition complication in this chapter. Further, they include the scrap and used vehicle markets in their analysis of passenger transport. As these markets are considerably smaller in heavy freight and supplies are known to ebb and flow year on year, I do not account for carbon leakage through the second-hand heavy truck market (IEA, 2017a).

There are two economic agents in the model: new truck producers and trucking companies. Trucks are distinguished only by fuel efficiency. For simplicity there are two types of trucks: high fuel efficiency and low fuel efficiency. The truck producer operates in both regions such that the price and fuel efficiency of each truck model sold are identical in both markets. However, the price, fuel efficiency, and R&D investment are determined by the fuel economy standards with which the new fleet must comply. The trucking companies purchase a suite of trucks to meet their annual driving needs at the lowest cost.

The model solves for supply and demand equilibrium prices and quantities in the new truck market in both regions in both periods.

2.3.2 Demand

There are two representative trucking companies, one for each region. The company's demand for trucks is a function of the purchase price and expected operating cost, both of which depend on fuel economy. There are two periods $t = 1, 2$ and two regions $r = 1, 2$ where $r = 1$ represents the region with stricter policy. Further, there are two truck types $f = 1, 2$ that represent the low and high fuel efficiency trucks. Trucks that are mainly used for short, national trips will have a lower annual mileage. Conversely, trucks that are used for international trips will have a higher annual mileage. Operating costs increase as annual mileage increases, though the rate of this cost increase depends on the fuel efficiency of the truck. While low fuel efficiency trucks have low purchase costs, the operating costs increase steeply and therefore, they are preferred for national trips. High fuel efficiency trucks have higher purchase costs, but the operating costs are gradually increasing with annual mileage. Therefore, high fuel efficiency trucks are preferred for international trips.

As shown in Figure 2.1, high fuel efficiency trucks become optimal as the annual mileage increases, while low fuel efficiency trucks are optimal for low annual mileage requirements. However, as fuel efficiency improves (and operating cost decreases) as a result of R&D investment, high fuel efficiency trucks become optimal also for lower annual mileage (national and international trips). I assume

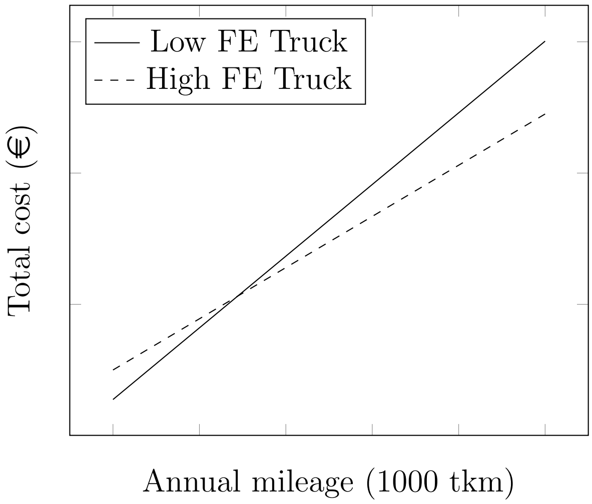

Figure 2.1: Annual cost of low and high fuel efficiency trucks

that each truck operates 300 days of the year and on each day makes either a national or international trip. The lengths for a national trip l_n and an international trip l_i are fixed. The annual number of national and international trips for an individual trucking company j are fixed and the annual total of freight for each region is fixed. In this way, the trucking companies are differentiated by the number of national and international trips they make annually.

Let $q_{t,r,f}$ be the number of trucks with fuel efficiency f in region r in period t. The total annual cost for a truck in period t is the annuity of the purchase price $p_{t,f}$ plus the operating costs. Purchase price $p_{t,f}$ and the purchase tax $\tau_{t,r,f}$ depend on the fuel efficiency $e_{t,f}$ of the truck. Operating cost is a function of the variable fuel cost $v_{t,r}$ and the distance tax $\phi_{t,r}$. The distance tax corrects for the operating externalities such as noise, non-carbon emissions, accidents, and congestion, which are, for simplicity, assumed to be identical for low and high fuel efficiency trucks. Variable fuel cost $v_{t,r}$ is the sum of the fuel tax $\omega_{t,r}$ and the fuel resource cost $r_{t,r}$ in units €/L. The representative trucking company j in region r chooses the quantities of low fuel efficiency and high fuel efficiency trucks that minimize the annual cost:

$$C(j) = \sum_{t,f=1,2} q_{t,r,f}(j) \left[p_{t,f} + \tau_{t,r,f} + (x_n \cdot l_n + (300 - x_n)l_i) \left(e_{t,f} v_{t,f} + \phi_{t,f}\right)\right] \quad (2.1)$$

where x_n and $(300 - x_n)$ are the total number of national and international trips driven by a given truck annually.

Each trucking company will allocate their fixed number of annual national and international trips among their truck fleet by minimizing the sum of fixed costs and operating costs for a given annual mileage $m = (x_n \cdot l_n + (300 - x_n)l_i)$.

$$\frac{\partial C(j)}{\partial q_{t,r,f}} = p_{t,f} + \tau_{t,r,f} + m(e_{t,f}v_{t,f} + \phi_{t,f}) = 0 \tag{2.2}$$

For the annual mileage m^*, the sum of fixed and operating costs is the same for a low and high fuel efficiency truck. For annual mileages $m \geq m^*$ the trucking company will purchase a high fuel efficiency truck and for $m < m^*$ a low fuel efficiency truck.

2.3.3 Supply

Truck producers maximize profits under perfect competition subject to the EU fuel economy standards and strict national policy in region 1. The demand for heavy freight trucks is highly fragmented. Producers sell both types of trucks in both regions. They determine the level of fuel economy by taking into account the cost of fuel economy improvements and the effect of improved fuel economy on demand. The marginal cost of fuel economy improvements for the high fuel efficiency truck can decrease as a result of technological change through R&D investment. A key assumption for the choice of R&D investment is that producers have perfect foresight and take the prices in period 1 and 2 as given.

The knowledge stock from R&D Z_t is built up with annual investments z_{t-1} in R&D, such that the knowledge stock Z_2 is built up with annual R&D investments z_1. I normalize the first period stock of R&D knowledge, such that $Z_1 = 1$. Fuel efficiency can improve with or without R&D investment. In the first period, there is fuel efficiency improvement for high fuel efficiency trucks as the producer is bound to the fleet-wide standard that cannot be met unless they sell trucks with higher fuel efficiency. The investment in R&D occurs in period 1 and reduces the fuel efficiency related costs in period 2, such that the stock of R&D knowledge in period 2 is given by

$$Z_2 = (n_1 z_1)^k \tag{2.3}$$

where k is the elasticity of fuel efficiency related costs with respect to R&D investment. The R&D investment function is $h(z_1) = \gamma_0 z_1^{\gamma_1}$ and therefore has constant elasticity, where γ_0 is an estimate of baseline R&D spending and γ_1

represents the elasticity of knowledge generation and R&D investment.

A representative truck producer maximizes the sum of profits in the first period and the discounted sum of profits in the second period generated in both regions subject to the EU truck fuel economy standards and the stricter standard in the adopting region. As I assume perfect competition, each producer takes the prices of trucks as given. The minimum fleet-wide fuel efficiency on new trucks for truck producers is constrained by government policy. The truck producers meet these standards by making the high fuel efficiency truck more fuel efficient. I assume that there is reliable monitoring of the realized fuel efficiencies for new trucks sold and that governments levy a fine high enough to ensure that truck producers comply with the fuel efficiency standards.

$$\Pi = \max_{p_{t,f}, e_{t,f}, z_{t,f}} \sum_{r=1,2,f=1,2} \begin{bmatrix} n_1(p_{1,f}q_{1,r,f} - C(Z_t, e_{1,f})) \\ + \delta n_2(p_{2,f}q_{2,r,f} - C(Z_t, e_{2,f})) - (1-\sigma)h(z_1) \end{bmatrix} \tag{2.4}$$

where n_1 is the number of years in period 1, n_2 is the number of years in period 2, δ is the discount factor, and σ is the fraction of R&D investment $h(z_1)$ that is paid by the government(s).

The production cost $C(Z_t, e_{t,f})$ has constant returns to scale and consists of a fixed cost A and a variable cost that is a function of fuel efficiency. The cost of the fuel efficiency improvement is quadratic in $e_{t,f}$ and decreasing in knowledge stock Z_t from R&D investment. Cost savings from knowledge generation are not region-specific.

$$C(Z_t, e_{t,f}) = q_{t,f}\left[A_{t,f} + \frac{1}{Z_t}\left(b_{t,f} + \frac{1}{2}g_{t,f}e_{t,f}^{-1}\right)e_{t,f}^{-1}\right] \tag{2.5}$$

where $b_{t,f}$ and $g_{t,f}$ are calibration parameters.

$$\frac{\partial \Pi}{\partial q_{t,r,f}} = p_{t,f} - C_q(Z_t, e_{t,f}) = 0 \tag{2.6}$$

In maximizing profits, the purchase price of a truck is equal to the marginal production cost. For period 1, simultaneously solving Equations 2.2 and 2.6

as a system of linear equations subject to the production constraint on average emissions of the fleet of new trucks sold returns the equilibrium price $p_{1,f}$ for high fuel efficiency trucks and the equilibrium fuel efficiency $e_{1,f}$. For period 2, simultaneously solving Equations 2.2, 2.6, and 2.7 as a system of linear equations returns the equilibrium price $p_{2,f}$ for high fuel efficiency trucks, the equilibrium fuel efficiency $e_{2,f}$, and the annual investment z_1 in R&D.

$$\frac{\partial \Pi}{\partial z_1} = -(1-\sigma)h(z_1) - \delta\rho n_2 C_{Z_2}(Z_2, e_{2,f})kz_1^{(k-1)} = 0 \tag{2.7}$$

Rearranging gives

$$h(z_1) = -\delta\frac{\rho}{(1-\sigma)}n_2 C_{Z_2}(Z_2, e_{2,f})kz_1^{(k-1)} \tag{2.8}$$

I assume that a given producer does not retain all of the knowledge generated from their R&D investment. The return on a representative producer's R&D investment is based on the benefit from their own stock of R&D knowledge as well as benefits spilt over from other firms' stocks of knowledge. Thus, ρ represents the fraction of knowledge that is retained by a representative producer and appropriated from other producers. This spillover factor is only in the first-order condition as it affects the share of future profits that the inventor retains (Fischer and Newell, 2007). Truck producers invest the amount $h(z_1)$ in R&D until the discounted returns from R&D investment are equal to the investment cost of fuel efficiency improvement. The stricter the fuel efficiency standard, the higher the marginal investment cost of fuel efficiency improvement and the higher investment in R&D.

A representative truck producer faces the following overall fleet fuel efficiency constraint for trucks sold in region 1:

$$\frac{e_{t,1} \cdot q_{t,1,1} + e_{t,2} \cdot q_{t,1,2}}{q_{t,1,1} + q_{t,1,2}} \leq \bar{e}_s \tag{2.9}$$

And the same representative truck producer faces the overall fleet fuel efficiency constraint for trucks sold in the rest of the EU (region 2):

$$\frac{e_{t,2} \cdot q_{t,1,2} + e_{t,2} \cdot q_{t,2,2}}{q_{t,2,1} + q_{t,2,2}} \leq \bar{e}_{EU} \tag{2.10}$$

where $\bar{e}_s$ refers to the stricter fuel economy standard in region 1 and $\bar{e}_{EU}$ refers to the EU fuel economy standard.

2.3.4 Carbon emissions

Total annual carbon emissions intensity D in tonnes CO_2 per 1000 tkm of the new trucking fleet is

$$D_{t,r} = \sum_{r=1,2,f=1,2} X_d e_{t,f} q_{t,r,f} \tag{2.11}$$

where X_d is the carbon intensity of diesel in tonnes CO_2 per liter consumed.

By nature of the stricter fuel economy standard, a less carbon intensive fleet will operate in region 1. Therefore, the fleet in the rest of the EU can be more carbon intensive, as the EU-wide fleet must comply with the EU-wide fuel economy standard. Hence, the stricter the region 1 policy compared to the EU standard, the higher will be the fleet emissions intensity in the rest of the EU. I refer to this result as 'carbon leakage'. The carbon leakage is determined by the difference between the fleet emissions intensity where there is one EU standard, $D_{t,EU}$, and the fleet emissions intensity in region 2 when there is a stricter emissions policy adopted in region 1, $D_{t,2}$. The total annual carbon leakage in tonnes CO_2 per 1000 tkm is given by

$$D_{leakage} = D_{t,2} - D_{t,EU}(1 - S_1) \tag{2.12}$$

where S_1 is the fraction of total freight in the EU that takes place in region 1.

2.3.5 Policy cost and cost of saved CO_2

To evaluate the different policy scenarios and simulations, I use the total policy cost and cost of saved CO_2 emissions.

In this chapter, I work with 3 main scenarios: I define a Business-as-Usual (BAU) scenario where the total demand for EU road freight is met with trucks of uniform constant fuel efficiency equivalent to the current average. In this scenario, there is no fuel efficiency standard policy. I define a baseline scenario where the EU acts as a single region to meet the EU fuel economy standard. In the central scenario, the EU is divided into two regions. Region 1 adopts a stricter fuel economy standard and region 2 adheres only to the EU fuel economy standard. Later, I conduct several different policy simulations of the central scenario, where I vary the size of region 1 and the magnitude of the financial incentive for high fuel efficiency trucks in region 1.

The total policy cost PC is the additional costs incurred by the trucking companies, truck producers, and government compared to the costs that they would have incurred in the Business-as-Usual scenario where there is no policy.

$$PC = n_1(TC_{1,S} - TC_{1,BAU}) + \delta n_2(TC_{2,S} - TC_{1,BAU}) \tag{2.13}$$

The total cost TC_S in each scenario is the sum of purchase and operating costs for all trucks, the non-carbon external costs, and the government purchase subsidies expenditure and investment in R&D minus the purchase tax revenue. I specifically do not include the diesel tax revenue as it is effectively a carbon tax and thereby a policy for emissions reductions. Therefore, it would muddle the cost of the fuel efficiency policy.

To determine the average cost of saved CO_2 emissions, for each policy scenario, I compare the total cost TC minus the total carbon costs DC to that of the BAU scenario. Then, divide this cost by the carbon savings D in the policy scenario compared to the BAU scenario.

$$\frac{\begin{bmatrix} n_1[(TC_{1,S} - DC_{1,S}) - (TC_{1,BAU} - DC_{1,BAU})] \\ + \;\delta n_2[(TC_{2,S} - DC_{2,S}) - (TC_{2,BAU} - DC_{2,BAU})] \end{bmatrix}}{n_1(D_{1,BAU} - D_{1,S}) + n_2(D_{2,BAU} - D_{2,S})} \tag{2.14}$$

2.4 Solving the model

As producers sell the same two types of trucks to region 1 and region 2, producers will base their investment and manufacturing decisions on the stricter fuel economy standard. Consequently, the fuel efficiencies of the high fuel efficiency trucks will be higher than in the case where they must only comply with an EU fuel economy standard. To determine the effects of one region adopting a stricter policy, there must be a baseline scenario. Therefore, the model first solves for the market equilibrium when the EU truck fleet must comply with only the EU fuel economy standard. This provides the baseline values for fuel efficiency, prices, and quantities of new trucks sold. Additionally, with these values the research expenditure and economic surplus are estimated.

In the next step, the model solves for market equilibrium when one region of the EU adopts a stricter fuel economy standard. Now, producers optimize their output for the stricter region. In this new market equilibrium, there are different prices and fuel efficiencies to meet the stricter standard. The truck producers will then optimize their fleet production based on these augmented fuel efficiencies and prices. It is important to note that the truck producers will count the additional emissions reduction taking place in region 1 toward the overall EU fleet emission standard, allowing the producer to increase the fleet emissions from trucks sold in region 2. Such that

$$\frac{e_{t,1} \cdot q_{t,2,1} + e_{t,2} \cdot q_{t,2,2}}{q_{t,1,1} + q_{t,1,2} + q_{t,2,1} + q_{t,2,2}} \leq \bar{e}_{EU} - \frac{e_{t,1} \cdot q_{t,1,1} + e_{t,2} \cdot q_{t,1,2}}{q_{t,1,1} + q_{t,1,2} + q_{t,2,1} + q_{t,2,2}}$$

Meaning that the fleet fuel efficiency of trucks sold in region 2 will be lower than the EU fuel efficiency standard.

With the market equilibria for regions 1 and 2, I can evaluate the effects of incongruous national and international fuel economy standards on the rate of high fuel efficiency truck adoption, the investment in high fuel efficiency truck technology, and the change in regional carbon emissions reductions.

2.5 Data and numerical calibration

2.5.1 Cost parameters

To evaluate the international freight market, I calibrate the model using data for the entire EU. In 2018, the total road freight within the 27 countries of the EU amounted to 13.417 billion tonne-km (tkm) (Eurostat, 2020b). This includes national trips within individual EU countries and international trips between EU countries. I set the lengths for a national trip l_n and an international trip

l_i to 150 km and 500 km, respectively. This gives the total annual mileage for a truck operating 300 days per year taking only national trips to be 45.000 km and 150.000 km taking only international trips (based on IEA (2017a)). While the baseline scenario keeps the EU intact, the central scenario divides the EU into two regions. The region with the stricter fuel economy standard (region 1) represents 5% of the total road freight in the central scenario. In Section 2.6, I conduct policy simulations varying the size of region 1.

The annualized fixed cost A for freight trucks is based on a heavy-duty truck with an annual mileage of 100.000 km and 20-tonne average payload. In all scenarios and policy simulations, both the low and high fuel efficiency trucks have a fixed cost of 55 €/1000 tkm (based on IEA (2017a), Delgado and Rodriguez (2018)). The total cost of a high fuel efficiency truck will be higher as it also includes the cost of fuel efficiency improvement. The fuel cost is set to 0,78 €/L and the fuel tax is set to 0,5 €/L, both represent the EU average and are exogenous (EEA, 2019). The current average fuel efficiency for heavy duty trucks is 24L/1000 tkm (IEA, 2017a). Low fuel efficiency trucks remain at this average value, while high fuel efficiency trucks use it as a starting point to improve.

Table 2.1: Annual costs in €/1000 tkm of low and high fuel efficiency trucks

	Fixed cost	FE cost	Purchase price	Variable cost	FE	Operating cost
Low FE	55	0	55	1,28	24	30,7
High FE	55	7,3	62,3	1,28	20,3	26,0

FE = fuel efficiency (L/1000 tkm)

Table 2.1 breaks down the components of the annual costs for low and high fuel efficiency trucks, using the results from period 1 of the baseline scenario to represent annual costs for a high fuel efficiency truck. The purchase price of the low fuel efficiency truck includes only the fixed cost as there is no fuel efficiency improvement. The purchase price of the high fuel efficiency truck is comprised of the fixed cost and the cost of fuel efficiency improvement. The improved fuel efficiency gives a lower operating cost for high fuel efficiency trucks. This annual cost breakdown mirrors the graphical representation in Figure 2.1.

As an additional incentive for high fuel efficiency trucks, region 1 adopts a Bonus-Malus feebate system. In the central scenario, the feebate consists of a purchase subsidy high fuel efficiency trucks that is equal to 5% of the purchase price of a low fuel efficiency truck and a purchase tax on low fuel efficiency trucks that is equal to 5% of the purchase price of a low fuel efficiency truck. In the policy simulation, I will evaluate the impact of the Bonus-Malus feebate by varying the amounts of the subsidies and taxes.

The external cost of trucks includes the cost of non-carbon emissions, noise, congestion, accidents, and infrastructure wear and tear. All are identical for both regions and the sum is set to 25 €/1000 tkm (van Essen et al., 2019). To calculate the cost of damages from carbon emissions, I use the average EU ETS value of 25 €/tonne CO_2 (ICE, 2020).[1]

2.5.2 Fuel efficiency parameters

The model has two periods; the first period of 5 years represents target year 2025 and a second period of 5 years represents the target year 2030. I discount the costs incurred in the second stage back to the present using a 10% private rate of return, such that $\delta = 0,38$. The European Commission set the EU fuel economy standard for 2025 to a 15% improvement in fleet fuel efficiency to 20,4 L/1000 tkm and for 2030 the standard is a 30% improvement in fleet fuel efficiency to 16,8 L/1000 tkm (EC, 2019c). The stricter region targets an additional 10% fleet fuel efficiency improvement in both periods, meaning 25% for 2025 and 40% for 2030.

In a report prepared for the ICCT, Norris and Escher (2017) delineate the incremental costs per liter diesel saved for a range of heavy freight truck fuel efficiency technologies. For individual technologies the cost is as low as 0,005 € per liter diesel saved, while for multi-technology packages the cost is 2,30 € per liter diesel saved. In my analysis, I use a conservative estimate for the incremental cost of fuel efficiency technologies of 2 € per liter diesel saved. With this value, I calculate the cost of fuel efficiency improvement required to reach the 2025 and 2030 EU fuel economy targets, which amounts to 7,2 €/1000 tkm and 14,4 €/1000 tkm, respectively. I calibrate the parameters $b_{t,f}$ and $g_{t,f}$ in the production cost

[1] While different countries have different perceptions of the true value of carbon damages, I take the value that is used in the EU market as a common estimate.

equation with these cost estimates to -832 and 39.951.

2.5.3 R&D parameters

In the model, the relationship between knowledge generated through R&D $z_{t,f}$ and stock of R&D Z_t has constant elasticity. I set this elasticity $k_f = 0,3$ based on several empirical studies that evaluate the elasticity of product costs with respect to cumulative production (see Argote and Epple (1990), Nadiri (1993)). In the R&D investment function, I set the elasticity of the relationship between R&D investment and knowledge generation $\gamma_1 = 1,2$ based on Bottazzi and Peri (2003), an empirical study regarding R&D spending and innovation measured by patents. Calibrating the model with all other parameter assumptions, baseline R&D spending for fuel efficiency improvement is $\gamma_0 = 545$ million € or 0,05 €/1000 tkm. Given that the automobile manufacturing industry as a whole reports spending 57,4 billion € annually on R&D, less than 1% being allocated toward fuel efficiency improvement for freight trucks is a conservative estimate (EAMA, 2019).

As I am calibrating the model for 27 EU countries with identical truck manufacturers, I use a knowledge appropriation factor $\rho = 0,5$. Meaning that 50% of the knowledge generated from R&D investment is retained by joint ventures among EU producers for R&D, although the producers remain competitors on the market. While each country is responsible for achieving the EU fleet fuel economy standard using any mechanism they deem appropriate, I assume that on average each country's government will support the policy by contributing 10% of the R&D expenditure required, so $\sigma = 0,1$. A summary of parameter values is given in Appendix B.1.

2.6 Policy impacts

In the baseline, central, and policy simulation scenarios, I hold the total emissions constant as in each scenario the EU policy for fleet fuel efficiency in 2025 and 2030 is met and the annual heavy truck road freight demand met by the fleet of new trucks is the same. In this way, I only consider the differences in producer, consumer, and government cost of achieving the same emissions reduction. I use policy cost and cost of CO_2 savings for the entire EU to meet the EU fuel economy standard to compare the different scenarios and simulations. The Business-as-

Usual scenario represents the case with no policy and therefore does not have the same emissions reductions as all other scenarios (see Section 2.6.1).

To discern the insights of my results, I omit distance taxes for the various trucks operating nationally and internationally within the 27 countries of the EU. This removes any distance tax competition which distorts the incentives for high fuel efficiency trucks. In this way, there are two key variables that drive the results: the size of the region with stricter fuel efficiency standards and the magnitude of the Bonus-Malus feebate in the region with stricter fuel efficiency standards.

The results reported in Table 2.2 represent the baseline scenario where all countries meet the EU policy of fleet fuel efficiency standards in 2025 and 2030. Table 2.3 represents the results of the central scenario where the EU is split into two regions. Region 1 represents 5% of the EU and meets a fuel efficiency standard stricter than the EU policy, while region 2 represents 95% of the EU and meets the EU policy. Table 2.4 represents results of the policy simulations varying the size of the region with the stricter fuel efficiency standard and the value of the Bonus-Malus feebate incentivizing high fuel efficiency trucks in the stricter region.

2.6.1 No policy: Business-as-Usual Scenario

Producers sell trucks at the lowest marginal cost. Fuel efficiency improvement increases the purchase price, so without a binding constraint on the fuel efficiency of the fleet of trucks sold, the purchase price is equal to the fixed cost. Given that heavy duty truck production is a well-established and mature market, it is not likely that there are significant learning by doing effects that will improve fuel efficiency (IEA, 2017a). Therefore in the absence of a fuel efficiency standard, low fuel efficiency trucks remain the only option for trucking companies and there are no high fuel efficiency trucks developed, produced, or sold. Consequently, the average fleet fuel efficiency remains 24 L/1000 tkm.

2.6.2 Baseline scenario

The introduction of a fuel efficiency standard causes producers to invest in R&D to the extent that the discounted returns from selling high fuel efficiency trucks is equal to the marginal investment cost. As a result, producers invest 1.463 million

€ in R&D which decreases the marginal cost of fuel efficiency improvement by 28,6% in period 2 compared to the marginal cost in period 1. Lower fuel requirements means lower operating costs, so trucking companies deploy high fuel efficiency trucks for all international trips. Further, high fuel efficiency trucks become cost-competitive for national trips, such that they are used for both national and international trips. Consequently, 98% of new heavy trucks have high fuel efficiency. However, the cost of the fuel efficiency improvement gives a 13% higher purchase cost than that of low fuel efficiency trucks (see Table 2.1), leading trucking companies to continue to purchase a small number of low fuel efficiency trucks deployed solely for national trips.

Table 2.2: Baseline scenario results

	Period 1	Period 2
Share high FE trucks	98%	99%
Price of high FE truck (€/1000 tkm)	62,3	65,5
High FE (L/1000 tkm)	20,3	16,7
Average fleet FE (L/1000 tkm)	20,4	16,8
R&D expenditure (million €	1.463	
Cost of policy (billion €)	418	
Cost of CO_2 saved (€/tonne CO_2)	36	

FE = fuel efficiency

The cost per tonne of CO_2 saved is 36 €/tonne CO_2. This is the lowest value of all the scenarios and simulations run as this is the only case with a single policy to which each EU country adheres. Following the significant literature on the importance of international policy coordination (see Buiter and Marston (1986), Canzoneri, Cumby, and Diba (2005)), the desired emissions reduction is achieved at the lowest cost in the baseline scenario. The main reason being when one country adopts a stricter standard, all producers must invest in R&D such that the returns are equal to the marginal cost of fuel efficiency improvement. While this stricter standard prompts producers to develop an even more fuel efficient truck, it also leads to a higher price for high fuel efficiency trucks. A producer charges the same price in all regions in which she operates, so the total cost of meeting the same standard significantly increases. Conversely, when there is a single (less strict) standard, producers develop a truck to meet the fuel efficiency requirements which hold in all regions where they operate. While this may lead to a less fuel efficient truck compared to the aforementioned scenario, the price will be lower and the standard will still be met though, now, it is at the optimal (and significantly lower) cost.

In this scenario, the total policy cost of achieving the fuel efficiency standards is 418 billion €. If the EU were split into regions 1 and 2 according to the central scenario, assuming the costs are uniformly distributed, the cost is 21 billion € (5%) in region 1 and 397 billion € (95%) in region 2.

2.6.3 Central scenario

The central scenario divides the EU into two regions: region 1 represents 5% of the total road freight in the EU and adopts a fleet fuel economy standard that is stricter than the EU standard and region 2 represents the rest of the EU. Region 1 requires 10% more fuel economy improvement compared to the EU standard in both periods and employs a purchase subsidy for high fuel efficiency trucks and a purchase tax for low fuel efficiency trucks, the value of the respective subsidy and tax are equal to 5% of the purchase price of the low fuel efficiency truck. Because region 1 adopts stricter fuel economy standards, truck producers invest more in R&D to produce trucks that are even more fuel efficient compared to the baseline scenario in period 2 (see Equation 2.8). Producers increase R&D spending by 31%, which enables a 29,5% decrease in the marginal cost of fuel efficiency improvement in period 2 compared to the marginal cost in period 1. Of course, this improvement comes at the cost of 7% and 5% increase in the purchase price of high fuel efficiency trucks in periods 1 and 2. However, the Bonus-Malus feebate in region 1 reduces the purchase price for trucking companies and allows high fuel efficiency trucks to be cost-competitive for national and international trips. Consequently, high fuel efficiency trucks comprise 99% of the trucking fleet.

Given that region 1 overshoots the EU standard, truck producers sell a fleet of trucks to region 2 that does not achieve the target EU average fleet fuel economy. Therefore, the effective fuel economy standard for region 2 is 20,5 L/1000 tkm in period 1 and 16,9 L/1000 tkm in period 2. This relaxed average fleet fuel economy

Table 2.3: Central scenario results

	Period 1	Period 2
Share high FE trucks in region 1	99%	99%
Share high FE trucks in region 2	57%	73%
Price of high FE truck (€/1000 tkm)	67,2	68,7
High FE (L/1000 tkm)	17,9	14,3
Δ Carbon emissions region 1 compared to baseline	- 12%	- 14%
Δ Carbon emissions region 2 compared to baseline	+ 0,6%	+ 0,8%
R&D expenditure (million €)	1.928	
Cost of policy (billion €)	669	
Cost of CO_2 saved (€/tonne CO_2)	49,3	

requirement coupled with higher fuel efficiencies, enables truck producers to sell fewer high fuel efficiency trucks in region 2. All of the additional emissions reductions occurring in region 1 are leaked to region 2. Consequently, carbon emissions in region 2 increase by 0,6% and by 0,08%, while carbon emissions decrease by 12% and 14% in periods 1 and 2 relative to the baseline scenario.

Together, the introduction of the Bonus-Malus feebate and higher prices for high fuel efficiency trucks drive the policy cost up to 287 billion € in region 1 (see Table 2.5). Although the purchase price of high fuel efficiency trucks is higher, trucking companies in region 2 purchase far fewer. Therefore, compared to the baseline scenario, the total policy cost is lower in region 2 at 382 billion €. The high policy cost induces a high cost of carbon saved of 49 €/tonne CO_2.

It is important to note how the distribution of costs changes significantly in this scenario. As one country institutes a stricter national policy, it also ends up paying the brunt of the costs of meeting the international policy. The nonconforming country does itself no favors by enacting a stricter standard that effectively drives up the price for high fuel efficiency trucks.

2.6.4 Policy variations

In the policy simulations, I vary the relative size of region 1 and the amount of the Bonus-Malus feebate in region 1. The total costs of achieving the policy range in magnitude and regional distribution for each simulation. Table 2.4 displays the policy simulation results relative to the baseline scenario. Table 2.5 indicates the total cost of achieving the EU fuel economy standard policy and the effective average fleet fuel efficiency in each region, as well as the cost per tonne of carbon saved.

Table 2.4: Policy results relative to baseline (period 1 | period 2)

	High FE (L/1000 tkm)	High FE price (€/1000 tkm)	Share high FE region 2	Carbon leakage to region 2 (tonne CO_2)	R&D expenditure (mill €)
Baseline	20,3 | 16,7	62,3 | 65,5	98% | 99%	– | –	1.463
Central	-11,8%| -14,3%	+7,7%|+5,0%	-41,7%| -26,0%	+0,6%|+0,8%	+31,8%
No B-M R1	-12,0%| -14,5%	+8,0%|+5,2%	-42,1%| -26,3%	+0,6%|+0,8%	+32,4%
High B-M R1	-11,6%| -14,0%	+7,5%|+4,8%	-41,3%| -25,6%	+0,6%|+0,8%	+31,1%
R1 1%	-11,8%| -14,3%	+7,7%|+5,0%	-40,0%| -24,9%	+0,12%|+0,14%	+31,8%
R1 10%	-11,8%| -14,3%	+7,7%|+5,0%	-44,0%| -27,4%	+1,3%|+1,6%	+31,8%

2.6.4.1 No Bonus-Malus region 1

I start by removing the Bonus-Malus feebate in region 1. As I assume perfect competition in truck production, prices are determined by demand. Trucking companies make purchase decisions based on the annual costs which includes the purchase tax or subsidy (see Equation 2.2). While removing only the subsidy would decrease the equilibrium price for high fuel efficiency trucks, removing only the tax would increase the equilibrium purchase price for high fuel efficiency trucks. In the central scenario, the subsidy represents 4% of the high fuel efficiency truck purchase price and the tax represents 5% of the low fuel efficiency truck purchase price, therefore tax effect dominates and the equilibrium purchase price of the high fuel efficiency truck increases.

The marginal production cost (and therefore the purchase price) for high fuel efficiency trucks consists of the fixed cost A and the variable cost for fuel efficiency improvement (see Equation 2.5). A higher purchase price allows producers to spend more on the fuel efficiency improvement. In period 1, marginal cost of fuel efficiency is the same as the central scenario, so with the higher purchase price, fuel efficiency improves more. As producers have perfect foresight, they invest in R&D in period 1 until the returns from R&D equal the marginal cost of investment in fuel efficiency improvement in period 2. Without the Bonus-Malus feebate, the optimal R&D investment in period 1 is higher, reflecting the higher return from R&D generated from the higher purchase price. This increase in R&D investment enables the truck producers to achieve even better fuel efficiencies at a lower marginal cost in period 2.

As the new trucks are more fuel efficient than in the central scenario, truck producers sell fewer high fuel efficiency trucks in region 2 compared to the central scenario. However, the higher purchase price for high fuel efficiency trucks leads the policy cost in region 2 to be higher compared to the central scenario. The total policy cost is lower for region 1, as the higher purchase price is outweighed by the cost savings from removing the feebate system. It follows that the cost of carbon saved is also lower at 36,3 €/tonne CO_2. As regions 1 and 2 are the same relative size as in the central scenario, the amount of carbon leakage is the same.

2.6.4.2 Increased Bonus-Malus region 1

Now, I increase the Bonus-Malus feebate by 100%. Increasing the feebate system decreases the equilibrium purchase price for high fuel efficiency trucks. As the fixed cost remains 55 €/1000 tkm, the variable cost of fuel efficiency is now lower than the central scenario. In period 1, marginal cost of fuel efficiency is the same as the central scenario, and as a result of the lower purchase price, fuel efficiency does not improve as much. Producers invest less in R&D compared to the central scenario as the purchase price in period 2 is lower than in the central scenario, and thus the return on R&D investment is lower. With less R&D, the marginal cost of fuel efficiency does not decrease as much as in the central scenario. The lower purchase price for high fuel efficiency trucks combined with the smaller investment in R&D result in less fuel efficiency improvement in period 2. This requires truck producers to sell more high fuel efficiency trucks in region 2 to reach the effective average fleet fuel efficiency.

With lower purchase prices, the total cost of achieving the policy is lower in region 2 than in the central scenario. However, the increased feebate system drives up the cost of the policy in region 1 to 541 billion €. This gives a higher cost of carbon saved at 62 €/tonne CO_2. Again, as regions 1 and 2 are the same relative size as in the central scenario, the carbon leakage is unchanged.

2.6.4.3 Region 1 1% of total EU

Returning the Bonus-Malus feebate implemented in the central scenario, I reduce the size of region 1 to just 1% of the total EU road freight demand. Given the same feebate system as the central scenario, producers will invest the same amount in R&D, which yields the same purchase prices, fuel efficiencies, and operating costs. Therefore, truck producers sell the same shares of high fuel efficiency trucks and low fuel efficiency trucks in region 1, but the absolute number of trucks purchased is 80% lower. Fewer trucks also means fewer purchase taxes and subsidies. Taken together, the total cost of meeting the policy decreases in region 1 to 261,1 billion €.

Since region 1 is smaller, the average fleet fuel economy required for region 2 to meet the EU standard is more stringent than the central scenario. Consequently, truck producers must sell more high fuel efficiency trucks in region 2. Therefore, the total cost of meeting the EU fuel economy standard policy increases in region 2 to 408 billion €. The total cost of meeting the policy is 669,2 billion €, which is approximately equal to the central scenario policy cost of 669,0 billion €. The key difference is the distribution of the costs between regions 1 and 2. The added costs of more high fuel efficiency trucks in region 2 outweighs the cost savings of fewer trucks in region 1, leading to a slightly higher policy cost. Nearly identical policy costs yields nearly identical costs of saved carbon of 49,3 €/tonne CO_2. With region 1 80% smaller than in the central scenario, the carbon emissions leakage from region 1 to region 2 is 80% lower at 0,12% in period 1 and 0,14% in period 2.

2.6.4.4 Region 1 10% of total EU

Now, I increase the size of region 1 to 10% of the total EU road freight demand. Again, the fuel efficiency improvements, R&D investment, and purchase prices are identical to the central scenario because the Bonus-Malus feebate system is the same magnitude. Again, the total policy cost 668,8 billion € is approximately the same as the central scenario and the distribution of costs between regions is different. Truck producers make the same production decisions as in the central scenario, though there are 100% more trucks sold and 100% more taxes and subsidies levied. As a result, the policy cost in region 1 is higher at 319 billion €.

In this case, the average fleet fuel economy in region 1 accounts for twice as much of the total EU fleet fuel economy, such that the average fleet fuel economy in region 2 is more lax than the EU fuel economy standard at 20,7 L/1000 tkm in period 1 and 17,1 L/1000 tkm in period 2. This enables truck producers to sell fewer high fuel efficiency trucks in region 2 than in the central scenario which decreases the policy cost to 349 billion € in this region. In this case, the lower costs from fewer high fuel efficiency trucks in region 2 outweighs the cost increase of more trucks in region 1, leading to a slightly lower total policy cost. However, the total policy cost is close enough to the central scenario that the cost of carbon saved is approximately the same at 49,3 €/tonne CO_2. Lastly, the carbon emissions leakage from region 1 to region 2 increases in proportion to the size of region 1. Meaning that the more countries that adopt road freight economy standards that are stricter than the EU standard, the more carbon leakage there will be to the rest of the EU.

Table 2.5: Cost of policy relating to cost of saved CO_2

	Cost of Policy (bill €)			€/tonne CO_2 saved
	Region 1	Region 2	Total	
Baseline scenario values	20,9	396,8	417,7	36,2
Central scenario	287,0	382,1	669,0	49,3
No Bonus-Malus region 1	32,9	385,4	36,3	
Increased Bonus-Malus region 1	541,4	378,7	920,1	62,3
Region 1 1% of total EU	261,1	408,1	669,2	49,3
Region 1 10% of total EU	319,4	349,5	668,8	49,3

It is clear from Table 2.5 that removing the Bonus-Malus feebate system produces a lower cost of meeting the policy and thus a lower cost of carbon savings. Varying the size of region 1 affects the magnitude of inadvertent carbon leakage in the rest of the EU and the distribution of costs between the regions.

It is clear that the magnitude of the Bonus-Malus policy has a significant impact on the fuel efficiency improvement and producer investment in R&D, while there is no effect on carbon leakage. The larger the feebate policy for consumers, the lower the equilibrium price of high fuel efficiency trucks. So, producers have less capital to invest in R&D and fuel efficiencies do not improve as much as in the

Table 2.6: Change in fleet fuel efficiency (period 1 | period 2)

	Average Fleet FE (L/1000 tkm)		
	Region 1	Region 2	Total
Baseline scenario values	20,4|16,4	20,4|16,4	20,4|16,4
Central scenario	18,0|14,4	20,5|16,9	20,4|16,4
No Bonus-Malus region 1	18,0|14,4	20,5|16,9	20,4|16,4
Increased Bonus-Malus region 1	18,0|14,4	20,5|16,9	20,4|16,4
Region 1 1% of total EU	18,0|14,4	20,4|16,8	20,4|16,4
Region 1 10% of total EU	18,0|14,4	20,7|17,1	20,4|16,4

central scenario. Because producers can charge a higher purchase price when the feebate system is removed, there is more capital for fuel efficiency improvement and they develop trucks with higher fuel efficiencies than in the central scenario (see Table 2.6.

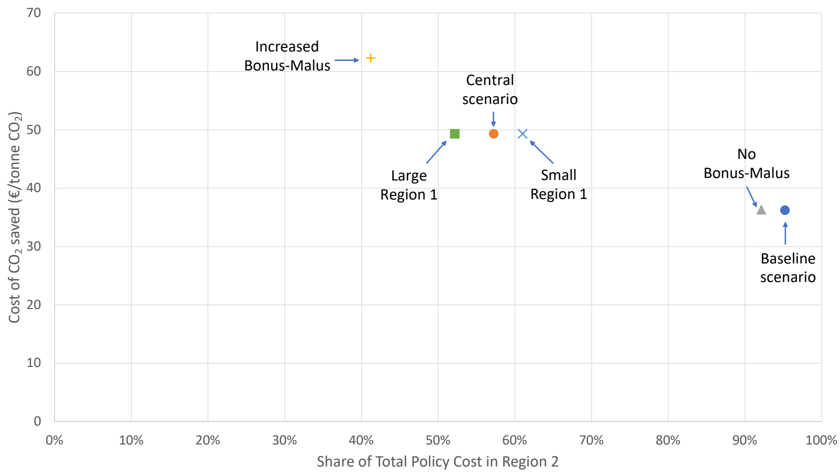

Figure 2.2: Distribution of policy costs vs. cost of carbon saved

Figure 2.2 illustrates the relationship between the cost of carbon saved and the share of the total policy cost in region 2. In the baseline scenario, the policy costs are distributed proportional to size, such that 95% of the costs occur in region 2. When region 1 adopts a stricter policy and introduces a feebate system, it takes on a larger share of the costs. Therefore, in the central scenario, the share of policy cost in region 2 shrinks to 57%. Not only does varying the magnitude of the Bonus-Malus feebate system affect the cost of carbon savings, it significantly changes the distribution of costs between regions 1 and 2. Removing the feebate system reduces the costs in region 1 significantly, such that the total policy costs are distributed similar to the baseline scenario with 92% occurring in region 2. Increasing the feebate system increases the policy cost in region 1, such that the total cost of the policy is high and the share in region 2 is lower at 41%. While changing the size of region 1 affects the distribution of costs between regions, the total policy cost, and thereby the cost of CO_2 saved, remains approximately the same. Reducing the size of region 1 shifts the policy cost burden to region 2, while increasing the size of region 1 shifts the policy costs away from region 2.

2.7 Conclusions

I evaluate the impact of an EU member country enacting a stricter fuel economy standard on the total cost of meeting the EU policy for the rest of the EU. In my analysis, I find that any EU member country, regardless of its size, introducing a stricter standard will increase the average cost of carbon savings for all EU members. The stricter standard increases the marginal cost of fuel efficiency and increases the investment in R&D to lower this marginal cost. This translates to a higher policy cost of achieving the same total emissions reductions. With increased fuel efficiency improvement, truck producers sell fewer high fuel efficiency trucks in region 2 to meet the EU standard, such that the policy cost in region 2 is lower. The stricter standard in region 1 requires truck producers to sell more high cost, high fuel efficiency trucks. This production behavior coupled with the introduction of a feebate system gives a significantly higher policy cost in region 1, which gives a higher total cost of reaching the policy and cost of carbon saved. When all countries across the EU adhere to the same standard, the policy is met at the lowest cost.

In my analysis, I find that the magnitude of the Bonus-Malus feebate has a significant impact on the distribution of costs between regions 1 and 2. Without purchase taxes and subsidies, the policy cost in region 1 is higher solely as a result of the stricter policy increasing the marginal cost of fuel efficiency. Removing the feebate system lowers the cost of carbon saved and achieves the policy cost closest to the optimal scenario where all EU countries adhere to the same standard. Hence, this chapter reveals an inadvertent trade-off between a feebate system and the producer investment in R&D.

Finally, I find that the size of the country (or countries) adopting a stricter fuel economy policy minimally affects the total cost of achieving the EU standard. These countries will take on a larger share of the policy costs compared to the baseline central scenario. At the end of the day, the EU fleet is what is measured, so taking on additional emissions reductions only enables other countries to relax their efforts.

Chapter 3

How to be a Good Forerunner in Carbon Neutral Trucking

3.1 Introduction

The main purpose of this chapter 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 chapter: 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 chapter, 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 3.1)[1].

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. 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

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

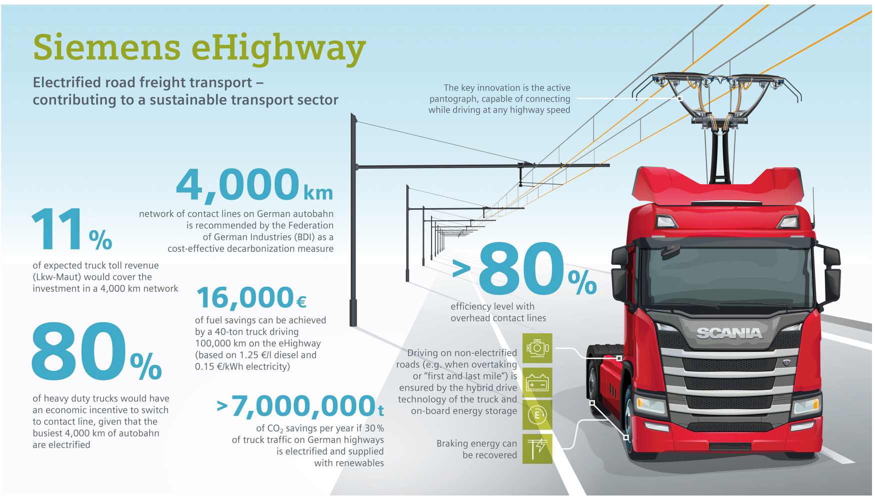

Figure 3.1: Siemens eHighway catenary electric truck

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 chapter 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? Second, how costly is the forerunner strategy for this country? Third, what are the possible gains of cooperation when both countries install electric highways?

This chapter is organized as follows: Section 3.2 will outline the game tree and define the analytical model. Section 3.3 deals with the model calibration, Section 3.4 discusses the numerical results, and Section 3.5 concludes.

3.2 Building the model

3.2.1 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 3.2 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.

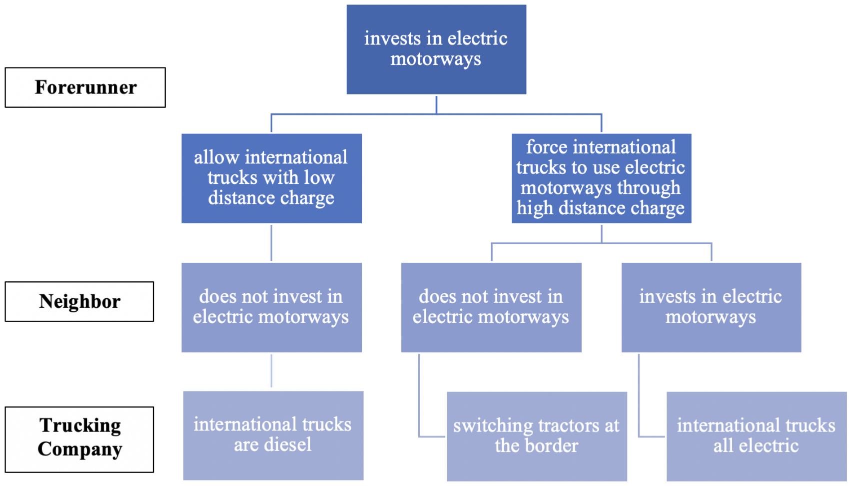

Figure 3.2: The game scenarios

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.

3.2.2 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.

$$\begin{aligned} d_F &= a - bk_F \\ d_N &= a - bk_N \end{aligned} \tag{3.1}$$

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}.

$$d_{int} = \alpha - \beta K_{int} \tag{3.2}$$

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:

$$\begin{aligned} k_F^f &= (1-\gamma)(c_F^f + t_F^f + t_{FT,F}^d) \\ k_F^e &= (1-\gamma)(c_F^e + t_F^e + t_{ET,F}^d) \end{aligned} \tag{3.3}$$

$$\begin{aligned} k_N^f &= \gamma(c_N^f + t_N^f + t_{FT,N}^d) \\ k_N^e &= \gamma(c_N^e + t_N^e + t_{ET,N}^d) \end{aligned} \tag{3.4}$$

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:

$$\begin{aligned} TC_F &= d_F(1-\gamma)\min\Big((c_F^f + t_F^f + t_{FT,F}^d), (c_F^e + t_F^e + t_{ET,F}^d)\Big) \\ TC_N &= d_N(1-\gamma)\min\Big((c_N^f + t_N^f + t_{FT,N}^d), (c_N^e + t_N^e + t_{ET,N}^d)\Big) \end{aligned} \tag{3.5}$$

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

$$\begin{aligned} K_{int}^f &= c^f + \gamma t_{FT,N}^d + (1-\gamma)t_{FT,F}^d + \sigma[\![t_F^f, t_N^f]\!]t_N^f + (1-\sigma[\![t_F^f, t_N^f]\!])t_F^f \\ \text{where: } & \sigma[\![t_F^f, t_N^f]\!] = \gamma - \rho(t_N^f - t_F^f) \end{aligned} \tag{3.6}$$

Note that,

$$\begin{aligned} \sigma[\![t_F^f, t_N^f]\!] &= 1 \text{ when } t_F^f - t_N^f \geq \frac{1-\gamma}{\rho} \\ \sigma[\![t_F^f, t_N^f]\!] &= 0 \text{ when } t_N^f - t_F^f \geq \frac{\gamma}{\rho} \end{aligned} \tag{3.7}$$

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:

$$K^e_{int} = c^e + \gamma(t^d_{ET,N} + t^e_N) + (1-\gamma)(t^d_{ET,F} + t^e_F) \tag{3.8}$$

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

$$K^{switch}_{int} = \gamma(c^f + t^d_{FT,N} + t^f_N) + (1-\gamma)(c^e + t^d_{ET,F} + t^e_F) + SC \tag{3.9}$$

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:

$$\begin{aligned} &cs_N\{k_N(.)\} + d_N\{.\}\,\gamma\,(t^d_{FT,N} + t^f_N - ec^f_N) \\ &+0.5CS\{K_{int}(.)\} + d_{int}\{.\}(\gamma t^d_{FT,N} + \sigma t^f_N - \gamma ec^f_N) - IT_N \end{aligned} \tag{3.10}$$

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.

3.3 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.

3.3.1 No electric highways

Assume first inelastic domestic demand, then:

$$t^d_{FT,N} = \frac{0.5 d_{int}}{-\frac{\partial d_{int}}{\partial t^d_{FT,N}}} + ec^f_N - \frac{\sigma}{\gamma} t^f_N \tag{3.11}$$

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:

$$t^d_{FT,N} = \left(0.5 d_{int} + (ec^f_N - t^f_N) \frac{\partial d_N}{\partial t^d_{FT,N}} + (ec^f_N - \frac{\sigma}{\gamma} t^f_N) \frac{\partial d_{int}}{\partial t^d_{FT,N}} \right) (-A)^{-1}$$
$$\text{where } A = \frac{\partial d_{int}}{\partial t^d_{FT,N}} + \frac{\partial d_N}{\partial t^d_{FT,N}} \tag{3.12}$$

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.

3.3.2 Electric highways 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 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 distance tax reaction function as before except that $\sigma = 1$.

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

$$t^d_{FT,F} = \left(0.5d_{int} + ec^f_F \frac{\partial d_{int}}{\partial t^d_{FT,F}}\right)\left(-\frac{\partial d_{int}}{\partial t^d_{FT,N}}\right)^{-1} \tag{3.13}$$

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

3.3.3 Electric highways 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:

$$t^d_{ET,F} = -0.5 d_{int} \left(\frac{\partial d_F}{\partial t^d_{ET,F}} + \frac{\partial d_{int}}{\partial t^d_{ET,N}} \right)^{-1} + (ec^{el}_F - t^d_{ET,F} - t^e_F) \tag{3.14}$$

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.

3.3.4 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 distance tax on electric trucks that is too high.

3.4 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 importance of the relative size 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 3.1 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 3.1: 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 3.1 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 chapter.

The technological progress for catenary electric trucks can only make them com-

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

petitive if the cost of installing electric highways (EH) is not prohibitive. Fraunhofer ISI (2018) 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 3.1 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 C.1.

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.

3.4.1 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 3.2 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 3.3.

Table 3.2: 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

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 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.

3.4.2 Welfare

In Table 3.3, we calculate the welfare gains of the scenario where both countries have the same size for each of the four scenarios. Table 3.3 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 minus 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 minus external costs. The last column gives the annualized cost of electric highways.

Table 3.3: Welfare 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

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 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 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

[3]This is the result of optimal distance charges that are slightly different than the one of Table 3.2 because the optimal tax setting depends on the operating costs.

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 3.4 reports the welfare effects with technological progress for this case where the forerunner is smaller ($\gamma = 0, 1$).

Table 3.4: 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.

3.5 Conclusions

The aim of this chapter 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 A

Appendix to Chapter 1

A.1 Parameter values

Parameter	Value	Units
Gasoline vehicle parameters		
Annual ownership tax (GV)	100	€
GV market price	3500	€/veh
GV production tax	0	€/veh
GV production cost	3000	€/veh
GV non-FE cost	2500	€/veh
GV fuel efficiency	0,056	L/km
Gasoline cost	0,6	€/L
Gasoline tax	0,68	€/L
Gasoline carbon intensity	0,023	tonne CO_2/L
External cost of non-carbon emissions (L)	0,0049	€/km
External cost of non-carbon emissions (S)	0,0148	€/km
External cost of noise emissions (L)	0,0002	€/km
External cost of noise emissions (S)	0,02	€/km
Initial stock	2500000	veh
i	99,5	
j	50,4	

Electric vehicle parameters		
EV market price	6073	€/veh
Annual ownership subsidy (EV)	-400	€
EV production tax	0	€/veh
EV battery cost	2429	€/veh
EV non-battery cost	3644	€/veh
Lifetime of EV	10	years
Battery capacity	30	kWh
EV energy efficiency	0,2	kWh/km
Price of off-peak electricity	0,15	€/kWh
Price of on-peak electricity	0,3	€/kWh
Price of charging electricity	0,6	€/kWh
Off-peak electricity carbon intensity	0	tonne CO_2/kWh
On-peak electricity carbon intensity	0,0004408	tonne CO_2/kWh
External cost of non-carbon emissions (L)	0,0099	€/km
External cost of non-carbon emissions (S)	0,0072	€/km
External cost of noise emissions (L)	0,0001	€/km
External cost of noise emissions (S)	0,0105	€/km
Disutility of charging	1	€/kWh
Cost for home charging station	500	€
Gov't subsidy for charging station	0	€
Price of network externality	0,0000003	€/kWh
Initial stock	75000	veh
General parameters		
Target fuel efficiency 1	0,041	L/vkm
Target fuel efficiency 2	0,0287	L/vkm
Distance tax	0	€/km
External cost of congestion (L)	0,11	€/km
External cost of congestion (S)	0,28	€/km
External cost of accidents (L)	0,0214	€/km
External cost of accidents (S)	0,0543	€/km

Emissions tax	25	€/tonne CO_2
ρ	0,5	
σ	0,1	
Discount rate	0,62	
Rate of learning by doing	0,15	
Rate of knowledge building with R&D	0,15	

Appendix B

Appendix to Chapter 2

B.1 Parameter values

Parameter	Value	Units
Total EU road freight	13.417	billion tkm
Fixed cost low FE truck	55	€/1000 tkm
Fixed cost high FE truck	55	€/1000 tkm
Low fuel efficiency	24	L/1000 tkm
Diesel cost	0,78	€/L
Diesel tax	0,5	€/L
Diesel carbon intensity	2,67	kg CO_2/L
External cost	25	€/1000 tkm
Carbon damage cost	25	€/tonne CO_2
Baseline R&D expenditure	545	million €
Elasticity of productivity and R&D	0,3	
Elasticity of knowledge-building and R&D	1,2	
ρ	0,5	
σ	0,1	
Discount rate	0,38	

Appendix C

Appendix to Chapter 3

C.1 Parameter values

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

Bibliography

Acemoglu, D. et al. (2012). The Environment and Directed Technical Change. *American Economic Review 102*(1), 131-166.

Aghion, P., A. Dechezleprêtre, D. Hémous, R. Martin, and J. Van Reenen (2016). Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry. *Journal of Political Economy 124* (1), 1-51.

Anderson, S.T. and J.M. Sallee (2011). Using Loopholes to Reveal the Marginal Cost of Regulation: The Case of Fuel-Economy Standards. *American Economic Review 101* (4), 1375–1409.

Anderson, S.T. and J.M. Sallee (2016). Designing Policies to Make Cars Greener: A Review of the Literature. *Annual Review of Resource Economics 8*, 157–180.

Argote, L. and D. Epple (1990). Learning curves in manufacturing. *Science 247*, 920-924.

Association of International Motor Vehicle Manufacturers (2017). New motor vehicle tax regulation. Association of International Motor Vehicle Manufacturers, Hamburg.

Aune, F. R. et al. (2015). Fuel Efficiency Improvements - Feedback Mechanisms and Distributional Effects in the Oil Market. *CESifo Working Paper No. 5478.* Munich: CESifo.

Barker, T.S. et al. (2007). Carbon leakage from unilateral environmental tax reforms in Europe, 1995–2005. *Energy Policy 35*(12), 6281-6297.

Barla P. and S. Proost (2012). Energy efficiency policy in a non-cooperative world. *Energy Economics 34*(6), 2209-2215.

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*.

Bottazzi, L. and G. Peri (2003). Innovation and spillovers in regions: evidence from European patent data. *European Economic Review 47*, 687-710.

Brown, M.A. (2001). Market failures and barriers as a basis for clean energy policies. *Energy Policy 29* 14, 1197-1207.

Brownstone D., D. S. Bunch, and K. Train (2000). Joint mixed logit models of stated and revealed preferences for alternative-fuel vehicles. *Transportation Research Part B Methodological 34*(5), 315-338.

Bruninx, K., M. Ovaere, and E. Delarue (2019). The Long-Term Impact of the Market Stability Reserve on the EU Emission Trading System. Discussion Paper KU Leuven.

Buiter, W. and R.C. Marston (1986). International Economic Policy Coordination. Cambridge University Press.

Busse, M. R., C. R. Knittel, and F. Zettelmeyer (2013). Are consumers myopic? Evidence from new and used car purchases. *American Economic Review 103* (1), 220-256.

Cahill, E., J. Davies, T.S. Turrentine (2014). New Car Dealers and Retail Innovation in California's Plug-In Electric Vehicle Market. *Institute of Transportation Studies Working Paper Series*, University of California, Davis.

Calel, R. and A. Dechezleprêtre (2016). Environmental policy and directed technological change: evidence from the European carbon market. *Review of Economics and Statistics 98*(1), 173-191.

Canzoneri, M., R. Cumby, and B. Diba (2005). The need for international policy coordination: What's old, what's new, what's yet to come? *Journal of International Economics 66*(2), 363-384.

Coffman, M., P. Bernstein, and S. Wee (2017). Electric vehicles revisited: a review of factors that affect adoption. *Transport Reviews 37*(1), 79-93.

Creti, A., A. Kotelnikova, G. Meunier, and J.-P. Ponssard (2018). Defining the Abatement Cost in Presence of Learning-by-Doing: Application to the Fuel Cell Electric Vehicle. *Environmental Resource Economics 71*, 777–800.

Dallinger, D., S. Gerda and M. Wietschel (2013). Integration of intermittent renewable power supply using grid-connected vehicles – A 2030 case study for California and Germany. *Applied Energy 104*, 666-682.

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.

Delgado, O. and F. Rodríguez (2018). CO_2 emissions and fuel consumption standards for heavy duty trucks in the EU. The International Council on Clean Transportation.

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

Eggert, H. and M. Greaker (2014). Promoting Second Generation Biofuels: Does the First Generation Pave the Road? *Energies 7*, 7, 4430-4445.

Eliasson, J. and S. Proost (2015). Is sustainable transport policy sustainable? *Transport Policy 37*, 92-100.

European Alternative Fuels Observatory (2019). Germany - Incentives and Legislation. `https://www.eafo.eu/countries/germany/1734/incentives`

European Automobile Manufacturers Association (2019). ACEA Economic and Market Report – Full-year 2019.

European Commission (2016). A European Strategy for Low-Emission Mobility. {COM 0501 final}. European Union, Brussels.

European Commission (2017a). EC impact assessment for enhanced fuel efficiency in cars and zero emission vehicles. {COM SWD 650 final}, Brussels.

European Commission (2017b). Electrification of the Transport System. European Union, Brussels.

European Commission (2019a). The European Green Deal. {COM 640 final}European Union, Brussels..

European Commission (2019b). Regulation (EU) 2019/631 setting CO_2 emission performance standards for new passenger cars and for new light commercial vehicles. textitOfficial Journal of the European Union, L 111 / 13 - 53.

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 Commission (2020). Stepping up Europe's 2030 climate ambition - Investing in a climate-neutral future for the benefit of our people. {COM 562 final}European Commission Directorate General for Climate Action, Brussels.

European Environment Agency (2017). Transport greenhouse gas emissions. EEA, Copenhagen.

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

European Parliament (2019). Parliament backs new CO_2 emissions limits for cars and vans.`https://www.europarl.europa.eu/news/en/press-room/20190321IPR32112/parliament-backs-new-co2-emissions-limits-for-cars-and-vans`. Accessed 05 April 2019.

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.

Eurostat (2020a). Electricity prices for household consumers. `https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics#Electricity_prices_for_household_consumers`. Accessed 10 July 2020.

Eurostat (2020b). Summary of annual road freight transport. `https://ec.europa.eu/eurostat/databrowser/view/road_go_ta_tott/default/table?lang=en`. Accessed 25 August 2020.

Felder, S. and T.F. Rutherford (1993). Unilateral CO_2 reductions and carbon leakage: the consequences of international trade in oil and basic materials. *Journal of Environmental Economics and Management 25*(2), 162-176.

Fischer, C. and R.G. Newell (2007). Environmental and technology policies for climate mitigation. *Resources for the Future Discussion Paper 04-05 (revised)*, Washington DC.

Fischer, C. and R.G. Newell (2008). Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management 55*, 142-162.

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

Gillingham, K. and J.H. Stock (2018). The Cost of Reducing Greenhouse Gas Emissions. *Journal of Economic Perspectives 32*(4), 53–72.

Goulder, L.H., Jacobson M.R., and van Benthem A.A. (2012). Unintended consequences from nested and federal regulations: the case of the Pavley greenhouse-gas-per-mile limits. *Journal of Environmental Economics and Management 63*, 187-207.

Goulder, L.H. and S.H. Schneider (1999). Induced technological change and the attractiveness of CO_2 abatement policies. *Resource and Energy Economics 21*(3-4), 211-253.

Greaker, M. and M. Kristoffersen (2017). Charging of electric cars: Should we accept several standards? Research Council of Norway, Oslo, 2017.

Greaker, M. and K. Midttømme (2016). Network effects and environmental externalities: Do clean technologies suffer from excess inertia? *Journal of Public Economics 143*, 27-38.

Greaker, M., C. Hagem, and S. Proost (2019). Optimal battery size for EV and storage services to the grid. DP CREE.

Greene, D. (2010). Why the market for new passenger cars generally undervalues strongly fuel economy. OECD/ITF Joint Transport Research Centre Discussion Paper No. 2010-6.

Grigolon, L., M. Reynaert and F. Verboven (2018). Consumer Valuation of Fuel Costs and tax policy: evidence from the European car market. *American Economic Journal: Economic Policy, 10*(3), 193-225.

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

Hardman, S., A. Chandan, G. Tal, and T. Turrentine (2017). The effectiveness of financial purchase incentives for battery electric vehicles - A review of the evidence. *Renewable and Sustainable Energy Reviews 80*, 1100-1111.

Haugneland, P. et al. (2017). Put a price on carbon to fund EV incentives - Norwegian EV policy success. EVS30 International Battery, Hybrid, and Fuel Cell Electric Vehicle Symposium, Stuttgart.

ICCT (2018). Statistical Yearbooks.

IEA (2007). Mind the Gap, Quantifying Principle-Agent Problems in Energy Efficiency. IEA, Paris.

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

IEA (2017b). Mobility Model. IEA, Paris.

IEA (2019). World Energy Outlook 2019. IEA, Paris.

IEA (2021). Electric car registrations and market share in selected countries, 2015-2020. IEA, Paris.

Intercontinental Exchange (2020). ECX EUA Futures. `https://www.quandl.com/data/CHRIS/ICE_C1-ECX-EUA-Futures-Continuous-Contract-1-C1-Front-Month` Accessed 10 November 2020.

IPCC (2018). An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Poertner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. In Press.

Kochhan, R. et al. (2017). An Overview of Costs for Vehicle Components, Fuels, Greenhouse Gas Emissions and Total Cost of Ownership Update 2017. ResearchGate.

Li, W., R. Long, H. Chen, and J. Geng (2017). The market for electric vehicles: indirect network effects and policy design. *Journal of the Association of Environmental and Resource Economists 4*(1), 89-133.

Li, S., L. Long, J. Xing and Y. Zhou (2017). A review of factors influencing consumer intentions to adopt battery electric vehicles. *Renewable and Sustainable Energy Reviews 78*, 318-328.

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

Maciuli, P., I. Konstantinaviciute, and V. Pilinkiene (2018). Evaluation of the Role of National and Local Authorities in Electric Vehicle Promotion Systems. IAEE Energy Forum.

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.

Muncrief, R. and B. Sharpe (2015). Overview of the heavy duty vehicle market and CO_2 emissions in the European Union. *ICCT Working Paper 2015-6*. Washington DC: ICCT.

Nadiri, M.I. (1993). Innovations and technological spillovers. *NBER Working Paper No. 4423*.

Nordhaus W. (2014). The Perils of the Learning Model for Modeling Endogenous Technological Change. *The Energy Journal 35*(1), 1-13.

Norris, J. and G. Escher (2017). Heavy Duty Vehicles Technology Potential and Cost Study. ICCT.

Oates, W.E. (1972). Fiscal Federalism. Harcourt Brace and Jovanovich, New York.

OECD (2013).Taxing Energy Use: A Graphical Analysis. OECD Publishing, Paris.

OECD (2016a). Effective Carbon Rates: Pricing CO_2 through Taxes and Emissions Trading Systems. OECD Publishing, Paris.

OECD (2016b). Consumption Tax Trends 2016: VAT/GST and excise rates, trends and policy issues. OECD Publishing, Paris.

OECD/IEA (2017). Global EV Outlook 2017, OECD/IEA, Paris.

Paltsev, S. et al. (2018). Reducing CO_2 from cars in the European Union. *Transportation 45*(2), 573-595.

Pasaoglu, G. et al. (2012). Driving and parking patterns of European car drivers - a mobility survey. Joint Research Centre of the European Commission, Luxembourg.

Perino, G. (2018). New EU ETS Phase 4 rules temporarily puncture waterbed. *Nature Climate Change 8*(4), 262-264.

Perino, G., R.A. Ritz, and A. van Benthem (2019). Understanding Overlapping Policies: Internal Carbon Leakage and the Punctured Waterbed. *NBER Working Paper No. 25643.* Cambridge, Massachusetts: National Bureau of Economic Research.

Pietzcker, R et al. (2013). Long-term transport energy demand and climate policy. Alternative visions on transport decarbonization in energy-economy models. *Energy 64*, 95-108.

Popp, D. (2019) Environmental policy and innovation: a decade of research. *CESifo Working Paper No. 7544.* Munich: CESifo.

Proost, S. and K. van Dender (2008). Optimal urban transport pricing in the presence of congestion, economies of density and costly public funds. *Transportation Research Part A - Policy and Practice 42*(9), 1220-1230.

Reynaert, M. (2020). Abatement Strategies and the Cost of Environmental Regulation: Emission Standards on the European Car Market. *The Review of Economic Studies.*

Richardson, D. (2013). Electric vehicles and the electric grid. A review of modeling approaches, impacts, and renewable energy integration. *Renewable and Sustainable Energy Reviews 19*(C), 247-254.

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.

Simon, L.K. (1984). Bertrand, the Cournot Paradigm and the Theory of Perfect Competition. *The Review of Economic Studies 51*(2), 209–230.

Springel, K. (2018). Network externality and subsidy structure in two-sided markets: Evidence from electric vehicles incentives. Forthcoming.

Tagliapietra, S. and G. Zachmann (2018). Addressing Europe's failure to clean up the transport sector. Bruegel Policy Brief (2).

Tattini, J., M. Maurizio, and K. Karlsson (2018). Reaching carbon neutral transport sector in Denmark – Evidence from the incorporation of modal shift into the TIMES energy system modeling framework. *Energy Policy 113*(C), 571-583.

U.S. Department of Energy: Office of Energy Efficiency and Renewable Energy (2017). Electric Vehicles: Tax Credits and Other Incentives, U.S. DOE, Washington DC.

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

van Biesebroeck, J. and F. Verboven (2018). Barriers to the large-scale production of zero-emission vehicles. Final report prepared for the OECD.

van der Steen, M. et al. (2015). EV Policy Compared: An international comparison of governments' policy strategy towards E-Mobility. *E-Mobility in Europe*, 27-53.

van der Zwaan, B. et al. (2002). Endogenous Technological Change in Climate Change Modelling. *Energy Economics 24*(1), 1-19.

van der Zwaan, B., I. Keppo, and F. Johnsson (2013). How to decarbonize the transport sector? *Energy Policy 61*, 562-573.

Wangsness, B. et al. (2020). Vehicle choices and urban transport externalities. Are Norwegian policy makers getting it right? *Transportation Research Part D-Transport and Environment 86*.

Yao, D. A. (1998). Strategic responses to automobile emissions control: A game-theoretic analysis. *Journal of Environmental Economics and Management 15*(4), 419-438.

Zhang, R. et al. (2017). Modelling Transport Energy Demand and Emissions: Development of a Global Passenger Transport Model Coupled with Computable General Equilibrium Model. IAEEE.

Zhou, Y. and S. Li (2018). Technology adoption and critical mass: the case of the U.S. electric vehicle market. *The Journal of Industrial Economics 66*(2), 423-480.

Eidesstattliche Versicherung

Ich versichere hiermit eidesstattlich, dass ich die vorliegende Arbeit selbständig und ohne fremde Hilfe verfasst habe. Die aus fremden Quellen direkt oder indirekt übernommenen Gedanken, sowie mir gegebene Anregungen, sind als solche kenntlich gemacht. Die Arbeit wurde bisher keiner anderen Prüfungsbehörde vorgelegt und auch noch nicht veröffentlicht. Sofern ein Teil der Arbeit aus bereits veröffentlichten Papers besteht, habe ich dies ausdrücklich angegeben.

Ort, Datum: München, 21.07.2021

Christina Littlejohn